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RECEIVED 17 April 2025

ACCEPTED 21 May 2025

PUBLISHED 09 June 2025

CITATION

Mane S, Patil RB, Siddiqui MIH, Chan CK and Xu Y (2025) Effect of cutting parameters and tool coating on residual stress and cutting temperature in dry hard turning of AISI 52100 steel using finite element method. *Front. Mater.* 12:1613630. doi: 10.3389/fmats.2025.1613630

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Effect of cutting parameters and tool coating on residual stress and cutting temperature in dry hard turning of AISI 52100 steel using finite element method

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Hard turning is a high-precision machining approach widely adopted in manufacturing for finishing hardened alloy steels that exhibit superior hardness and excellent wear resistance. The residual stresses induced during the hard turning process significantly impact the performance and reliability of the machined component. This study presents a comprehensive finite element analysis to predict residual stress distribution and thermal behavior during dry hard turning of AISI 52100 steel under varying cutting conditions. The Power Law material model, incorporating a strain hardening function, was employed to simulate the material's behavior at high strain rates, accounting for strain rate sensitivity and thermal softening due to elevated temperatures during machining. The model further includes a Coulomb friction approach to capture the interactions between the tool, chip, and workpiece. The cutting speed was found to have the most significant impact on surface tensile stresses. The subsurface residual stresses were greatly affected by the feed rate. The elevated feed rates resulted in increased compressive residual stresses being induced in the machined component. The developed FEM model demonstrated its effectiveness as an essential tool for pre-processing residual stress predictions, which in turn helps in the design and manufacture of reliable, high-quality, components. The thermal performance of coated carbide tools; more specifically, the performance of titanium nitride (TiN), titanium carbonitride (TiCN), and aluminum oxide (Al₂O₃) coating layers were examined. Tools coated with multilayer structures incorporating Al₂O₃ as the top layer demonstrated superior thermal barrier performance, leading to a notable reduction in both heat generation and maximum cutting temperatures. The cutting temperature data recorded using embedded thermocouple technique with infrared thermometers showed a good agreement with the FEM results. This validation confirms the

AdvantEdge's simulation precision and enhances understanding of machining dynamics, contributing to robust component design with superior surface integrity.

KEYWORDS

hard turning, residual stresses, finite element method (FEM), strain-rate sensitivity, surface integrity, process innovation

1 Introduction

Machining hardened materials using hard turning has gradually emerged as a viable alternative to conventional grinding, owing to its efficiency and cost-effectiveness. It offers several advantages, including reduced setup times, improved process efficiency, shorter cycle times, and lower costs. However, the high thermo-mechanical loads involved in this high-strain-rate material removal process result in elevated cutting temperatures and induce complex residual stress distributions, which significantly influence the machined surface properties such as surface integrity, fatigue life, and dimensional stability. These residual stresses play a crucial role in determining the structural integrity and service performance of components, especially under dynamic loading conditions. The residual stress formation during machining of hard-to-cut material is a crucial area of research where the interest in the prediction of these stresses and understanding their origins and mitigating their adverse effects is increasing. The research shifted its focus from measuring post-process residual stresses to developing methods for predicting pre-process residual stresses through numerical simulations using finite element method (FEM). Tool coatings significantly influence temperature distribution within the cutting zone by acting as thermal barriers that reduce heat conduction into the tool substrate. Coatings such as TiN, TiCN, TiAlN or Al_2O_3 exhibit low thermal conductivity and high oxidation resistance, effectively confining heat to the chip and reducing thermal load on the cutting edge. This localized heat management not only delays tool wear but also stabilizes cutting temperatures, leading to improved surface integrity and process consistency during dry hard turning of hardened steels. In this context, specialized simulation platforms are widely used for stress analysis, facilitating a comprehensive understanding of thermo-mechanical interactions during the metal-cutting process. The experimental and empirical studies examined the influence of process parameters, such as feed rate, depth of cut, and tool geometry on residual stress states in precision hard turning. [Table 1](#) presents the literature review of residual stress formation, tool coatings, thermal effects, and simulation approaches.

Modeling the machining process with FEM-based simulation offers valuable insights into process dynamics. DEFORM and AdvantEdge are simulation platforms with extensive modeling capabilities and can integrate material properties, tool geometries, and process parameters. AdvantEdge provides the best predictions compared to several other software within the cutting conditions used. However, the combined influence of cutting speed, feed rate, and depth of cut on residual stress formation in dry hard turning requires further exploration. Additional research is needed

to understand how these parameters interact when subjected to increased mechanical and thermal stresses during dry machining, as they do affect stress distribution. Heat dissipation is greatly influenced by tool coatings such as TiN, TiCN, and Al_2O_3 , although the effect of coating material and thickness on thermal performance is not well demonstrated and the stated results in the literature are inconsistent and contradictory. The objectives of this research are as below:

- To develop a FEM-based predictive model for pre-process residual stress prediction and tool coating selection to achieve improved machining performance in dry hard turning.
- To analyze the influence of cutting parameters: cutting speed, feed rate, and depth of cut on residual stresses induced during dry hard turning using Finite Element Method (FEM).
- To study the effect of different coating materials on temperature distribution and heat rate in the cutting zone.

2 Materials and methods

Finite element analysis is an essential and integral tool for the simulation of machining processes. These methods facilitate the analysis of the metal cutting process with all its difficulties in terms of fracture mechanics, heat transfer, performance in the plastic and elastic state of a material, metallurgy, and the effect of using coolants. The finite element method (FEM) based commercial software 'AdvantEdge' was used in this study for process simulation and analysis. AdvantEdge is an explicit dynamic Lagrangian code capable of conducting conjugate thermo-mechanical transient analysis. This software uses an adaptive meshing for both chips and workpieces, that ensure accurate results. It has an extensive database of workpieces and tool materials that are typically used in cutting operations and provide all the data necessary for efficient material modeling. The workpiece material, cutting tools, and process settings were modeled from the software menu and data library. Cutting parameter combinations were chosen based on practical machining conditions, prior research, and industry relevance. This systematic selection provides a comprehensive analysis of residual stress distribution and temperature behavior in dry hard turning, ensuring direct applicability to real-world machining. This research gap highlights the importance of the development of accurate FEM models that incorporate complex heat transfer mechanisms and investigate the combined influence of cutting parameters on residual stresses and thermal performance in the hard turning process. [Figure 1](#)

TABLE 1 Review of residual stress formation, tool coatings, thermal effects, and simulation approaches.

Author(s)	Material & method	Key findings
Residual Stress Formation and Analysis		
Astakhov (2011)	Review on machining of hard materials and its industrial applications	Hard turning is a practical alternative to conventional grinding for hardened materials, offering reduced setup times and improved efficiency
Bana et al. (2007)	Machining of small bores with a focus on thermal distortions	Identified thermal distortions as a critical issue in precision machining, which hard turning helps to mitigate due to lower heat generation compared to grinding
Lalwani et al. (2008)	Finish hard turning of MDN250 steel; analysis of cutting parameters	Showed that optimized cutting parameters in hard turning can significantly reduce cutting forces and surface roughness
Wang et al. (2017a)	Ball end milling of Inconel 718	Residual stresses greatly influenced by cutting speed and depth of cut; thermal effects produced more tensile stresses, while mechanical effects induced more compressive stresses
Dahlman et al. (2004)	Hard turning; varied feed rate, depth of cut, and rake angle	Increased feed rate and more negative rake angle led to higher compressive residual stresses and deeper affected zones
Bordinassi et al. (2006)	Hard turning with specific cooling-lubricating methods	Residual stress distribution in the surface layer is significantly influenced by cutting parameters
Warren and Guo (2009)	Hard turning of AISI 52100 (62 HRC); X-ray diffraction	Both surface and subsurface exhibited compressive residual stresses; white layer surfaces showed elevated tensile stress within the white layer
Leppert and Peng (2012)	Turning AISI 316L under dry, MQL, and wet conditions	Cutting speed increased hoop and axial residual stresses; feed rate had less effect on hoop stress but increased axial stress; depth of cut showed no significant effect
Hosseini et al. (2014)	Turning hardened AISI 52100 with CBN inserts	Thermally expanded white layer contained more retained austenite and higher residual stress; surface and subsurface stresses were inherently compressive
Laubscher et al. (2014)	Computational analysis using AdvantEdge on Ti6Al4V	Titanium's poor thermal conductivity induced compressive residual stresses near the surface; model had limitations at elevated cutting speeds
Caruso et al. (2014)	Machining hardened AISI 52100 under dry and cryogenic cooling; X-ray diffraction	Cryogenic cooling limited white layer thickness, shifting residual stress profile nearer the surface, resulting in less compressive surface stress and maximum compressive stress below the surface
Wang et al. (2017b)	3D numerical and empirical models for Inconel 718 ball end milling	Numerical model effectively estimated residual stresses; empirical model correlated well with experimental results
Bertolini et al. (2020)	Machining under various cooling conditions	Radial residual stresses more influenced by cooling condition than cutting speed; cryogenic cooling led to compressive residual stress, while flood coolant led to tensile stress near the surface
Chavan and Sargade (2020)	Hybrid nanofluid MQCL vs. dry machining	Hybrid nanofluid MQCL achieved lowest surface roughness, microhardness, compressive residual stresses, and thin white layer; dry machining showed worse surface integrity
Luo et al. (2020)	AdvantEdge simulation of 7075-T651 aluminum alloy turning	Higher cutting speeds and feed rates increased residual stresses due to higher thermal loads and mechanical deformation

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TABLE 1 (Continued) Review of residual stress formation, tool coatings, thermal effects, and simulation approaches.

Author(s)	Material & method	Key findings
Li et al. (2022)	Predictive model for Ti-6Al-4V turning	Residual stresses changed from compressive to tensile with increased cutting speed
Zhou et al. (2024)	FEM analysis on AISI H13 steel	Increasing depth of cut increased tensile residual stresses near the machined surface, reducing fatigue life
Chen et al. (2024)	AdvantEdge simulation focusing on tool-chip interface	Accurate modeling of tool-chip interface friction significantly influences residual stress formation
Weng et al. (2023)	Coupled Eulerian–Lagrangian (CEL) FEM simulations	CEL approach facilitated precise predictions of residual stresses during sequential cuts, validated by experimental results
Wan et al. (2019)	Analytical and FEM methodologies	FEM allows in-depth understanding of plastic deformation and residual stress distribution during machining
Feng et al. (2024)	Spray cooling parameters in GH4169 steel turning	Different cooling parameters significantly affect cutting temperature, influencing residual tensile stresses; offers systematic approach for optimizing cooling parameters
Sharif and Rahim (2007)	Drilling of Ti-6Al-4V using coated and uncoated carbide tools	Coated tools (e.g., TiN, TiC, TiCN, Al ₂ O ₃ , TiAlN) exhibited higher hardness, lower surface roughness, and better thermal resistance than uncoated tools, leading to improved tool life and reduced cutting temperature
Ucun and Aslantas (2011)	Numerical simulation of orthogonal cutting using multilayer and single-layer coated tools	Tool coatings like TiC, TiCN, and TiN reduced crater wear and interfacial friction, while Al ₂ O ₃ acted as a thermal barrier, enhancing dimensional accuracy and cutting performance
Özel and Altan (2000)	High-speed cutting; determination of flow stress and chip-tool contact friction	Highlighted the critical role of temperature in machining; accurate modeling of flow stress and friction helped in understanding temperature rise and its effects on tool-workpiece interaction
Du et al. (2001)	Thermal analysis of coated cutting tools using the boundary element method	Found that tool coatings reduce temperature transfer to the tool substrate; coatings act as thermal insulators and improve heat management during machining
Tool Coatings and Thermal Effects		
Kusiak et al. (2005)	Al ₂ O ₃ , TiN, TiAlN, TiAlN + MoS ₂ coatings on steel	Al ₂ O ₃ coating produced the lowest heat flux in the tool; other coatings showed no significant effect compared to uncoated tool
Kivak et al. (2020)	Turning using PVD TiN coated Al ₂ O ₃ +TiCN ceramic tool with nano-solid particle reinforced cutting fluid	TiN coating oxidizes to TiO ₂ at elevated temperatures, leading to crack formation and brittle delamination, which deteriorates the mechanical and tribological properties of the coated tool
Sahoo and Sahoo (2012)	Multi-layer TiN/TiCN/Al ₂ O ₃ /TiN coated carbide tool on AISI 4340	Outperformed uncoated and TiN/TiCN/Al ₂ O ₃ /ZrCN coated tools in surface finish, flank wear, chip removal volume, tool life, and economic aspects during dry hard turning
Chinchanikar and Choudhury (2013)	MT-TiCN/Al ₂ O ₃ /TiN CVD-coated vs. TiAlN PVD-coated tools	Multi-layer CVD-coated tools reduced abrasion at higher temperatures and improved tool life compared to single-layer PVD-coated inserts
Panda et al. (2018)	TiN/TiCN/Al ₂ O ₃ coated carbide inserts on AISI 52100	Multilayer coated inserts with Al ₂ O ₃ top layer significantly improved surface finish and reduced tool wear

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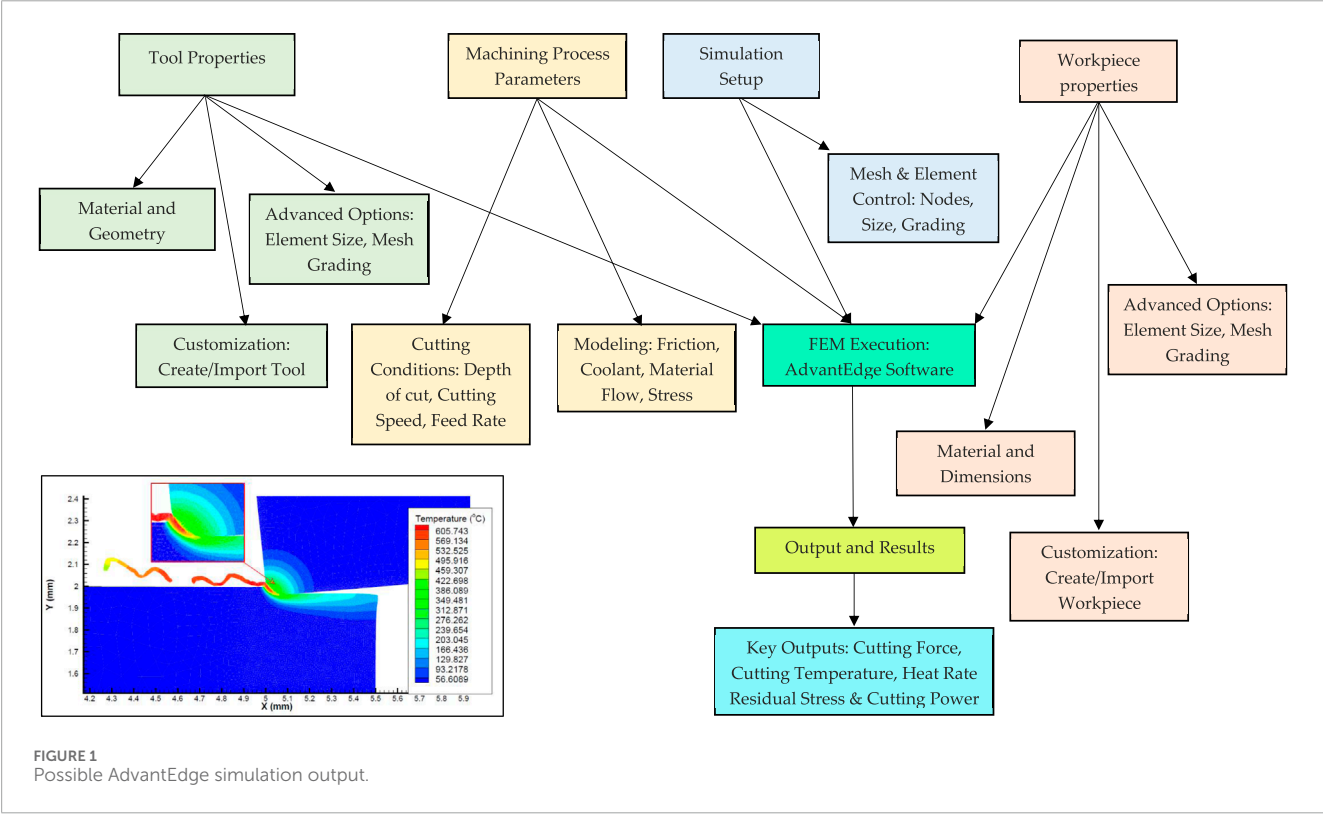
TABLE 1 (Continued) Review of residual stress formation, tool coatings, thermal effects, and simulation approaches.

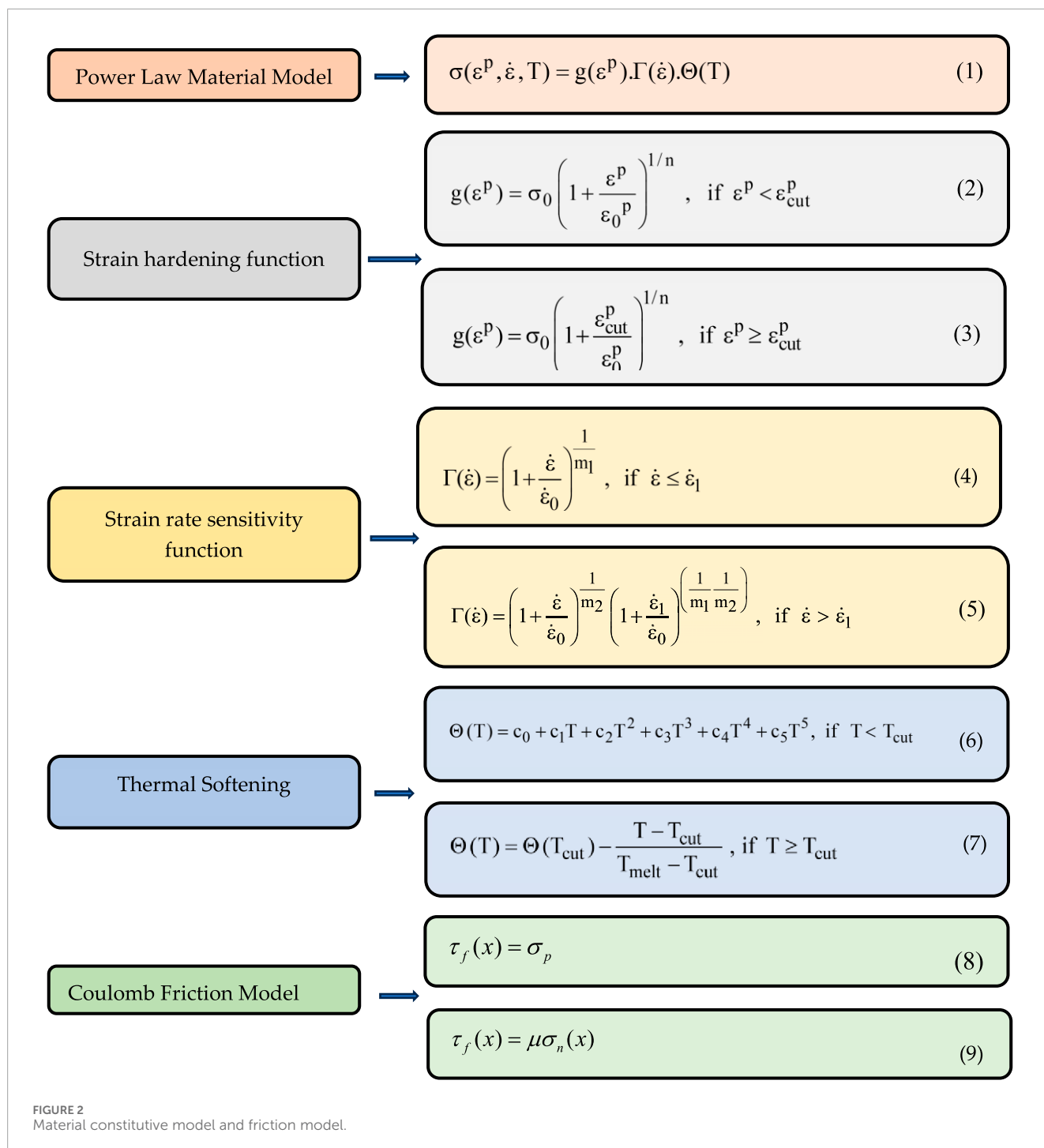
Author(s)	Material & method	Key findings
Aslantas et al. (2012)	Turning of hardened alloy steel using coated and uncoated $\text{Al}_2\text{O}_3/\text{TiCN}$ ceramic tools	Coated tools exhibited superior tool life and distinct wear mechanisms compared to uncoated tools, contributing to extended operational performance
Kurniawan et al. (2010)	Hard machining of stainless steel using wiper coated carbide tools	Demonstrated increased tool life and improved surface integrity with coated tools, confirming their advantage in hard turning operations
Zhang and Liu (2008)	Analytical modeling of transient temperature distributions in coated carbide tools	Coated tools showed reduced temperature rise due to better thermal management, contributing to higher cutting efficiency and stability during machining
Zhao et al. (2022)	PVD $\text{Ti}_{0.55}\text{Al}_{0.45}\text{N}$ coatings on Inconel 718	Moderate thickness improved anti-friction properties and thermal barrier effect
Zhang et al. (2022)	Monolayer and multilayer-coated tools on AISI H13	Studied heat transfer mechanisms; multilayer coatings offered better thermal barrier performance
Hao et al. (2024)	TiC, TiN, Al_2O_3 , TiAlN coatings on AISI H13	TiAlN coating revealed as the best thermal barrier, effectively reducing cutting temperature
Simulation and Modeling Approaches		
Grzesik et al. (2005)	FEM model on coated tools	TiN and Al_2O_3 coatings effectively reduced cutting temperature, enhancing tool life and workpiece quality
Thakare and Nordgren (2015)	Thirdwave AdvantEdge-2D FE software on AISI 4340	Significant fit between predicted rake face temperature and values measured through infrared CCD camera
Ceretti et al. (2007)	DEFORM-2D FE V9.0 system on AISI 1045	Arbitrary Lagrangian-Eulerian approach adopted; cutting temperature findings verified using embedded thermocouple
Zhang and Liu (2017)	Non-Fourier heat conduction model	Coated tools effectively reduced temperatures: Al_2O_3 coatings offered superior thermal barrier performance
Hao et al. (2019)	Study on TiAlN coating	TiAlN coating significantly reduced friction in AISI H13 hardened steel machining, minimizing tool-chip contact length and cutting temperatures
Corrêa Ribeiro et al. (2022)	COMSOL [®] simulations on Al_2O_3 and TiN coatings	Al_2O_3 acted as an effective thermal barrier; TiN exhibited a comparatively moderate temperature gradient
Corrêa Ferreira et al. (2023)	Adaptive Sequential Function Specification Method (ASFSM)	Coatings reduced tool-chip contact and improved thermal protection at higher cutting speeds
Sadeghifar et al. (2023)	3D FEM model on forged steel blocks	Double tempering generated sufficient compressive stress, potentially eliminating the need for a second tempering step
Journal and Mechanical (2024)	Turning with Preventive Heating (TPH) approach	AdvantEdge™ offered as the most effective tool for simulating hard-to-cut materials
Elsheikh et al. (2022)	FEM modeling	Residual stress modeling remains challenging due to plasticity complexities; AdvantEdge offers reliable simulations through adaptive meshing and built-in tool-material databases
Leveille et al. (2024)	3D hybrid modeling method on reaming operation	Numerical results aligned closely with experimental residual stresses obtained from X-ray diffraction
Tounsi and El-Wardany (2022)	FEM analysis	Mesh size and cutting edge radius significantly influence residual stress prediction; finer meshes needed for steep gradients

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TABLE 1 (Continued) Review of residual stress formation, tool coatings, thermal effects, and simulation approaches.

Author(s)	Material & method	Key findings
Yao et al. (2022)	AdvantEdge FEM 5.6 software on GH4169	Simulation of residual stress during sequential side milling demonstrated high consistency with experimental findings, achieving 92.8% prediction accuracy
Jiang et al. (2023)	ABAQUS simulation on Inconel 718	Simulation model predicted residual stress in micro-milling of thin-walled components, validated against XRD measurements
Sharma et al. (2024)	Bayesian machine learning approach	Predicted cutting forces and residual stresses in micro end milling of aluminum alloys with high accuracy
Han et al. (2024)	3D simulation model on AISI 4140	MISULAB server-based software capable of predicting residual stress profiles
Zhou (2024)	FEM, mesh-free methods, and machine learning models	Recent advancements improved residual stress prediction; future focus on hybrid strategies for multiscale cutting-induced stresses
Sofuoğlu et al. (2025)	DEFORM 3D model on aerospace alloy machining	Experimental and simulation results showed strong agreement, validating the model's accuracy
Kadirgama and Bakar (2005)	Analytical and numerical modeling of residual stress in machining	Residual stress distribution is significantly influenced by cutting speed, feed rate, and thermal effects; essential for optimizing machining-induced stress
ThirdWaveSystems (2015)	FEA-based simulation using AdvantEdge™ software	Accurately predicts residual stress, temperature, and chip formation
Umbrello et al. (2007)	Evaluation of global heat transfer coefficient during metal cutting	Determined the global heat transfer coefficient to be approximately 60 W/m²K during machining operations





presents the possible simulation output of AdvantEdge Software.

2.1 Material constitutive model and friction model

The material model is a crucial aspect of finite element simulation, significantly influencing the accuracy of the results. To ensure precise simulations, the Power Law material

model was selected to conduct the simulation. It comprises a strain hardening function, denoted as $g(\varepsilon^p)$, and a thermal softening function, denoted as $\theta(T)$. The strain rate sensitivity function is represented by $\tau(\dot{\varepsilon})$. Figure 2 illustrates the material constitutive model based on the Power Law and Coulomb friction model. Material constitutive model describes the relationship between stress and strain in the plastic deformation region. This model accounts for strain hardening behavior, where the flow stress is a function of strain, strain rate, and temperature, making it essential

TABLE 2 Thermo-mechanical properties AISI 52100 alloy steel (58 HRC).

Sr. No.	Material properties	Magnitudes
01	Elastic Modulus	200–210 GPa
02	Yield Strength	2000 Mpa
03	Ultimate Tensile Strength	2500 Mpa
04	Hardness	58 HRC
05	Density	7.81 g/cm ³
06	Poisson's Ratio	0.27–0.39
07	Thermal Conductivity	21–46.6W/m°C, (f(t)-temperature-dependent)
08	Specific Heat Capacity	460 J/kg-K f(t)
09	Thermal Expansion Coefficient	11.3–15.3 × 10 ⁻⁶ K ⁻¹ f(t)
10	Strain Hardening Exponent	0.08–0.15
11	Strain Rate Sensitivity Exponent	0.01–0.03
12	Strain Rate ($\dot{\epsilon}$)	10 ⁵ to 10 ⁷ s ⁻¹
13	Emissivity	0.6–0.7
14	Cut-off Temperature	1200–1400°C

TABLE 3 Thermo-mechanical properties of coating materials.

Material	Al ₂ O ₃	TiCN	TiN	WC-uncoated
Coating thickness (μm)	3–5	4–8	1.5–3	-
Hardness (HV)	2,000	3,000	2,300	-
Thermal expansion coefficient (x10 ⁻⁶ ; K ⁻¹)	8.4	8	9.4	5
Modulus of elasticity (GPa)	415	448	600	650
Poisson ratio	0.22	0.23	0.25	0.25
Density (kg/m ³)	3,780	4,180	4,650	11,900
Heat capacity (N/mm ² °C)	3.42	2.5	3	15
Thermal conductivity (W/m°C)	33 (50°C)	26 (25°C)	20 (40°C)	30 (30°C)
	28 (90°C)	27 (100°C)	21 (100°C)	32 (100°C)
	19 (300°C)	28 (300°C)	22 (300°C)	34 (300°C)
	13 (500°C)	30.5 (500°C)	23.5 (500°C)	37 (500°C)
	7 (1000°C)	33.5 (1000°C)	26 (1000°C)	44 (1000°C)
	7 (1300°C)	35 (1300°C)	27 (1300°C)	47.5 (1300°C)

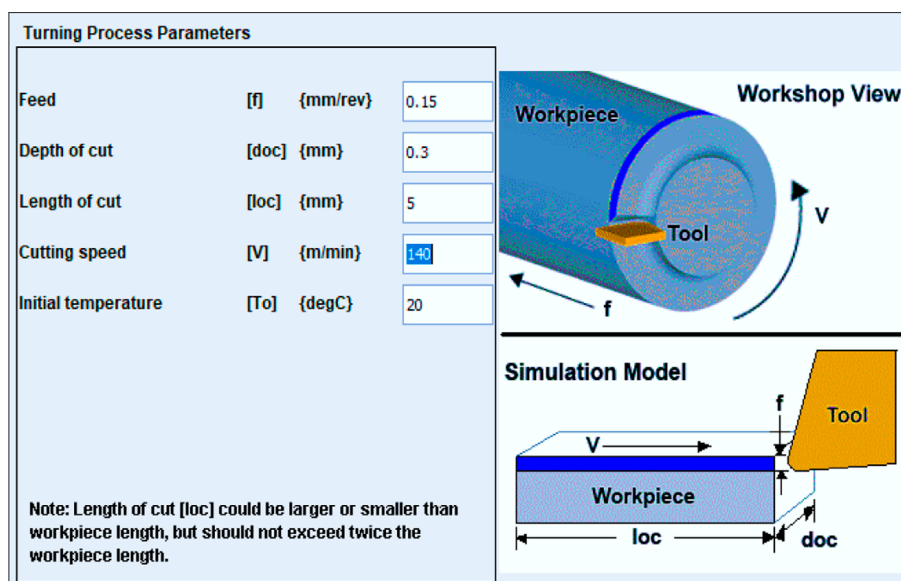


FIGURE 3
Schematic representation of turning process in 2D and turning process parameters.

for accurately simulating material behavior in machining processes.

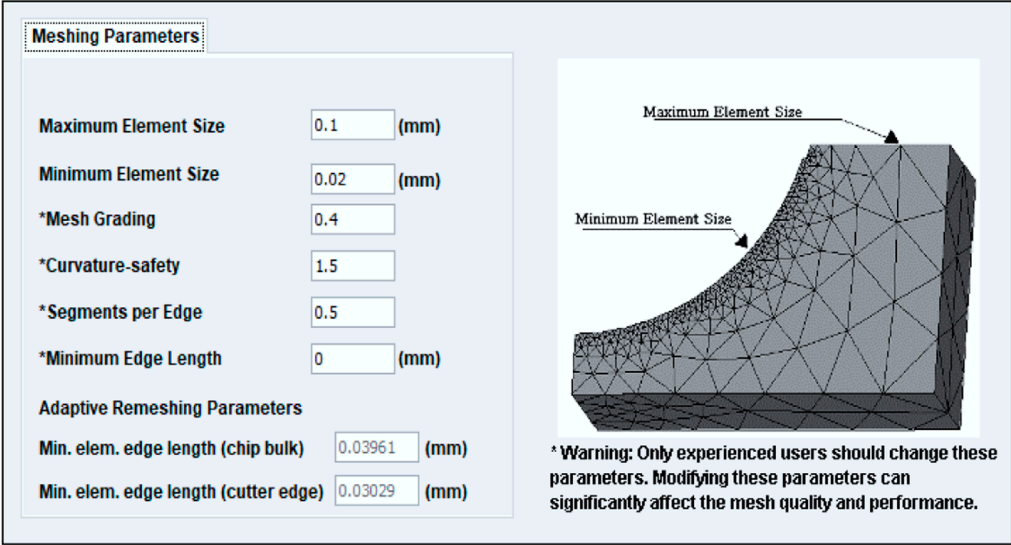
The material constitutive model governed by the Power Law is illustrated in Figure 1. During metal cutting processes, the material undergoes deformation in both the primary and secondary cutting zones. This deformation takes place at high temperatures and involves extremely high stresses and strain rates (ranging from 10^5 to 10^7 s⁻¹). Conversely, the rest of the workpiece undergoes deformation at moderate or even modest rates of strain. The strain hardening function $g(\epsilon^p)$, the strain rate sensitivity model used for computing flow stress and thermal softening function $\Theta(T)$ and the thermal softening function are all presented in the flowchart in Figure 2. The simulation results can be significantly influenced by the friction coefficient between the tool and the workpiece. AdvantEdge simulation software adopts the classical sliding friction approach to simulate the friction that occurs at the contact point between the tool and the chip. The concept is founded on the principle that the force of frictional sliding is directly proportional to the normal load. The relationship between these forces is defined by the coefficient of friction (μ), which is considered a constant value during contact between the tool and the chip. This model considers the combined length of the adhesive and sliding areas as the tool-chip contact length. The frictional behavior at the tool-chip interface, governed by Coulomb's model, is illustrated in Figure 2.

Thermo-mechanical properties substantially affect the parameters of constitutive models in AdvantEdge machining simulation. The basic option offers a predefined material library, whereas the custom option enables users to select specific properties. AdvantEdge automatically integrates these properties into its constitutive models, which govern strain hardening, strain rate sensitivity, and thermal softening. Table 2 delineates the thermo-mechanical properties of tool workpiece materials.

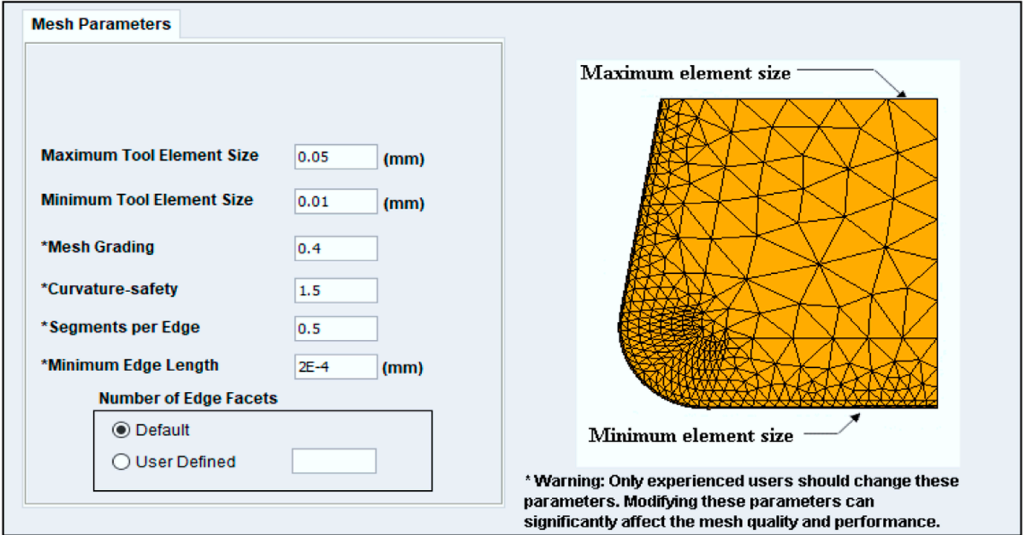
2.2 Tool modeling

The WC-Co sintered carbide tool coated with three layers (TiN/TiCN/Al₂O₃) coating was modeled. Tool coating within AdvantEdge was done using a thin layer of an explicitly meshed coating. Three layers of coating Al₂O₃: 5 μ m, TiCN: 3 μ m and TiN: 2 μ m were selected to leverage the distinct benefits of each coating material based on previous studies, simulation trials, and experimental measurements of cutting temperature. The 2 μ m TiN layer, positioned as the innermost coating, provides robust adhesion to the carbide substrate while ensuring excellent wear resistance. The 3 μ m TiCN intermediate layer enhances the tool's hardness and fracture toughness, serving as a transitional phase to absorb mechanical stresses between the ductile inner TiN and the outer Al₂O₃ layer. The 5 μ m Al₂O₃ layer, as the outermost coating, acts as a strong thermal insulator, preventing oxidation and maintaining tool integrity under high temperature cutting conditions. This combination of coatings ensures optimal performance and durability for hard turning applications. The tetrahedral-type mesh was used for the meshing process. A total of 24,000 nodes were applied for mesh generation, with a mesh grade of 0.4 and element sizes of 0.05 mm and 0.01 mm respectively.

For accurate predictions, temperature-dependent thermal conductivity values were used. The thermal conductivity of the multi-layer coated carbide tool exhibits considerable variation as a result of its layered structure. The coating materials, including TiN, TiCN, and Al₂O₃, demonstrate low thermal conductivity (7–33 W/m·K), functioning as thermal barriers that diminish heat dissipation into the tool. The tungsten carbide substrate exhibits notably higher thermal conductivity (30–47.50 W/m·K), facilitating effective heat dissipation from the cutting zone. Interactions between the tool and workpiece, as well as the tool



(a)



(b)

FIGURE 4 (a) Workpiece meshing parameters (b) Cutting tool meshing parameters.

TABLE 4 Chemical composition of AISI 52100 steel specimen.

Chemical composition of AISI 52100 steel specimen in percentage by weight (OES)								
C %	Si %	Mn %	P %	S %	Cr %	Ni %	Cu %	Fe %
0.98	0.277	0.391	0.026	0.022	1.410	0.060	0.058	Balance
Composition of AISI 52100 steel specimen (AdvantEdge Material Library)								
C %	Si %	Mn %	P %	S %	Cr %	Ni %	Cu %	Fe %
0.98	0.230	0.350	0.025	0.025	1.450	-	-	Balance

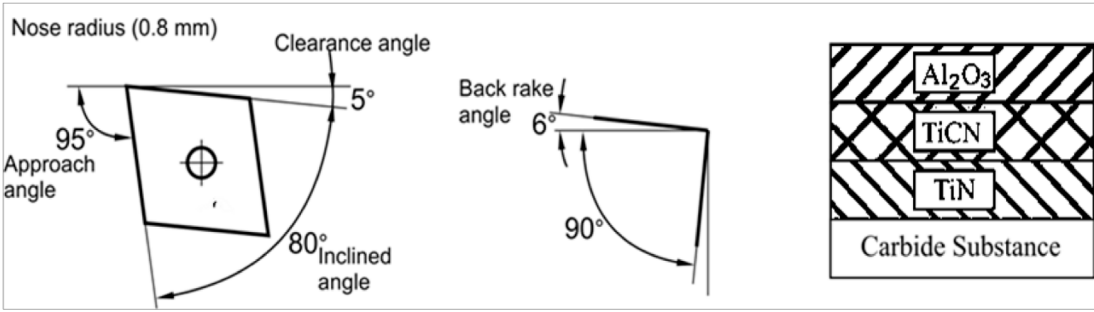


FIGURE 5
Geometry of cutting inserts and coating layer with carbide substrate.

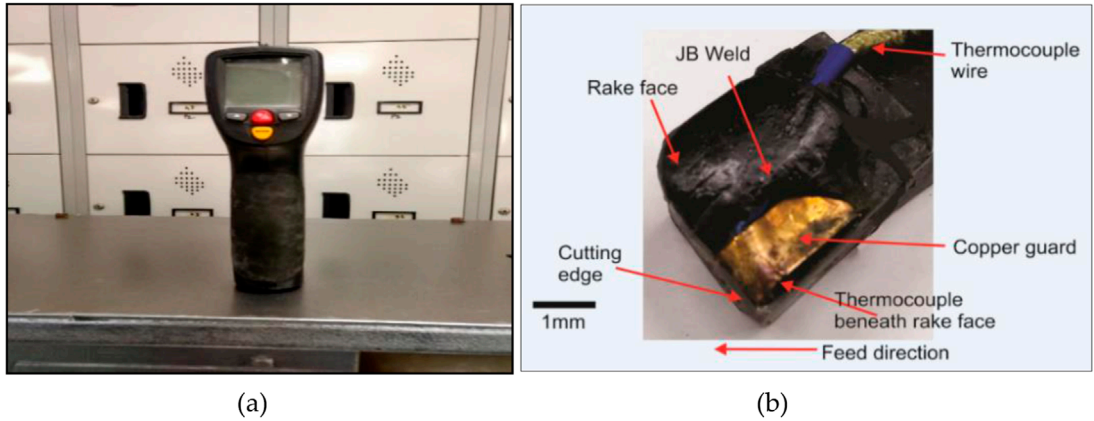


FIGURE 6
(a) Infrared thermometer (b) Cutting tool with embedded thermocouple.

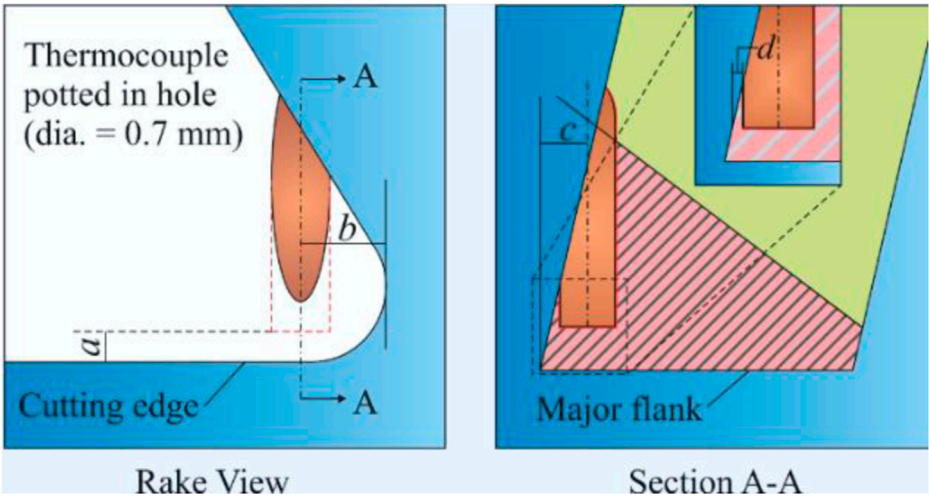


FIGURE 7
Thermocouple location.

TABLE 5 Blind hole dimensions on the inserts (mm).

a	b	c	d
0.15	1.25	0.47	0.15
0.25	1.25	0.49	
0.35	1.25	0.51	
0.45	1.25	0.53	

and chip, were modelled with friction coefficients ranging from $\mu = 0.5$ to 0.7 for hard turning. The heat partitioning ratios were established as follows: 80%–85% of heat was directed into the chip, 10%–15% into the workpiece, and 3%–7% into the tool. The thermal properties were incorporated according to established literature to ensure precise FEM-based thermal modelling and realistic temperature distribution in the simulation. Table 3 presents mechanical and thermal properties of coated and uncoated materials.

Figure 3 illustrates the turning simulation interface, allowing users to define workpiece dimensions and simulate machining process. Initial stress conditions can be adjusted through external file input for customized simulation configurations. A stress-free initial state assumption was adopted to ensure accurate thermal and mechanical behavior representation, with the interface offering a clear visual of the process for detailed analysis.

2.3 Mesh refinement

ThirdWave AdvantEdge employed a Lagrangian framework enhanced with adaptive mesh strategies to accurately track material deformation. Mesh behavior was controlled using two critical parameters: the coarsening factor, which regulated mesh expansion following large deformations, and the refinement factor, which ensured localized mesh precision. The meshing parameters for the workpiece were optimized to balance resolution and computational efficiency. The mesh featured a maximum element size of 0.1 mm and a minimum of 0.02 mm, with a mesh grading of 0.4 to ensure smooth size transitions. A curvature-safety factor of 1.5 was applied to capture complex geometries with fidelity, and edge discretization was refined using a setting of 0.5 segments per edge to enhance boundary accuracy. Figure 4 illustrates the meshing configuration adopted for the workpiece and cutting tool.

The meshing configuration adopted for the cutting tool was designed with optimized element resolution to balance accuracy and computational efficiency. The mesh featured a finest element size of 0.01 mm and a coarsest size of 0.05 mm. A mesh grading value of 0.4 was used to manage the transition between element sizes, while a curvature safety factor of 1.5 ensured the geometry's curved features were accurately captured. The edge discretization parameter was set to 6 segments per edge, and the minimum edge length was defined as 0.24 mm. Coarser mesh zones were applied to geometrically simpler regions, whereas finer meshes were allocated near critical zones to improve simulation fidelity without excessive computational load.

2.4 Friction model

The AdvantEdge simulation framework employs a classical Coulomb-based sliding friction model to characterize tool–chip interface behavior. This approach assumes a constant coefficient of friction (μ), where the frictional force scales linearly with the normal contact force. The total tool–chip contact length integrates both adhesive and sliding zones, enabling accurate prediction of interface stresses and heat generation during machining. This interaction model is represented in Figure 2. This study adopted a coefficient of friction (COF) value of 0.6 , consistent with established tribological behavior and thermomechanical conditions. This choice aligns with validated numerical modeling techniques and ensures realistic predictions of cutting forces, cutting temperatures, and temperature distributions.

2.5 Experimental method

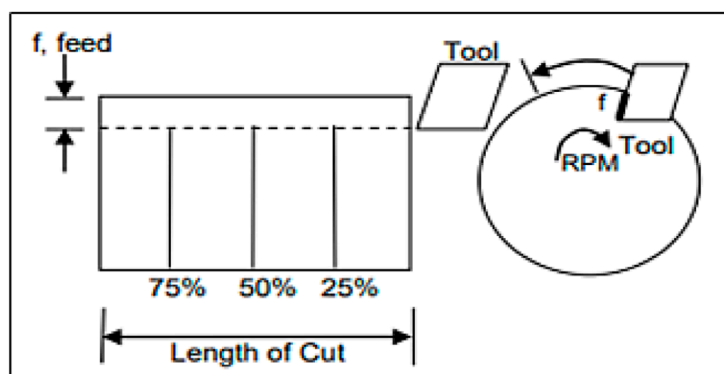
The experimental trials were conducted using an HMT NH-18 high-precision lathe, a machine well-regarded for its operational stability and consistent performance in precision turning applications.

2.5.1 Test specimen and its chemical composition

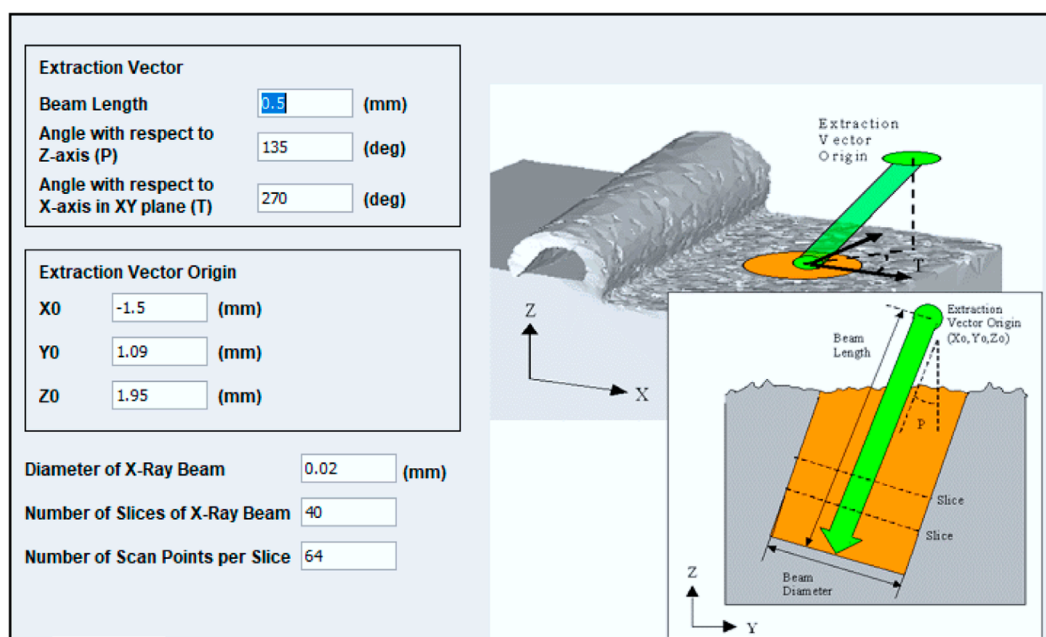
AISI 52100, a high-carbon, chromium-containing low-alloy steel, is extensively utilized in critical engineering applications such as aircraft bearing components, precision ball and roller bearings, CV joints, spinning tools, gauges, punches, dies, and ball screws. Its selection as the workpiece material in this study was driven by its prevalent use in automotive and precision manufacturing sectors. The received specimens exhibited a hardness of approximately 20 HRC. To validate the material's chemical composition, spectrometric analysis was conducted using a BRUKER optical emission spectrometer (Model: Q4 TASMAN), and the results were benchmarked against the composition data available in the AdvantEdge material database. The experimentally determined elemental composition closely matched the database entry, justifying the adoption of the standard AISI 52100 material from the simulation library. Utilizing the default material parameters from AdvantEdge enabled realistic modeling of material behavior while maintaining alignment with experimental and published references. Table 4 summarizes the elemental composition of AISI 52100 steel obtained via spectrometry and the corresponding composition from the simulation library.

2.5.2 Heat treatment of workpiece material

The heat treatment process for the AISI 52100 steel involved austenitizing the bars at 920°C for 30 min, followed by oil quenching to achieve the desired martensitic transformation. Subsequently, tempering was performed by reheating the quenched specimens to approximately 400°C , well below the lower critical temperature, threshold and maintaining this condition for 2 h. The components were then air-cooled to relieve internal stresses and promote microstructural uniformity. This thermal cycle produced a stable and homogeneous metallurgical state, thereby validating the assumption of an initially stress-free condition



(a)



(b)

FIGURE 8
(a) Lines of residual stress extraction (b) Thirdwave AdvantEdge model for residual stress.

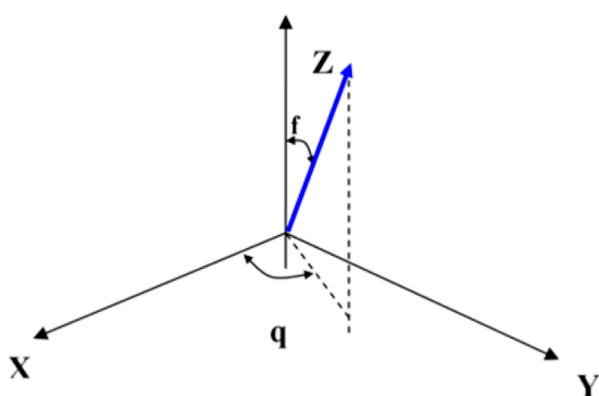


FIGURE 9
Angles for beam deflection.

in the finite element analysis. Post-treatment hardness was measured to be 58 ± 1 HRC, confirming the effectiveness of the heat treatment.

2.5.3 Cutting insert and tool holder

Multilayer-coated carbide inserts present a cost-effective solution for hard turning operations, particularly when compared to more expensive CBN, PCBN, and ceramic tools. In this study, hard turning experiments were performed using HK 150 grade inserts, which feature a multilayer coating structure designed to enhance wear resistance and thermal stability. These inserts were securely mounted on a PCLNR2020 K12 right-hand tool holder to ensure optimal cutting performance and tool alignment. The insert geometry, along with the coating architecture over the carbide substrate, is illustrated in Figure 5.

TABLE 6 Residual stress values at various cutting conditions in dry hard turning.

Sr. No.	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Tensile residual stress (MPa)	Compressive residual stress (MPa)
1	80	0.05	0.1	100	−145
2		0.10	0.1	125	−180
3		0.15	0.2	130	−200
4		0.20	0.2	140	−260
5	100	0.05	0.3	170	−210
6		0.10	0.2	150	−375
7		0.15	0.2	160	−390
8		0.20	0.3	180	−400
9	120	0.05	0.3	220	−360
10		0.10	0.4	270	−380
11		0.15	0.3	300	−500
12		0.20	0.4	320	−650
13	140	0.05	0.4	380	−340
14		0.10	0.5	400	−480
15		0.15	0.5	450	−465
16		0.20	0.4	375	−570

The detailed tool geometry, including critical angles and dimensional parameters, was meticulously embedded into the finite element model to maintain simulation accuracy and ensure alignment with actual machining configurations. This integration allowed the model to replicate realistic cutting interactions, thereby enhancing the consistency and credibility of the simulation results.

2.5.4 Measurement of cutting temperature

Accurately capturing the temperature at the tool–chip interface in metal cutting remains a complex and demanding task due to the transient and localized nature of heat generation during machining. The intricate thermal gradients and limited accessibility in the cutting zone pose significant difficulties in establishing a reliable measurement system. To address this, the present study employed a combination of an infrared thermometer and an embedded thermocouple technique to record the cutting edge temperature, in alignment with the methodology detailed by [Hoyne et al. \(2015\)](#).

[Figure 6](#) illustrate the experimental setup, featuring the infrared thermometer and the cutting tool embedded with a thermocouple, respectively. The HTC IRX-68 infrared thermometer was used for temperature measurement, offering a wide detection range of −50°C–1850°C via infrared (IR) and −50°C–1370°C via Type K thermocouple, with accuracy margins of ±1.0% for (IR) mode and

±1.5% for (Type K) thermocouple-based readings. Key features include a rapid response time under 150 ms, a high optical resolution of 50:1, and adjustable emissivity spanning from 0.10 to 1.0. Emissivity values for reliable thermal readings were derived from literature and validated experimentally. The tool exhibited emissivity in the range of 0.2–0.4, the chip between 0.5 and 0.8 (due to surface oxidation), and the workpiece between 0.4 and 0.7, depending on thermal and surface conditions. Final emissivity values were set at 0.4 for the tool and 0.6 for the workpiece based on infrared and thermocouple validation. A K-type thermocouple was precisely positioned in blind holes located less than 0.3 mm from the cutting edge, created using EDM perpendicular to the flank face. To minimize structural weakening and ensure optimal proximity (as close as 0.15 mm) to the cutting edge, blind hole dimensions were carefully chosen to preserve insert integrity post-EDM, as shown in [Figure 7](#).

To shield the thermocouple from direct interaction with chip formation during cutting operations, a copper guard was affixed over it using a high-strength metal adhesive, ensuring both thermal protection and mechanical stability. The thermocouple’s integration within the cutting insert was governed by four critical geometric parameters denoted as *a*, *b*, *c*, and *d*, which collectively defined its spatial positioning to maximize thermal sensitivity while preserving the tool’s mechanical integrity. Parameter *a* refers to the lateral

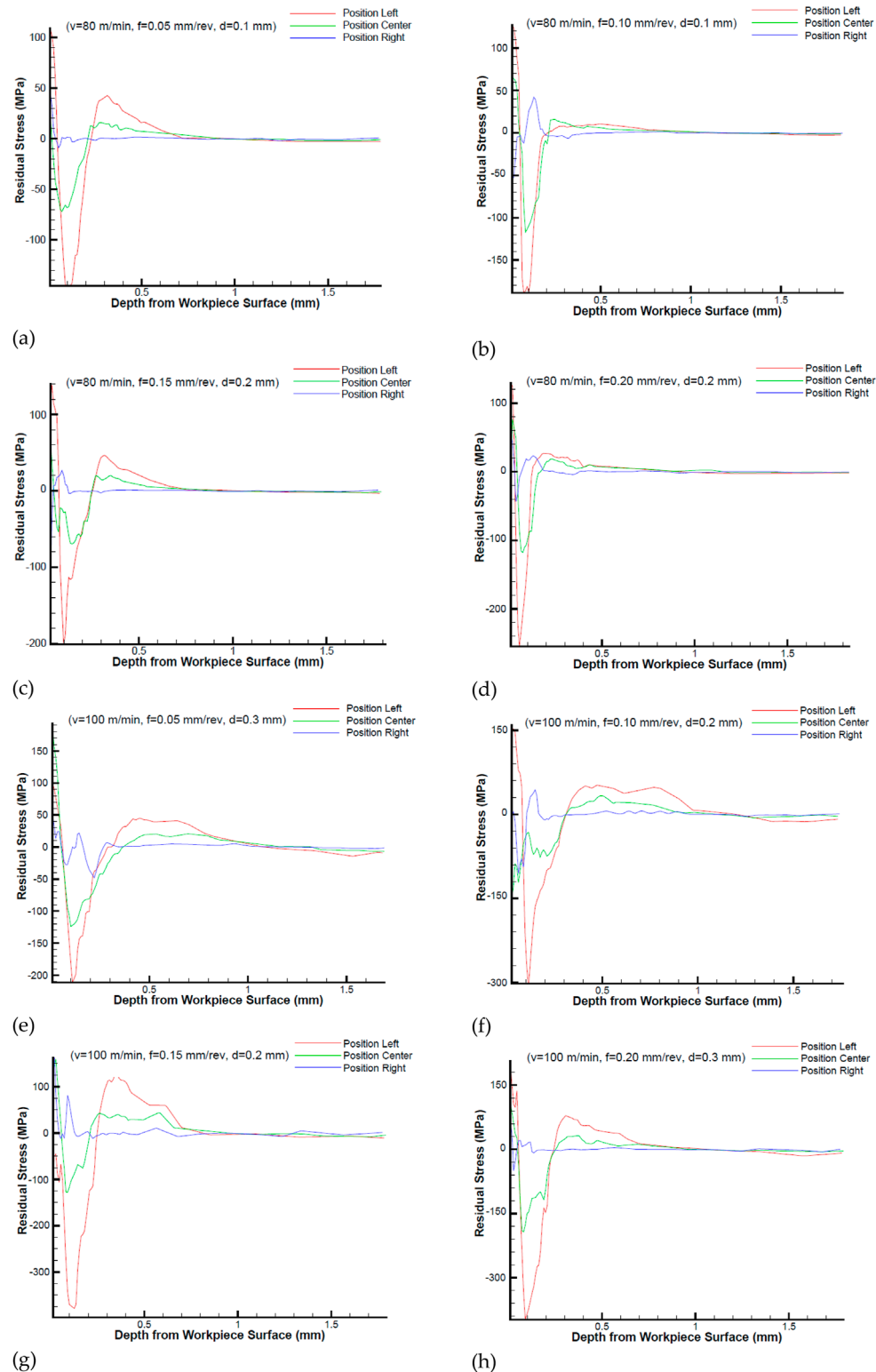


FIGURE 10
(Continued).

offset from the cutting edge along the rake face, a dimension selected to enhance thermal responsiveness while safeguarding the thermocouple from mechanical damage. Dimension b

corresponds to the vertical depth of the drilled blind hole, oriented perpendicularly to the rake surface, a key factor in determining the thermocouple's response time and positional rigidity. Parameter c

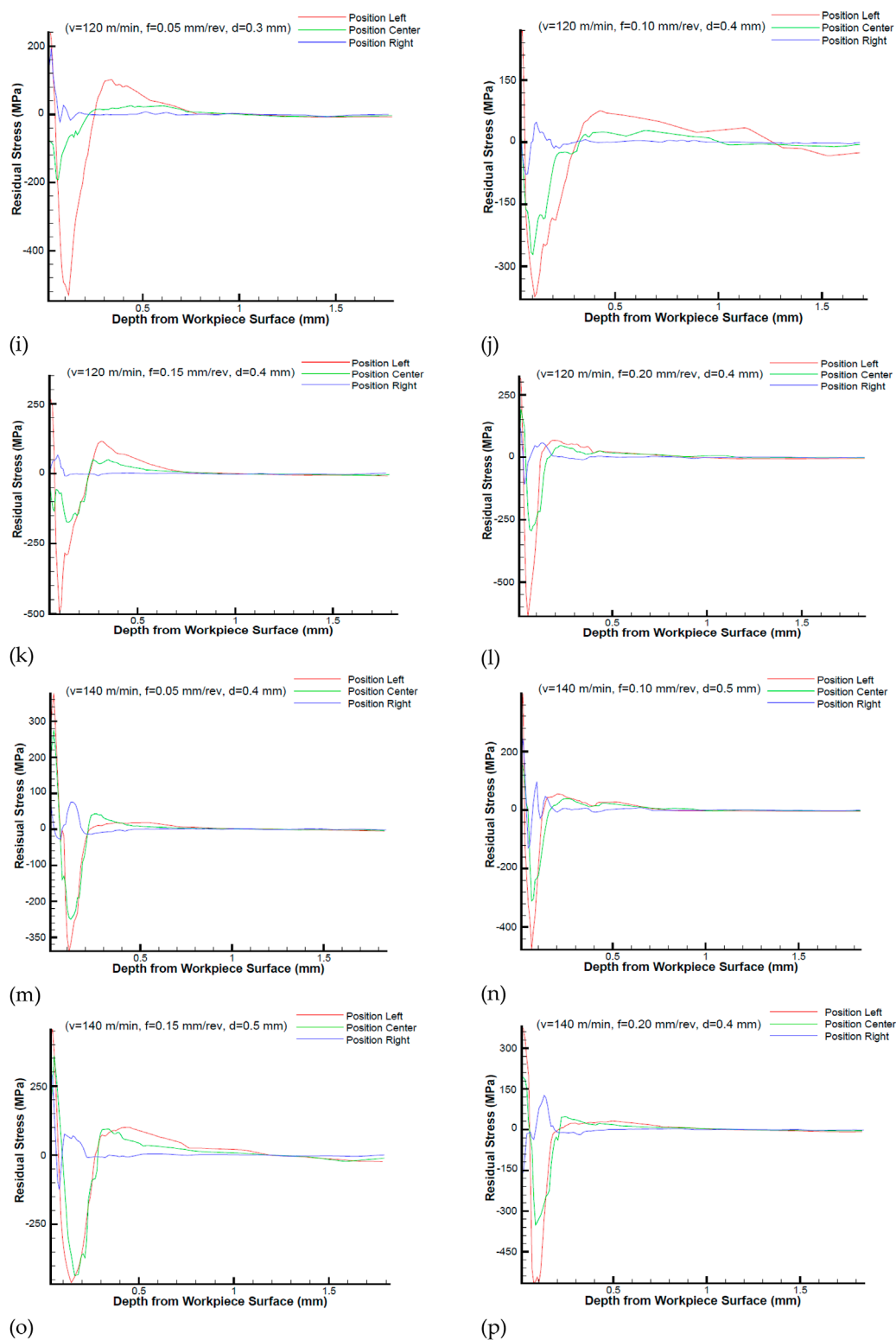


FIGURE 10
(Continued). (a–p) Residual stress profile in turning of AISI 52100 hardened alloy steel at various cutting conditions under dry environment.

measures the distance between the hole center and the principal flank face, offering flexibility for micro-adjustments in placement while avoiding compromise to tool robustness. The critical

dimension d defines the minimal remaining material thickness between the blind hole and the adjacent flank surface, meticulously controlled at 0.15 mm. This ensures a balance between proximity

TABLE 7 Machining conditions applied for modelling the process.

Cutting conditions	Descriptions
Workpiece	AISI 52100 (58 HRC)
Cutting Speed (v)	140 m/min
Feed (f)	0.20 mm/rev
Depth of cut (d)	0.4
Cutting Tool	Multilayer Coated carbide inserts (TiN/TiCN/Al ₂ O ₃)
Coating layer	Al ₂ O ₃ , TiCN and TiN
Tool Geometry	Back rake angle -6° , negative cutting edge inclination angle -6° , clearance angle 5° , approach angle 95° and nose radius 0.8 mm
Heat Transfer Coefficient	60 (W/m ² K) [57]

for accurate thermal capture and sufficient residual material to retain insert strength under load. These meticulously defined parameters collectively optimize the thermocouple's embedment, enabling precise, reliable temperature monitoring during machining. The detailed specifications for each dimension are provided in Table 5, outlining the geometry of the blind holes used in the study.

2.6 Residual stress volume averaging

Residual stresses generated during hard turning are caused due to mechanical and thermal influences, resulting in either compressive or tensile stress states on the surface, influenced by cutting parameters and the machining environment. Thermal effects have a completely different effect than mechanical effects. During exposure to intense heat fluxes, a significant temperature gradient causes localized plasticization of the workpiece material. As the surface returns to room temperature, residual tensile stresses remain on the surface accompanied by compressive stresses in the sub-surface.

The residual stress volume averaging feature within AdvantEdge software provides a residual stress prediction that mimics X-ray diffraction test data. Stress over an area is averaged as a function of depth into the workpiece surface. The stress distribution throughout an area is calculated by taking the average stress values at different depths into the surface of the workpiece. The measurement of residual stress was conducted in the circumferential direction (σ_{hoop}). The residual stress was graphed in units of stress (MPa) as a function of the distance from the surface of a machined workpiece to the center (mm). The extraction of residual stress can be performed by a single line positioned at the midpoint of the machined surface cut. The extraction was performed by taking the average of three sections (extraction at 25%, 50%, and 75%) of the machined surface. The process includes workpiece modeling, tool modeling, friction modeling, meshing, and boundary conditions. Figure 8 illustrates the lines of residual stress extraction and Thirdwave AdvantEdge

model for residual stress. The model parameters were selected based on the similar work carried out by Kadirgama et al. (2012) (Kadirgama and Bakar, 2005) and according to the guidelines given in the Third Wave AdvantEdge, AdvantEdge FEM 7.1 User's Manual (ThirdWaveSystems, 2015).

Figure 9 depicts the angles for beam deflection. Within the residual stress volumetric averaging window, a beam length and orientation were specified. Beam orientation was then calculated by considering the angle of the beam vector with respect to the Z-axis, and the angle of projection for the beam vector on the XY plane for the X-axis. Beam extraction vector origin, the diameter of the X-ray beam, the number of slices of X-ray beams, and the number of scan points per slice were specified.

3 Result and discussion

This section provides a comprehensive analysis of the effects of cutting parameters on residual stress and the role of tool coatings in controlling heat rate and temperature distribution in the cutting zone. Understanding these factors is crucial for optimizing machining performance, improving tool life, and ensuring superior surface integrity of the machined components.

3.1 Effect of cutting parameters on residual stress in dry turning environment

Numerical investigation was carried out using FEM to examine the effect of cutting parameters on surface and subsurface residual stresses (σ_{hoop}) induced after dry-hard turning. The workpiece modeling, tool modeling, friction modeling, and mesh refinement were carried out as described in previous sections. The residual stress volume averaging feature within AdvantEdge software was used to predict the residual stress which mimics X-ray diffraction test data. The cutting tool and its geometry used in the simulation and experimental work are discussed in detail in a subsequent section. The tests were conducted at various cutting conditions to understand their individual and interaction effect on residual stresses. Table 6 shows residual stress values at various cutting conditions in dry hard turning.

In the applied range of cutting conditions, the residual stresses were tensile in nature at surface and compressive in nature at subsurface, however, their magnitude varied, depending on the cutting conditions and cutting environment. Figures 10a–p presents the graphs of residual stresses vs. distance beneath the surface under different cutting conditions in dry cutting environment. The influence of cutting parameters on residual stresses in dry turning of AISI 52100 hardened alloy steel of hardness 58 HRC were studied. Figures 10a–d shows the tensile residual stresses of (100, 125, 130, and 140 MPa) at the surface and compressive residual stresses of (–145, –180, –200, and –260 MPa) at sub-surface at $v = 80$ m/min, $f = (0.05, 0.10, 0.15, \text{ and } 0.20 \text{ mm/rev})$ and $d = (0.1, 0.1, 0.2, \text{ and } 0.2 \text{ mm})$ respectively. The tensile residual stresses of 125 MPa and 130 MPa were observed at a cutting speed 80 m/min and depth of cut 0.1 and 0.2 mm, respectively. The increase of feed rate in the range

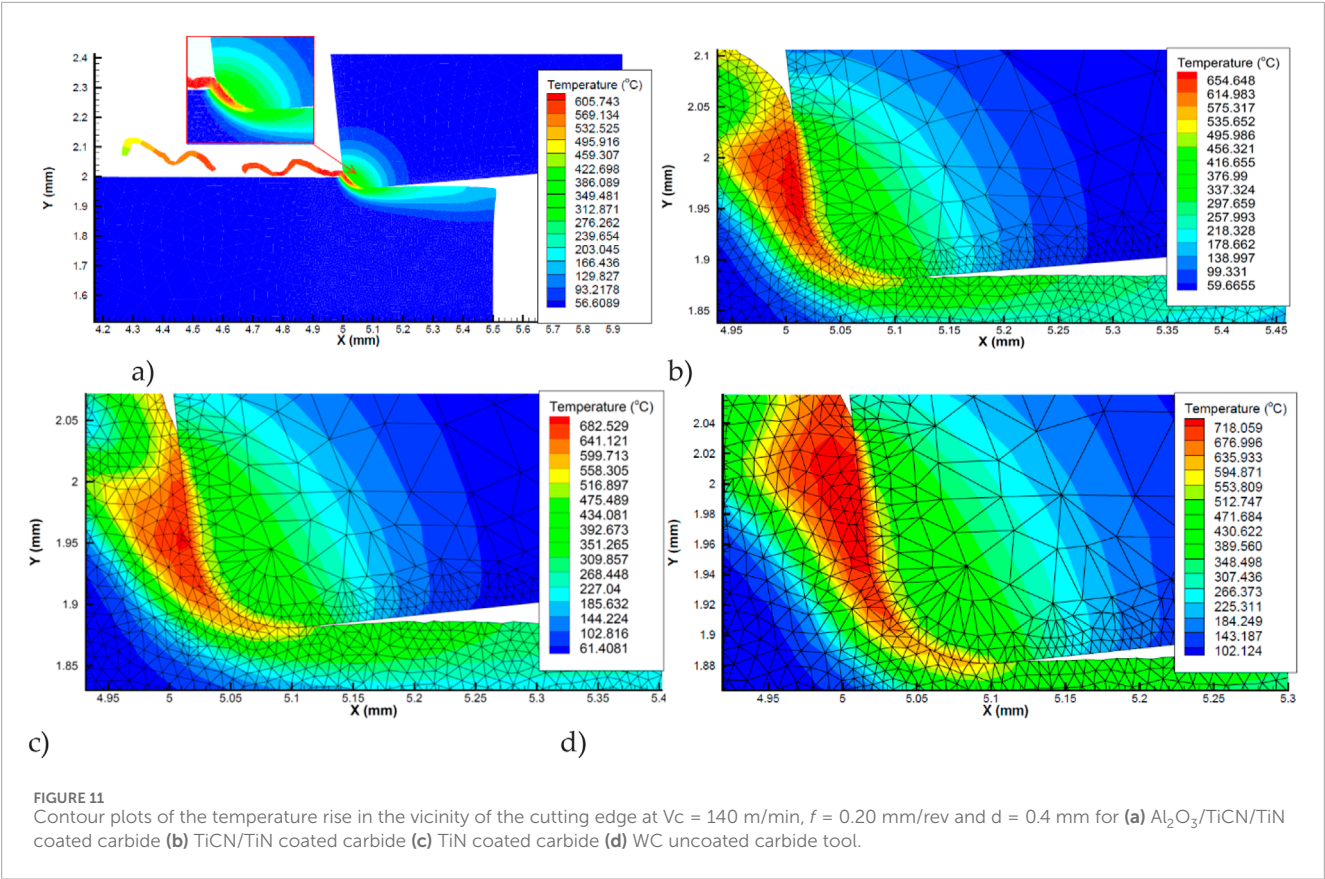


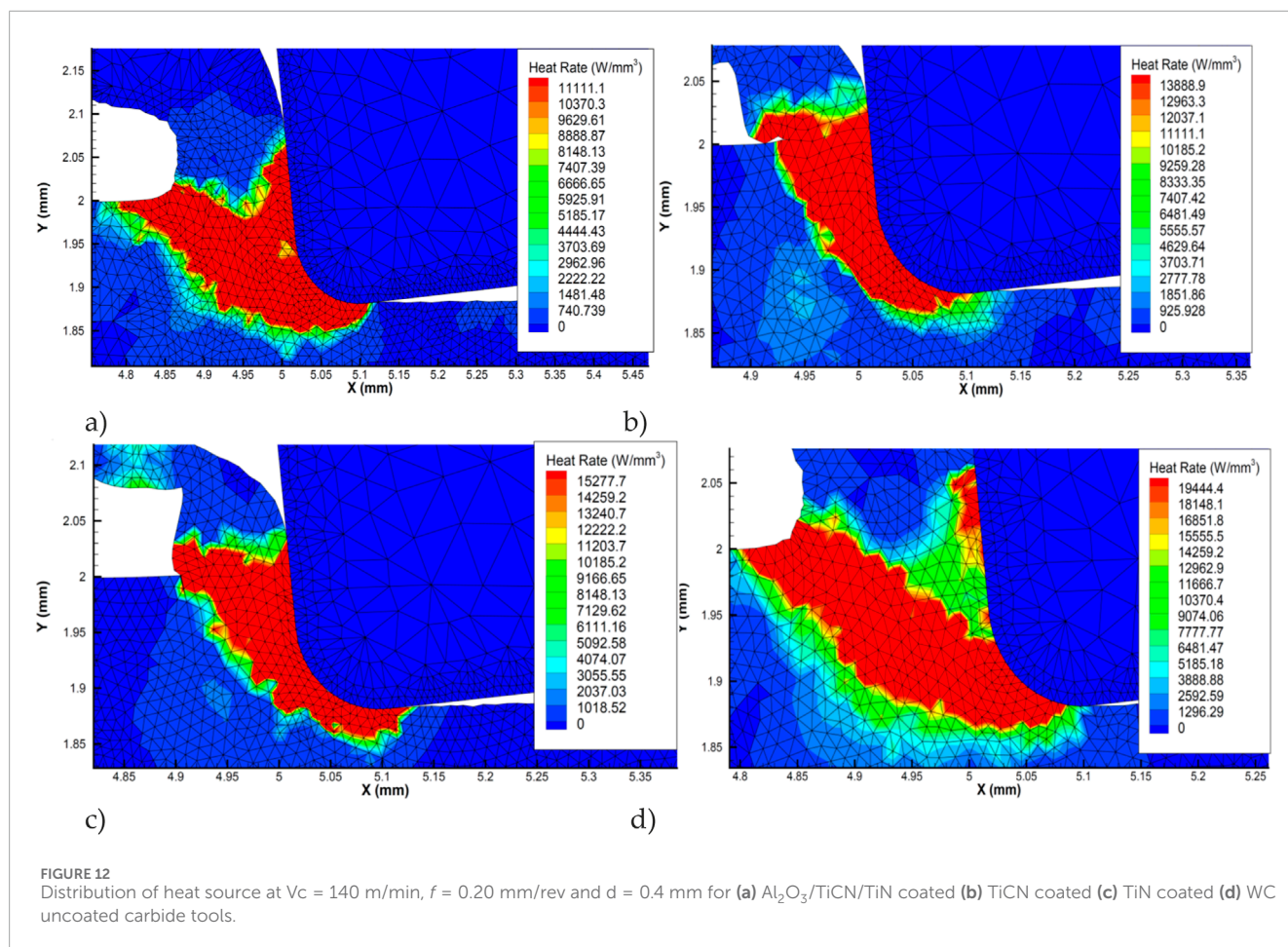
TABLE 8 Values of maximum temperature in tool (in °C).

Sr. No	Coating/Substrate material	Cutting temperature (°C)
1	WC	718
2	TiN-WC	682
3	TiCN/TiN-WC	654
4	$\text{Al}_2\text{O}_3/\text{TiCN}/\text{TiN}$ -WC	605

of 0.05–0.20 mm/rev at applied cutting speed generated higher compressive residual stresses at subsurface in the range of –145 MPa to –260 MPa, however, the less significant change was observed in tensile residual stress at the surface. Figures 10e–h shows the tensile residual stresses of (170, 150, 160, and 180 MPa) at the surface and compressive residual stresses of (–210, –375, –390, and –445 MPa) at subsurface at $v = 100$ m/min, $f = (0.05, 0.10, 0.15, \text{ and } 0.20 \text{ mm/rev})$ and $d = (0.3, 0.2, 0.2, \text{ and } 0.3 \text{ mm})$ respectively. It was shown that an increase in the depth of cut from 0.2 mm to 0.3 mm caused an insignificant increase in tensile residual stresses at surface, however, a minor increase of these stresses was observed. The significant increase in value of compressive residual stress of - 210 MPa to - 445 MPa at sub-surface was noticed at a feed rate of 0.05 mm–0.20 mm/rev. An increase of cutting speed from 80 to

100 m/min caused increased tensile residual stresses in the range of 125 MPa–170 MPa.

Figures 10i–l shows the tensile residual stresses of (220, 270, 300, and 320 MPa) at the surface and compressive residual stresses of (–360, –380, –500, and –650 MPa) at sub surface at $v = 120$ m/min, $f = (0.05, 0.10, 0.15, \text{ and } 0.20 \text{ mm/rev})$, and $d = (0.3, 0.4, 0.4, \text{ and } 0.4 \text{ mm})$ respectively. At cutting speed 120 m/min and depth of cut 0.3 and 0.4 mm, the tensile residual stresses of 220 MPa and 270 MPa were observed respectively. At the applied cutting speed of 120 m/min, the increase in feed rate range from 0.05 to 0.020 mm/rev caused higher compressive residual stresses in the range of –360 MPa to –650 MPa at subsurface. No significant influence was observed in tensile residual stress at the surface at applied feed range. Figures 10m–p shows the tensile residual stresses residual stresses of (380, 400, 450, and 375, MPa) at the surface and compressive residual stresses of (+340, –480, –465, and –570 MPa) at sub surface at $v = 140$ m/min, $f = (0.05, 0.10, 0.15 \text{ \& } 0.20 \text{ mm/rev})$ and $d = (0.4, 0.5, 0.5, \text{ and } 0.4 \text{ mm})$ respectively. The tensile residual stresses at surface increased drastically from 170 MPa to 450 MPa over the cutting speed range of 100 m/min to 140 m/min it was also noticed that the compressive residual stress at sub-surface significantly increases at cutting speed 140 m/min and feed rate range 0.05–0.20 mm/rev combination, on the other hand depth of cut of 0.3 mm and 0.4 mm at applied cutting speed did not show significant effect on tensile residual stress. The results closely align with the experimental findings reported in the literature, validating the accuracy and reliability of the proposed model. (Leppert and Peng, 2012) (Chavan and Sargade, 2020).



3.2 Effect of coating material on heat and temperature distribution

This study explored how various coating materials affect heat and temperature distribution during machining using FEM. The coatings were chosen for their thermal conductivity and heat resistance. Temperature data collected from different points in cutting zone and on the tool surface, provided insights into the thermal behavior influenced by the coatings. Table 7 illustrates the machining conditions employed for modeling and simulating the process.

The simulations were performed at cutting speed $v = 140$ m/min, feed rate $f = 0.20$ mm/rev and depth of cut $d = 0.4$ mm. From Figures 11a–d, the cutting temperature of 605°C with three layers of coating ($\text{Al}_2\text{O}_3/\text{TiCN}/\text{TiN-WC}$), 654°C with ($\text{TiCN}/\text{TiN-WC}$) coating, 682°C with (TiN-WC) coating and 718°C with uncoated WC cutting tool insert were observed. The significant reduction in cutting edge temperature was observed with $\text{Al}_2\text{O}_3/\text{TiCN}/\text{TiN-WC}$ coating material as compared to other coating material; this is due to the decrease in thermal conductivity of Al_2O_3 material with increase in temperature. Al_2O_3 acts as a thermal barrier and does not allow heat to penetrate and distribute along the rake face of tool, as a result of which the carbide substrate remains partly thermally insulated by the coating. TiN coatings demonstrated a higher cutting

edge temperature of 682°C , as it gets oxidize into TiO_2 above 500°C . The significant reduction in cutting temperature of 16% was observed with $\text{Al}_2\text{O}_3/\text{TiCN}/\text{TiN-WC}$ coating, 9% with $\text{TiCN}/\text{TiN-WC}$ coating and 5% with TiN-WC coating as compared to uncoated carbide tool. It is thus revealed from the result that cutting tool coatings influences the heat transfer and temperature distribution in the cutting zone when turning of AISI 52100 hardened steel. Table 8 depicts the cutting temperature obtained at different coating material.

Figures 12a–d shows distribution of heat source at $V_c = 140$ m/min, $f = 0.20$ mm/rev and $d = 0.4$ mm for coated carbide and uncoated tools, it can be concluded based on cutting simulations that the heat rate increases in the cutting zone and changes for the cutting tool coating materials used. The minimum value of e_c (volumetric specific cutting energy) equal to $11,111 \text{ W/mm}^3$ was computed for an $\text{Al}_2\text{O}_3/\text{TiCN}/\text{TiN-WC}$ coated carbide, whereas the maximum value of $19,444 \text{ W/mm}^3$ was obtained for a WC uncoated carbide tool. The predicted results are in good agreement with those in the literature regarding the effect of cutting tool coating materials on the cutting edge temperature and volumetric heat generation (volume specific cutting energy) e_c in hard turning under various cutting conditions (Grzesik et al., 2005).

TABLE 9 Comparison of Simulated and experimental values of cutting temperature in tool (in °C).

Sr. No.	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Types of coating	Cutting temp. (°C) (Simu.)	Cutting Temp. (°C) (Exp.)	% error
1	80	0.05	0.1	WC	581	541	7.39
2				TiN-WC	556	529	5.10
3				TiCN/TiN-WC	535	507	5.52
4				Al ₂ O ₃ /TiCN/TiN-WC	521	503	3.58
5	100	0.10	0.2	WC	606	566	6.54
6				TiN-WC	578	541	6.84
7				TiCN/TiN-WC	554	513	7.99
8				Al ₂ O ₃ /TiCN/TiN-WC	531	501	5.99
9	120	0.15	0.3	WC	641	603	6.80
10				TiN-WC	610	581	8.76
11				TiCN/TiN-WC	591	547	8.04
12				Al ₂ O ₃ /TiCN/TiN-WC	543	517	8.90
13	140	0.20	0.4	WC	718	663	8.30
14				TiN-WC	682	632	7.91
15				TiCN/TiN-WC	654	614	6.51
16				Al ₂ O ₃ /TiCN/TiN-WC	605	581	4.13

3.3 Model validation

Finite element predictions of residual stresses closely align with experimental data reported in the literature, underscoring the reliability and accuracy of predictive model. The residual stress prediction through AdvantEdge’s residual stress volume averaging feature closely matched with the X-ray diffraction test data. Hence the approach, that was used to develop the finite element model and modeling procedure, is considered reliable for pre-process residual stress prediction using FEM. Hard turning tests were conducted using HK 150 grade MTCVD multilayer coated carbide inserts mounted on a PCLNR2020 K12 type right-hand tool holder. Table 9 presents a comparison between simulated and experimental values of cutting temperatures at different cutting conditions and tool coatings. It highlights the effectiveness of coatings in reducing heat generation and evaluates the accuracy of FEM simulations in predicting cutting temperatures. The error between simulated and experimental results ranges from 3.58% to 8.90%, indicating a reasonable agreement. Despite incorporating appropriate boundary conditions, isotropic material modeling,

and thermo-physical properties, the observed discrepancy can be attributed to factors such as microstructural inhomogeneity, dynamic contact variations at the tool-chip-workpiece interface, and localized emissivity fluctuations phenomena that are inherently difficult to replicate within the constraints of current simulation techniques. Moreover, Al₂O₃/TiCN/TiN-WC coating was found to be more effective compared to other coatings, offering better thermal control.

4 Conclusion

The study confirmed that machining parameters notably affect residual stress in dry hard turning. Elevated temperatures in the cutting zone raise surface tensile stress due to high thermal gradient. Cutting speed had the most significant impact, while depth of cut showed minimal effect. Feed rate mainly influenced stress beneath the surface with higher rates increasing compressive stress and shifting the peak deeper. The simulated results closely matched with existing X-ray diffraction data, offering practical guidance

for optimizing cutting conditions to improve surface integrity of machined parts. The study also highlighted the impact of different coatings on cutting temperature and heat rate, with Al_2O_3 offering the best thermal insulation and resulting in the lowest cutting temperatures compared to the other coatings. The significant reduction in cutting temperature was observed in the range of 5%–16% with coated carbide tool, when compared to uncoated carbide tool. The relative percentage error between the experimental and simulated cutting temperature values was observed to range from 4% to 8%. A minimum heat rate of $11,111 \text{ W/mm}^3$ was computed for an $\text{Al}_2\text{O}_3/\text{TiCN}/\text{TiN}$ -WC coated carbide tool, while uncoated WC carbide tool exhibited a peak value of $19,444 \text{ W/mm}^3$. The FEM predictions exhibited strong agreement with experimental results confirming the model's accuracy in capturing thermal response, making it a useful tool for refining machining processes and improving product quality in industrial applications.

Future research should focus on integrating the machine learning with FEM models to predict cutting temperature and residual stresses under different cutting environments, enhancing the process optimization and machining performance.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SM: Writing – original draft, Writing – review and editing, Conceptualization, Investigation. RP: Writing – original draft, Writing – review and editing, Data curation, Methodology, Supervision. MS: Data curation, Writing – original draft, Writing – review and editing, Formal Analysis, Project administration. CC: Project administration, Writing – original draft, Writing – review and editing, Funding acquisition, Resources, Methodology. YX: Resources, Writing – original draft, Writing – review and editing, Conceptualization, Methodology, Supervision, Visualization.

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Funding

The author(s) declare that financial support was received for the research and/or publication of this article.

Acknowledgments

The Authors are thankful to Guangxi Science and Technology Program (No. AA24010001), Guangxi Natural Science Foundation (No. 2025GXNSFAA069536) and Ongoing Research Funding program, (ORF-2025-999), King Saud University, Riyadh, Saudi Arabia.

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Glossary

$g(\epsilon^p)$	Strain hardening function
$\Gamma(\dot{\epsilon})$	Strain rate sensitivity function
$\Theta(T)$	Thermal softening function
σ_0	Initial yield stress
ϵ^p	Plastic strain
ϵ_0^p	Reference plastic strain
ϵ_{cut}^p	Cut-off strain
n	Strain hardening exponent
$\dot{\epsilon}$	Strain rate
$\dot{\epsilon}_0$	Reference plastic strain rate
$\dot{\epsilon}_1$	Strain rate, where the transition between low and high strain sensitivity occurs
m_1	Low strain rate sensitivity coefficient
m_2	High strain rate sensitivity coefficient
$c_0 c_5$	Coefficients for the polynomial fit
T	Temperature
T_{cut}	Cut-off temperature
T_{melt}	Melting temperature
σ_p	Normal stress
σ_n	Flow stress
M	Coefficient of friction