



Thermo-mechanical performance of a TiAlN-coated micro-drill: effect of cutting speed and point angle on tool wear, cutting forces, and surface integrity

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Abstract

Cobalt Chromium Molybdenum (CoCrMo) alloys are essential for biomedical applications. However, their high hardness and low thermal conductivity severely hinder machinability. In micro-drilling, a geometric trade-off typically exists, where smaller point angles improve penetration but increase thermal loading, while larger angles reduce thermal stress at the expense of higher cutting resistance. Although recent studies highlight the importance of chip evacuation and cutting mechanics, the combined thermo-mechanical effects of advanced coatings and dedicated drill geometries in CoCrMo microdrilling remain insufficiently explored. This study evaluates the performance of a TiAlN-coated micro-drill incorporating an effective chip evacuation architecture. The effects of cutting speed (50, 65, and 80 m/min) and point angle (118°, 130°, and 140°) on axial thrust force, surface roughness, and steady-state tool wear were analyzed using Two-Way ANOVA. The results revealed that a cutting speed of 50 m/min with 118° point angle is the optimal machining condition, yielding the lowest axial thrust force (95.42 N), minimal flank wear (85.72 µm), and the finest surface finish (0.51 µm). Mechanistically, this condition preserves the TiAlN coating while enabling efficient chip segmentation and evacuation, thereby reducing thermal accumulation at the tool-chip interface. Conversely, higher cutting speeds promote rapid tool degradation and a shift towards chip-dominated material removal. Overall, the findings show that combining coating properties with chip evacuation geometry can significantly improve the performance of CoCrMo micro-drills, offering more stable operating window and wear resistance.

Keywords Cobalt chromium molybdenum · Micro drilling · Tool geometry · Tool wear

1 Introduction

Biomedical engineering relies heavily on cobalt-chromium-molybdenum (CoCrMo) alloys for orthopaedic and dental implants due to their mechanical properties, biocompatibility, and long service life [1, 2]. However, the properties that make CoCrMo biomedically attractive are specifically its high strength at elevated temperatures and very low thermal conductivity, which classify it as a highly “difficult to machine” superalloy [3]. Much like metal matrix composites (MMCs) [4] and nickel-based aerospace superalloys such as Inconel and Waspaloy, CoCrMo [5] is characterized by a high propensity for extreme strain-hardening during plastic deformation [6, 7]. During machining, these combined properties create a critical thermo-mechanical bottleneck, because the alloy cannot efficiently conduct heat away

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from the cutting zone and extreme thermal loads concentrate directly at the tool-chip interface. This causes aggressive accelerating abrasive wear, chemical dissolution, and adhesive built-up edge (BUE) formation [8, 9].

The manufacturing of these biomedical implants requires high-precision microdrilling to ensure tight dimensional accuracy and surface integrity [10]. These factors are vital for preventing in-vivo fatigue failure and the systemic release of submicron metallic wear debris, which are linked to adverse local tissue reactions, inflammation, and potential toxicological risks in the body environment [11]. However, CoCrMo microdrilling introduces severe size-dependent limitations. Microdrills have high hardness but limited fracture toughness, making them highly vulnerable to brittle failure under extreme thermo-mechanical loading [12, 13]. As a result, microdrill designs are governed by a strict geometric trade-off between chip evacuation capacity and structural stiffness [12]. In microdrilling, the large depth-to-diameter ratio makes timely chip evacuation very difficult, as demonstrated by Du and Liu [7], the volume occupancy rate of chips in helical flutes can reach up to 80%. This process remains a critical challenge in drilling, as inadequate clearance often leads to sudden torque spikes that induce catastrophic tool failure [14, 15]. Although expanding the flute width or reducing the web thickness provides the necessary space to clear these chips, static simulation analysis by Liang et al. [12] confirmed that this significantly reduces the structural stiffness of the drill. Under high-speed rotation, this loss of rigidity induces radial run-out, slippage, and deflection during the entry stage, drastically increasing the risk of catastrophic bending fracture [9, 10, 16]. To mitigate these limitations, current studies rely heavily on advanced coatings or geometric modifications. Titanium-Aluminum

Nitride (TiAlN) coatings are particularly attractive, as they form a thermally stable Al_2O_3 tribolayer that significantly improves high-temperature oxidation and wear resistance [4, 8, 13, 17, 18]. However, because TiAlN acts as an effective thermal barrier, it can inadvertently trap extreme heat directly in the cutting cavity if the chip is not evacuated promptly [19]. Alongside coating advancements, geometric innovations such as textured flutes and variable cross-sections, have been proposed to improve chip flow and reduce cutting forces [17, 20, 21]. Nevertheless, comprehensive research exploring the mechanistic synergy between thermal barrier coatings and active chip transfer architectures in superalloy microdrilling remains limited.

Therefore, this study establishes a new thermo-mechanical framework to investigate whether synergistic interactions between TiAlN coatings and specific chip transfer geometries can fundamentally circumvent the conventional geometric trade-offs. The EZ design, micro drill featuring a unique C-flute architecture and enhanced gash clearance, was evaluated across a range of cutting speeds and point angles during CoCrMo machining [22]. By analysing axial thrust, surface roughness, and steady-state tool wear through rigorous statistical modelling, this study isolates how this unique architectural synergy manages extreme localized thermal loads. Ultimately, this study aims to separate thermal failure from geometric brittleness, providing a statistically validated wear-resistant operating envelope for precision manufacturing of biomedical CoCrMo components and other difficult-to-cut superalloys.

2 Materials and methodology

This section presents the materials, machining setup, and experimental procedures used to evaluate microdrilling performance.

2.1 Workpiece material

The experimental material selected was a wrought cobalt–chromium–molybdenum (CoCrMo) alloy. Plates of 31 mm × 31 mm × 4 mm were precisely prepared using electrical discharge machining (EDM) wire cutting, with each plate containing 100 holes as shown in Fig. 1. The alloy's chemical composition is provided in Table 1, and its mechanical properties, including hardness, yield strength, and ultimate tensile strength, are summarized in Table 2.

2.2 Tooling and machining parameters

A 2.0 mm diameter Titanium–Aluminum Nitride (TiAlN) coated carbide drill from HPMT Industries was used in this

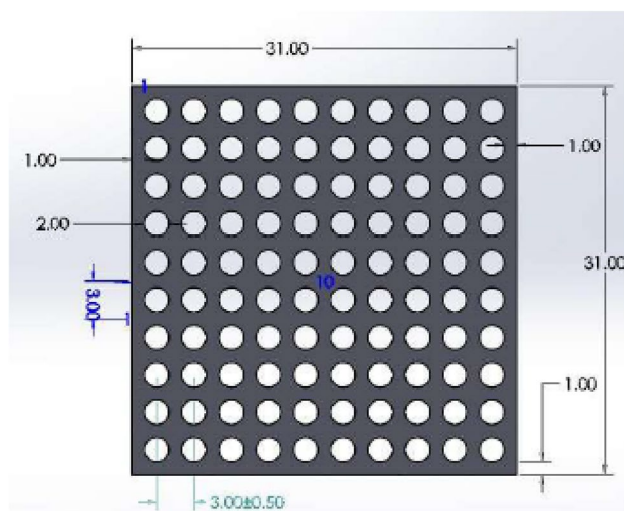


Fig. 1 Schematic illustration of a CoCrMo workpiece used for microdrilling experiments. The 31 mm × 31 mm × 4 mm plate with a center-to-center pitch of 3.0 mm

Table 1 Chemical composition of CoCrMo

Element	Weight (%)
Cr	26–30
Mo	5–7
Fe	0.75
Mn	1.0
Si	1.0
C	0.15–0.35
N	1.0
Ni	0.25
Co	Bal

Table 2 Mechanical properties of CoCrMo

Properties	Unit	Cobalt chrome ASTM 1537-Sandvik value
Proof Stress (0.2%)	MPa	928
Tensile Strength	MPa	1,403
Elongation	%	29
Young's Modulus	GPa	283
Density	kgm^{-3}	8,768
Thermal Conductivity	$W.m^{-1}.K^{-1}$	14.8
Specific Heat Capacity	$J.Kmg^{-1}.K^{-1}$	452
Thermal Diffusivity	$M^2.s^{-1}$	3.73E-06
Fracture Toughness	$Mpa.m^{1/2}$	100
Hardness	HRC	40

study. Although microdrilling is conventionally associated with sub-millimeter tools, diameters up to 2.5–3.175 mm are widely recognized in the micromachining regime [9, 23]. At this scale, the 2.0 mm drill exhibits similar size-dependent limitations, including reduced structural rigidity due to the high aspect ratio and limited flute volume that hinders chip evacuation [8]. During CoCrMo machining, these constraints promote chip clogging and torque spikes, leading to severe thermo-mechanical loading [4, 9], which is the focus of this study.

The EZ drill design used in this study, illustrated in Fig. 2, features a C-flute profile, generous gash clearance, and a chamfered point, which collectively facilitate chip evacuation and reduce cutting forces. In addition, corner reinforcement improved edge durability during drilling.

To improve heat dissipation and machining efficiency, nine experiments were conducted under flood cooling conditions using TOYO-G C70, a water-soluble cutting fluid (Table 4). The machining parameters (Table 3) consisted of cutting speeds of 50, 65, and 80 m/min, point angles of 118°, 130°, and 140°, and a constant feed rate of 0.1 mm/rev. These parameters are consistent with previous CoCrMo microdrilling studies [9], where a similar speed range was shown to produce high heat loads characteristic of superalloy machining.

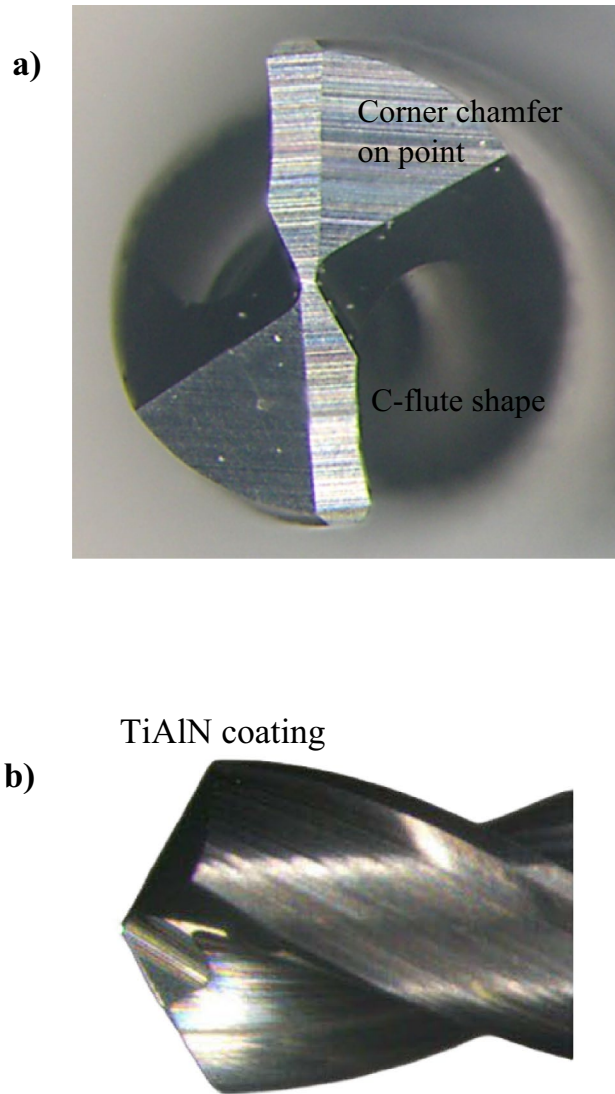


Fig. 2 Optical micrographs detailing the specific architecture of the TiAlN-coated EZ micro drill. **a** Axial cross-section highlighting the modified C-flute geometry and expanded gullet designed to maximize chip transfer. **b** Profile view showing the uniform distribution of the protective tribo-coating

Table 3 Machining parameters

Level	1	2	3
Cutting Speed (m/min)	50	65	80
Tool Point Angle	118°	130°	140°
Feed Rate (mm/rev)	0.1		
Drilling Depth (mm)	4		
Cooling Method	Flood		

Due to its low thermal conductivity (14.8 W/m·K) and significant strain hardening, CoCrMo promotes rapid heat accumulation at the tool-chip interface even at moderate cutting speeds. As a result, the range of 50–80 m/min

chosen is in the high-speed machining (HSM) regime for CoCrMo, consistent with the reported superalloy threshold where HSM begins near 50 m/min [9, 19, 22, 24]. In this range, higher speeds increase the thermal gradient and accelerate tool degradation, promoting edge blunting and ploughing, while lower speeds help preserve the integrity of the coating. While insufficient feed rates often cause a “size effect”, where the tool ploughs and rubs against the workpiece instead of cutting cleanly [25]. When machining superalloys, this rubbing action instantly hardens the machined surface, resulting in high cutting resistance and rapid tool wear during subsequent tool rotations [19, 26]. Therefore, a constant and heavier feed rate of 0.1 mm/rev was deliberately chosen for this study, the same as previous studies [9, 22]. This specific parameter ensures that the cutting edge consistently penetrates below the work-hardened zone, maintains a stable shearing action, and effectively transfers the excessive cutting heat into the chip rather than trapping it in the tool substrate.

In each run, a new tool was used to drill 30 holes. This specific duration was chosen to ensure that the evaluation captured the steady-state wear phase. When machining highly abrasive superalloys such as CoCrMo, the tool rapidly undergoes an unpredictable initial break-in period. Stopping exactly at 30 holes ensured that the process had entered a stable regime, provided reliable force and surface roughness data, and safely halted the operation before the onset of severe and catastrophic tool fracture.

2.3 Experimental setup

The micro drilling experiments were conducted using a DMG MORI DMU 50 CNC machine. Prior to the machining process, the tool length was calibrated using the Tool Master. The complete experimental setup, including the workpiece fixture and sensor array, is illustrated in Fig. 3. To manage the extreme thermal loads generated by CoCrMo superalloy, TOYO-G C70, a water-soluble petroleum-based cutting fluid (Specific gravity: 0.890, Flash Point: 212° C), was utilized throughout the experiments to provide continuous lubrication and cooling.

2.4 Measurement of cutting force and surface roughness

The measured responses included cutting force, surface roughness, and progressive tool wear. Cutting force was recorded using a Kistler Type 9443B dynamometer with DynoWare software. Thrust force (F_z) was used as a key indicator of cutting resistance and was measured every 5 holes to map the tool transition to the steady-state wear phase.

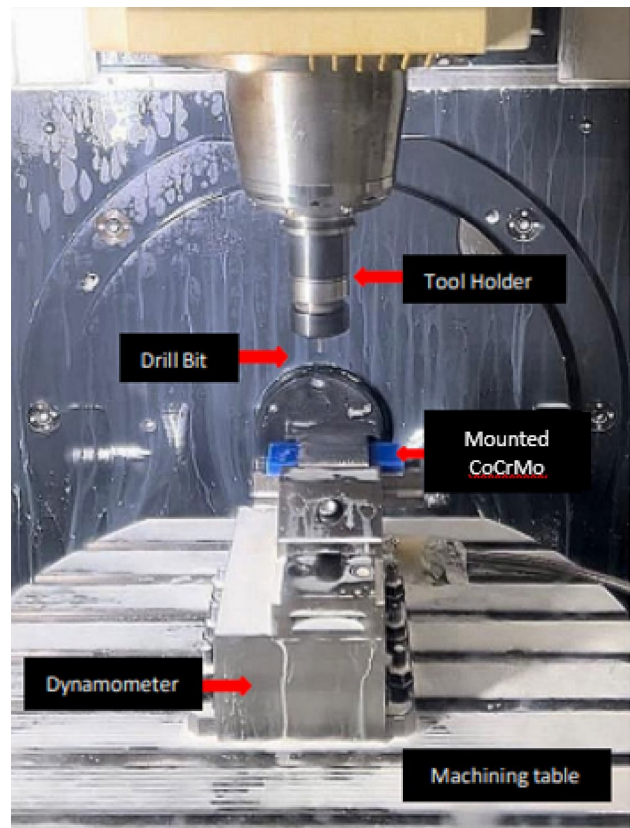


Fig. 3 Experimental setup for microdrilling on CNC Machine

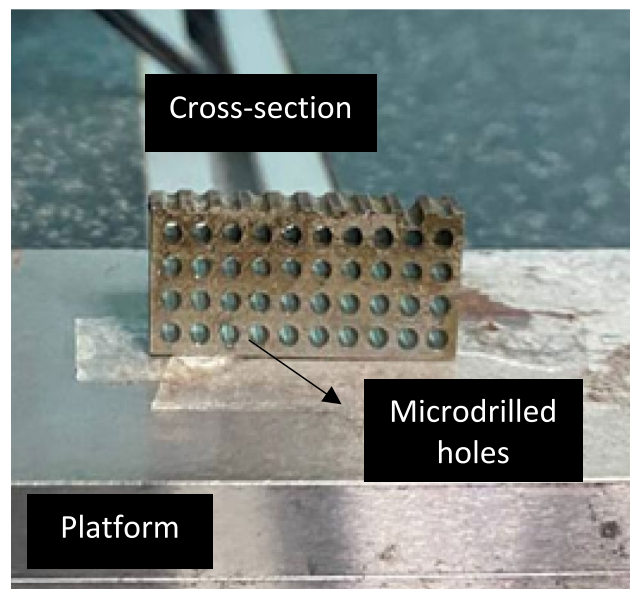


Fig. 4 Sectioned micro-drilled holes

The hole quality was similarly evaluated for every 5-hole interval. The CoCrMo plate was sectioned in Fig. 4 to expose the inner wall of the micro-drilled cavities. Surface roughness (R_a) was measured using a Mitutoyo SURFTEST SJ-210 with a 0.8 mm cut-off length. To eliminate geometric

errors due to hole curvature and to accurately capture the longitudinal feed marks, the stylus was traversed strictly in the axial direction, with three measurements averaged per hole. Furthermore, to ensure a standardized comparative analysis across all parameters, R_a values were extracted prior to the onset of the accelerated tertiary wear and catastrophic failure observed at high cutting velocities.

2.5 Tool wear characterization

Due to the lack of universally established ISO standards, specifically calibrated for microscale cutting tool failure modes [13, 18], traditional macroscale wear thresholds are not mechanistically valid for this study. Therefore, empirical tool life profiles were constructed to isolate the steady-state wear phase prior to catastrophic failure accurately. Progressive lateral wear was measured at 10, 20, and 30-hole intervals using a primary objective stereo microscope. After completing each 30-hole sequence, the microdrill was lightly etched in Kroll's reagent to selectively thin the TiAlN film. This chemical treatment significantly increased the visual contrast between the intact protective coating and the exposed carbide substrate and aided high-magnification wear analysis.

2.6 Statistical analysis and multi-objective optimization

To systematically identify the optimal machining parameters, which are the cutting speed and point angle, multi-objective optimization was performed using Minitab statistical software [27], which is a widely utilized tool for simultaneous process optimization [28]. The optimization framework uses a Desirability Function Approach (DFA) to evaluate the competing experimental outputs simultaneously [28]. This methodology was established as a benchmark by Derringer and Suich [29], who illustrated how multiple response variables can be transformed into a unified desirability function.

In this theory, each estimated response is mathematically transformed into a dimensionless individual desirability value (d_i) ranging from 0 (completely unacceptable) to 1 (ideal target) [28, 29]. For the specific requirements of CoCrMo microdrilling, the optimization criteria for thrust force, surface roughness, and tool wear were all set strictly to "Minimize," corresponding to the "Smaller-The-Better" (STB) utility function [27]. These individual desires were then geometrically aggregated into a single Composite Desirability score (D) [28, 29]. The use of geometric means is critical, as it ensures that if any single response is unacceptable ($d_i=0$), the entire process setting is rendered unacceptable [28, 29].

The parameter combination that yielded the highest Composite Desirability was identified using numerical optimization, utilizing search algorithms such as the pattern search method presented by Hooke and Jeeves [30]. To ensure a rigorous justification for the tool wear limit, the establishment of the tool life endpoint was guided by the ISO 8688-1:1989 international standard, which utilizes flank wear (V_B) as the principal failure criterion [28]. This methodology aligns with recent contemporary studies that have applied RSM and desirability functions to parallel machining problems, including the work on maximizing material removal rates [31], optimizing surface grinding [32], and parametric end-milling optimization [33].

3 Results and discussion

This study involved a total of 9 experiments that were conducted to evaluate the effects of cutting speed and tool point angle on cutting force, tool wear, and surface roughness during microdrilling on as-cast CoCrMo. The experiments were performed at three levels of cutting speed, which are 50 m/min, 65 m/min, and 80 m/min, and three levels of tool point angle, 118°, 130°, and 140°, with a constant feed rate of 0.1 mm/rev and a drilling depth of 4 mm. The cutting force was recorded in real time using a tool dynamometer for every 5th hole. Surface roughness is measured with the same interval as the cutting force. Tool wear was measured in situ using an optical microscope to track the wear progression of every 10th hole during drilling. Tool wear type and surface roughness were evaluated after each 30-hole drilling cycle.

3.1 Effect of cutting speed and point angle on thrust force

The thrust force was used to evaluate the cutting resistance and wear-induced ploughing during micro-drilling of CoCrMo. Multi-objective optimization in Table 4 identified 50 m/min and a point angle of 118° as the optimal conditions, resulting in a minimum force of 95.42 N with a composite preference of 0.8227. Two-way ANOVA in Table 5, confirmed cutting speed ($p=0.006$) and point angle ($p=0.001$) as significant factors. The complete dataset for the thrust force evaluation is included in Appendix 1.

Table 4 Response optimization solutions indicating the ideal parameter combination and composite desirability score to minimize Cutting Force, (F_z)

Solution	Cutting speed (m/min)	Point angle (°)	Cutting force (N) Fit	Composite desirability
1	50	118	95.422	0.822664

Table 5 Analysis of Variance (ANOVA) for Axial Thrust Force (F_z)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Cutting Speed (m/min)	2	812.9	406.46	5.82	0.006
Point Angle	2	1078.7	539.33	7.72	0.001
Cutting Speed (m/min)*Point Angle	4	1578.0	394.49	5.65	0.001
Error	45	3143.7	69.86		
Total	53	6613.3			

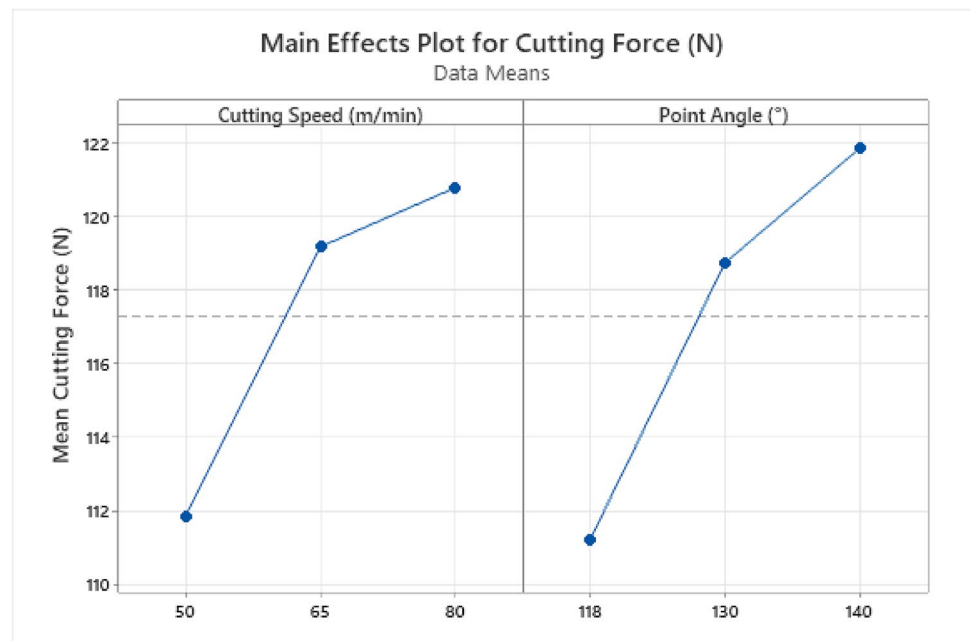
Fig. 5 Main effects plot for Cutting Force of Cutting Speed and Point Angle factors

Solution

Cutting Speed Solution (m/min)	Point Angle (°)	Cutting Force (N)	Composite Fit Desirability
1	50	118	95.422 0.822664

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Cutting Speed (m/min)	2	812.9	406.46	5.82	0.006
Point Angle	2	1078.7	539.33	7.72	0.001
Cutting Speed (m/min)*Point Angle	4	1578.0	394.49	5.65	0.001
Error	45	3143.7	69.86		
Total	53	6613.3			



in the tool wear analysis (Section 3.4), the extreme thermal gradient generated at 80 m/min rapidly degrades and blunts the tool cutting edge. This rapid degradation forces the microdrill out of clean shearing action and into a severe ploughing regime. As a result, a much higher axial load is required for the blunt edge to penetrate the strain-hardened material layer, completely overcoming the local benefit of thermal softening [9, 16, 19]. This thermo-mechanical degradation pattern in CoCrMo is consistent with dry turning of CoCrMo studies, where increasing cutting speeds intensifies adhesive wear on the rake face and promotes material plasticization, accelerating edge blunting [34].

As also detailed in the tool wear analysis Section 3.4, the extreme thermal gradients generated at 80 m/min rapidly degrade and blunt the tool's cutting edge. This severe wear forces the microdrill out of a clean shearing action and into a ploughing regime. As a result, a much higher axial load is required for the blunt edge to penetrate the strain-hardened material layer, completely overpowering the localized benefits of thermal softening. The force surge caused by wear at this high velocity is consistent with the rapid transition to severe phase wear in micro-drilling described by Prakash et al. [16]. Furthermore, while thermal softening nominally reduces flow stress at elevated temperatures, the simultaneous reduction in cutting edge integrity through wear-induced blunting offsets this effect, increasing thrust force at higher velocities [35].

3.1.2 Main effect of point angle on thrust force

ANOVA similarly identified that drill point angle had a very significant main effect on the axial thrust force, with ($p = 0.001$), making it the main geometric factor influencing the variation in cutting force. A larger point angle, such as 140° , spreads the cutting lip more horizontally across the material surface, causing the rake surface to align closer to the plane of the workpiece [17]. Numerical simulations of orthogonal cutting have confirmed that rake angles are the primary geometric driver of cutting force, with decreasing rake angles directly correlating with increasing cutting resistance in difficult-to-machine alloys. [36]. This geometry directly reduced the effective rake angle. A smaller rake angle reduced the shearing efficiency of the cutting edge, increased cutting resistance, and required greater force to remove material [20]. As a result, the flattened 140° geometry experienced extreme penetration resistance, while the sharper 118° point angle provided a sharper penetration profile and higher shear efficiency. This is consistent with previous studies showing that lower rake angles provided higher cutting resistance and greater cutting force [21]. This

behavior has been similarly documented in drilling steel, where increasing point angle increases cross-edge deformation and increases cutting temperature, further increasing penetration resistance [37].

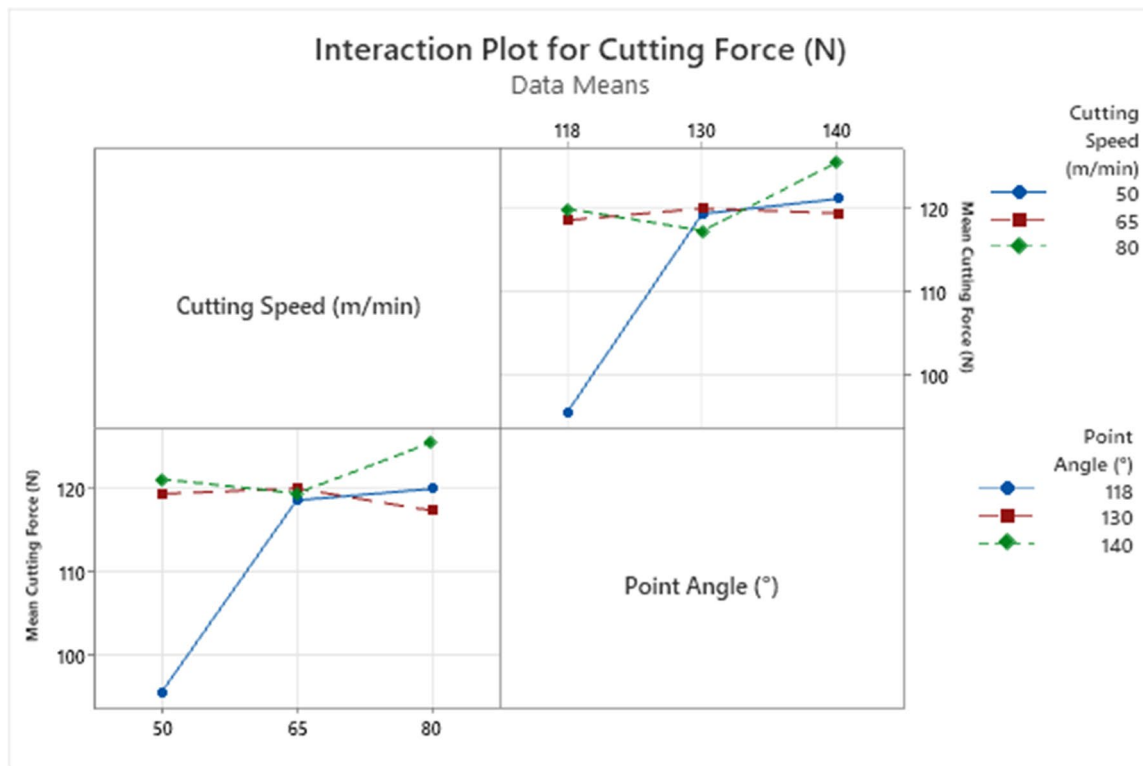
3.1.3 Interaction effect on thrust force

Crucially, the ANOVA identified a highly significant two-way interaction between cutting speed and point angle ($p = 0.001$). Visualized in Fig. 6, the intersecting 2D lines (Fig. 6a) and warped 3D surface topography (Fig. 6b) confirms this nonlinear relationship. At low speeds (50 m/min), cutting force spikes sharply as the angle flattens to 130° and 140° , indicating severe mechanical inefficiency. Conversely, at higher speeds (65–80 m/min), the contour gradient stabilizes at a consistently high value, rather than exhibiting continued escalation. This plateau is attributed to two competing thermo-mechanical effects operating on distinct timescales. Thermal softening of the workpiece initially reduces the flow stress required to shear the material. However, as established in Section 3.3.2, this benefit is outweighed by wear-induced edge blunting, which displaces the cutting mechanism into a ploughing-dominated regime. Consequently, the net force response stabilizes rather than continuing to increase despite the progressive accumulation of tool wear [24].

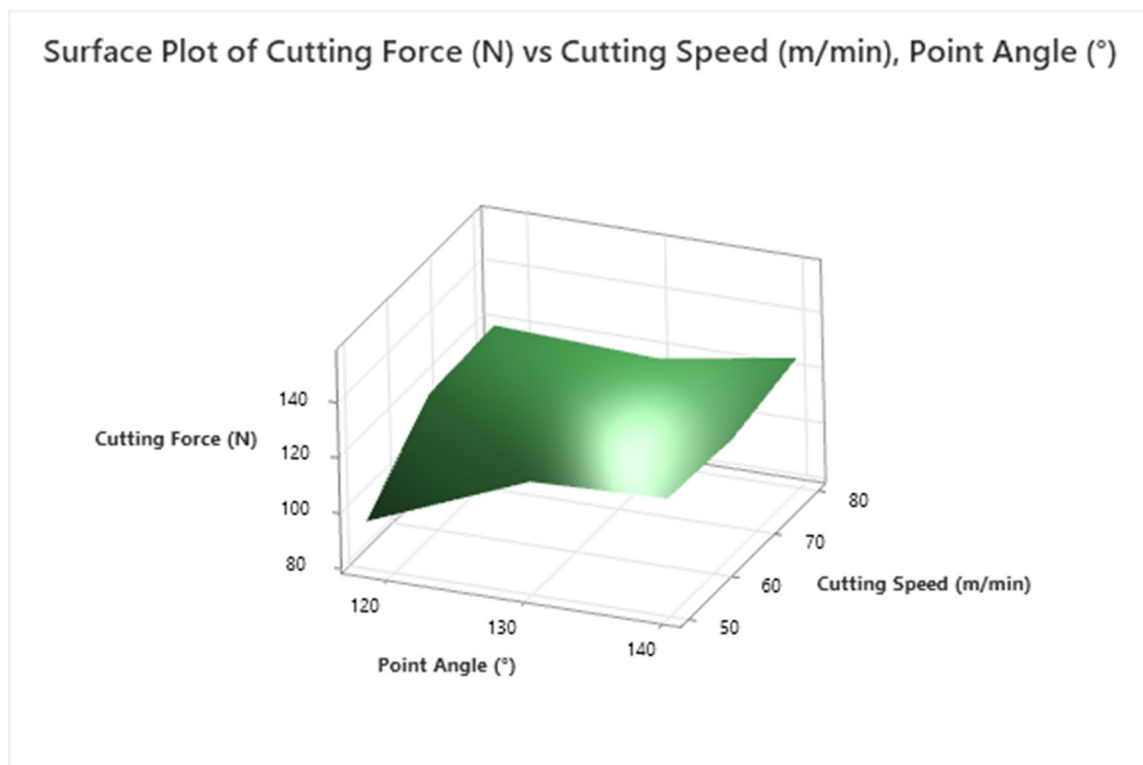
In conventional CoCrMo machining, a sharper point angle (118°) concentrates mechanical loads, often requiring flatter geometries (140°) or higher speeds to prevent tool failure [38]. This phenomenon occurs because the smaller point angle results in a longer cutting edge and a smaller contact area between the tool and the material, which results in a more dispersed force distribution and significantly higher thrust force [9]. In contrast, this study achieved the lowest thrust force (95.42 N) at 118° and 50 m/min, demonstrating improved cutting efficiency without excessive load concentration. This performance is attributed to the C-flute geometry, where enhanced gash clearance promotes effective segmentation and chip transfer, reducing stress accumulation compared to conventional U-profile flutes [22].

3.1.4 Comparative analysis of cutting force and coating synergy

Direct comparison with existing literature highlights the superior thermo-mechanical performance of the tool used in this study. This study's recorded optimal cutting force of 95.42 N (at 118° and 50 m/min) represents a 27.64% reduction compared to the 131.86 N reported for an uncoated EZ design micro drill under the same machining parameters (at 118° and 50 m/min) [22].



(a)



(b)

Fig. 6 **a** Interaction plot for cutting force between cutting speed and point angle. **b** Surface plot of effect of cutting speed and point angle on cutting force

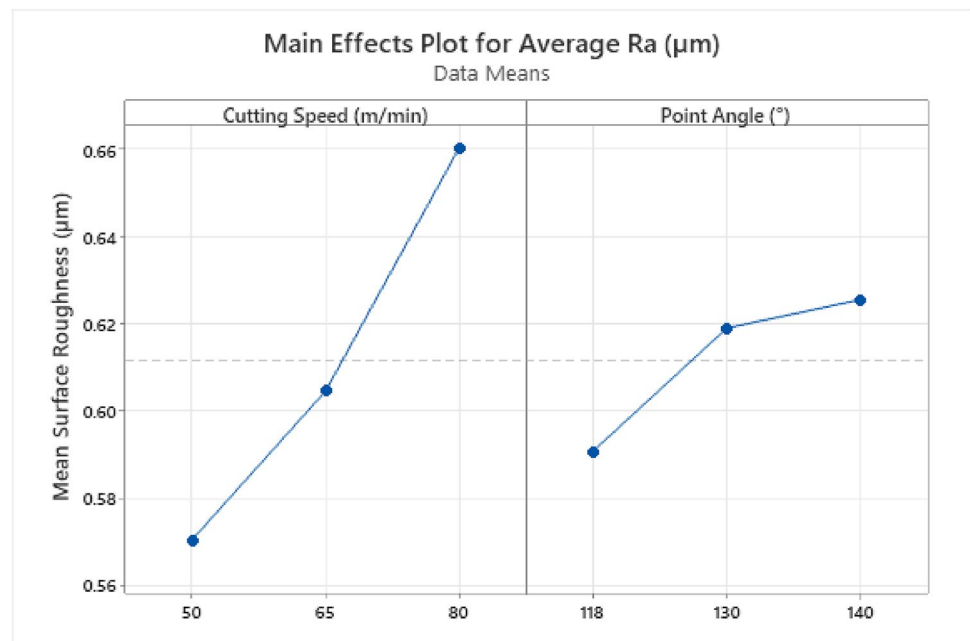
Table 6 Response optimization solutions indicating the ideal parameter combination and composite desirability score to minimize Surface Roughness, R_a

Solution	Speed (m/min)	Point angle (°)	Average Ra (μm) Fit	Composite desirability
1	50	118	0.514833	0.732413

Table 7 Analysis of Variance (ANOVA) for Surface Roughness R_a

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Speed (m/min)	2	0.07403	0.037016	1.64	0.206
Point Angle (°)	2	0.01234	0.006168	0.27	0.763
Speed (m/min) * Point Angle (°)	4	0.09943	0.024858	1.10	0.369
Error	45	1.01828	0.022629		
Total	53	1.20409			

This significant improvement provides empirical evidence for the synergistic interaction between the TiAlN coating and the specific EZ geometry. While the unique C-flute architecture of the EZ design and enhanced gash clearance are engineered to reduce initial thrust loads by improving initial tool-entry engagement and providing a larger chip holding space [22], the TiAlN coating acts as a critical thermal barrier and lubricant. This coating promotes the formation of a stable Al triboprotective layer, which successfully minimizes interfacial friction and prevents superheated, adhesive CoCrMo chips from micro-welding to the tool surface [13, 18]. By effectively managing the extreme local heat typical of superalloy micro-drilling, this combination avoids conventional geometry trade-offs, leading to a much more efficient and stable material removal process.

Fig. 7 Main effect plots for surface roughness of cutting speed and point angle factors

3.2 Effect of cutting speed and point angle on surface roughness

Surface roughness R_a was measured exclusively in the axial direction, and the reported values represent the arithmetic mean of measurements taken across the steady-state hole profile. A multi-objective optimization in Table 6 was performed rigorously to minimize R_a , identifying a cutting speed of 50 m/min and a point angle of 118° as the absolute optimal combination, with a composite desirability of 0.7324. Under these conditions, the model predicted an optimized steady-state surface roughness of 0.51 μm , corresponding to the lowest experimental average recorded. To validate this parametric envelope, a Two-Way Analysis of Variance (ANOVA) was conducted in Table 7. However, ANOVA revealed that neither the main effect of cutting speed ($p = 0.206$), the main effect of point angle ($p = 0.763$), nor the two-way interaction ($p = 0.369$) were statistically significant at the 95% confidence level. The complete dataset for the surface roughness evaluation is included in Appendix 2.

3.2.1 Main effect of cutting speed on surface roughness

Although visual inspection of the main effects plot in Fig. 7 shows an upward trend in R_a as the cutting speed increases from 50 m/min to 80 m/min, ANOVA confirms that this variation is not statistically dominant. The underlying mechanics of this slight upward drift are closely related to the increase in thermal phenomena that occur during the machining process. Higher cutting speeds increase the friction between the cutting tool and the workpiece, generating

excess heat that contributes to thermal expansion and accelerated wear of the cutting edge [25, 26]. This thermal effect leads to a progressive increase in the cutting-edge radius as tool sharpness deteriorates, resulting in edge rounding that directly increases R_a , as worn tools leave the workpiece with an uneven and less precise finish [38]. Furthermore, the intensified material removal process at higher speeds naturally accelerates wear mechanisms such as abrasion, adhesion, and penetration [38]. However, the important finding here is the limited scale of this increase.

Across all velocities tested, R_a remains tightly controlled below $0.70\text{ }\mu\text{m}$. In precision machining of biomedical superalloys, R_a machined below the $1.0\text{ }\mu\text{m}$ threshold is highly desirable to prevent deep subsurface damage and eliminate extensive post-process polishing [19, 39]. This threshold is particularly critical for CoCr alloys, where surface roughness directly affects biocompatibility, osseointegration, and the tendency for bacteria to adhere to the implant surface [40]. The ability to maintain this precision finish even at 80 m/min demonstrates the exceptional thermo-mechanical robustness of the TiAlN coating. At extreme temperatures, the aluminum content oxidizes to form a highly stable tribo-protective layer of Al_2O_3 . This layer drastically reduces interfacial friction and prevents highly adherent CoCrMo chips from micro-welding to the cutting edge, known as built-up edge. By maintaining high-temperature lubrication, the coating ensures clean material shearing rather than severe surface tearing.

3.2.2 Main effect of point angle on surface roughness

Similarly, the point angle shows a negligible effect on surface roughness, as evidenced by the relatively flat trend line in the main effects plot (Fig. 7) and the high p value ($p = 0.763$). Although modest geometric changes occur as the point angle increases from 118° to 140° , the surface quality remains very stable. This observation is strongly supported by Kurt and colleagues [39], which states that although point angle largely influences parameters such as hole size, it does not have a significant macro-effect on the final surface roughness. This stability is further aided by the superior chip evacuation capability of the EZ design. While conventional double U-profile flutes often suffer from severe chip packing, where long, continuous chips fold, jam, and scrape against the walls of the newly machined hole, the special C-flute geometry features a wider esophagus and optimized curvature. This specific shape actively forces the tough CoCrMo material to curl tightly and break into smaller, more manageable segments. By breaking the chips early and quickly evacuating them without allowing them to drag on the surface, the tool maintains a consistent surface finish regardless of the point angle engaged. This insensitivity

of R_a to point angle is in line with previous findings in CoCrMo machining, where the surface roughness results are driven primarily by thermal conditions and tool wear conditions rather than geometric parameters alone [41].

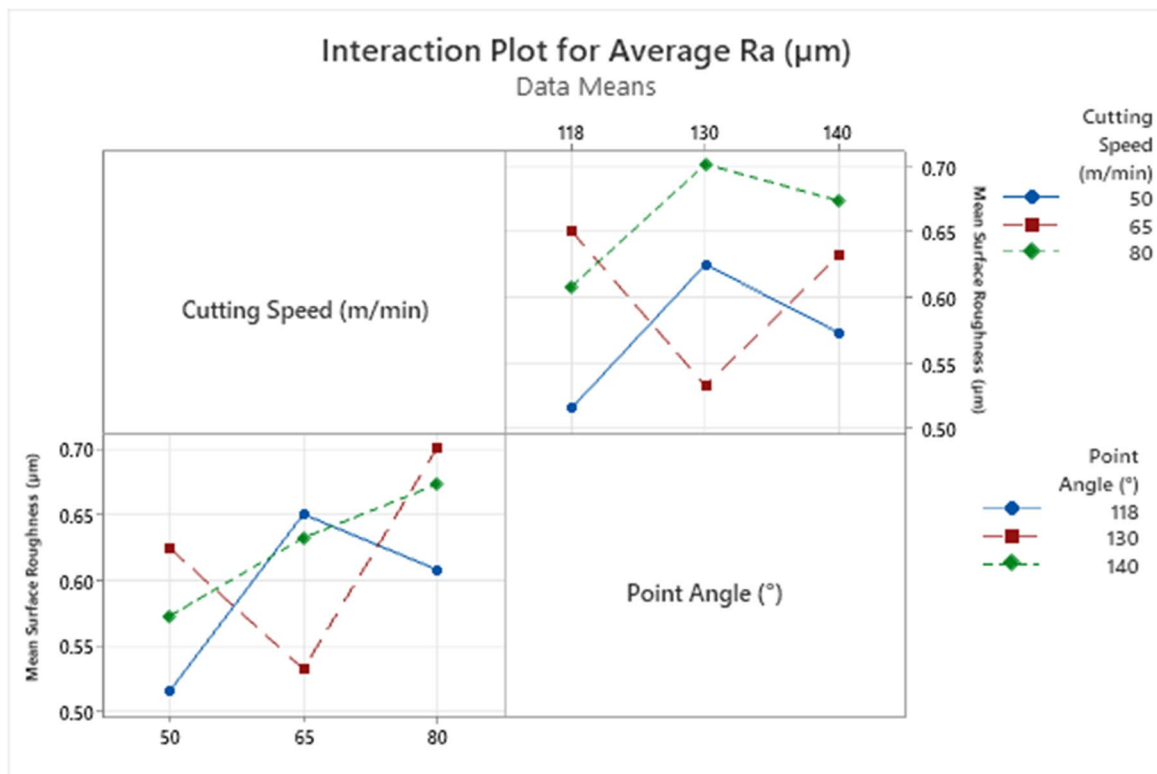
3.2.3 Interaction effect on surface roughness

The evaluation of the interaction effects on surface roughness is visually mapped in Fig. 8, which shows both the main 2D interaction plot (Fig. 8a) and the corresponding 3D surface topography (Fig. 8b). Initial visual inspection of the 2D plot reveals highly fluctuating and intersecting data lines, which may incorrectly suggest that the 130° point angle represents an extreme parametric sensitivity zone. However, ANOVA explicitly rejected this hypothesis, proving the interaction to be statistically insignificant ($p = 0.369$). The 3D surface plot visually supports this statistical reality. Mechanistically, this confirms that the jagged peaks and valleys seen in the plot are not due to underlying geometric defects or structural failures of the tool geometry, but rather to stochastic micro-level chaos at the tool-chip interface. In micro-drilling applications, chip evacuation issues, especially chips stuck in small cavities, can increase machining temperatures. If the cutting force becomes unbalanced, it leads to chip thickness variations, stick-slip vibrations, and inconsistent material removal [12]. The relationship between chip clearance efficiency and hole surface quality has been demonstrated in deep hole drilling studies, where well-segmented and cleared chips consistently produce lower wall roughness values compared to conditions where chip packing occurs [42]. Therefore, the local topological fluctuations observed at the 130° and 140° intervals on the reaction surface are a direct result of the random micro-welding events and stick-slip phenomena inherent in CoCrMo machining, rather than significant parametric interactions.

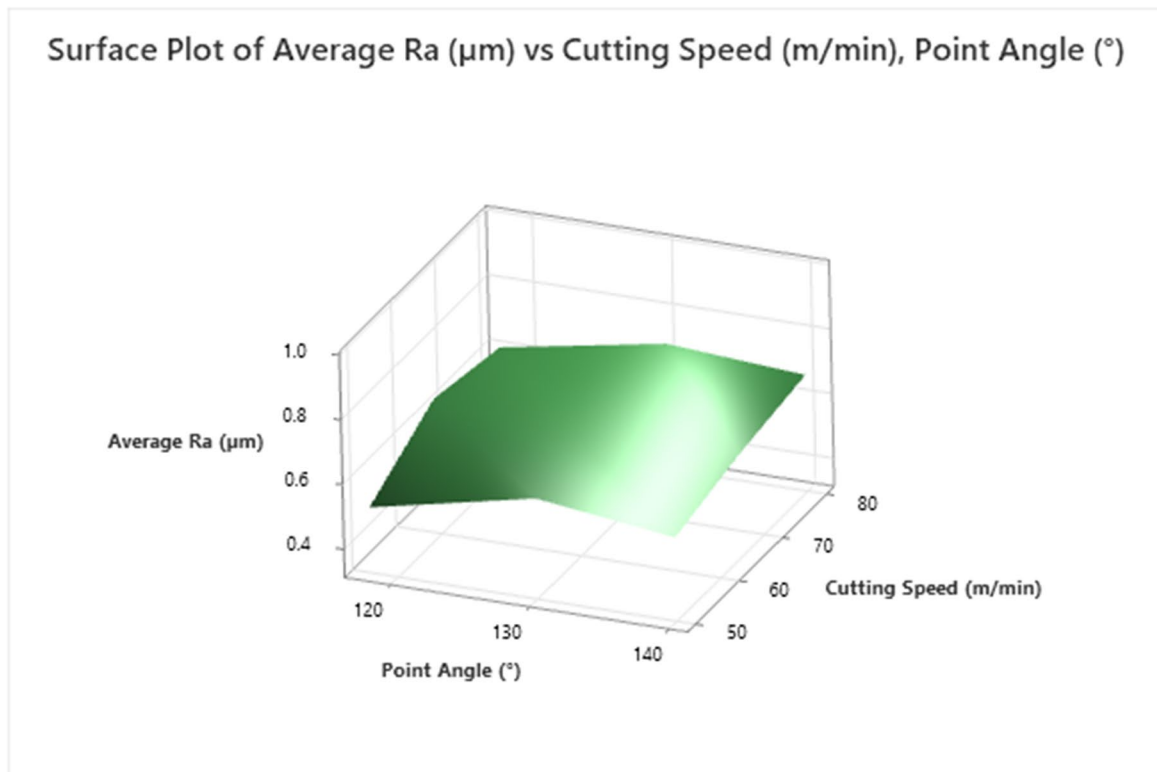
Ultimately, achieving optimal stability at 50 m/min and 118° , the tool operates under a balanced thermo-mechanical condition, that maintains a sharp and highly efficient cutting geometry without generating the catastrophic heat associated with higher velocities.

3.3 Effect of cutting speed and point angle on tool wear

To accurately assess the steady-state thermo-mechanical degradation of the TiAlN-coated EZ micro drill, tool wear was progressively evaluated at intervals of 10, 20, and 30 holes. The Response Optimization Model in Table 8 was used to identify the absolute optimal conditions for minimizing tool wear. The optimization yielded a strong composite desirability score of 0.7672, which mathematically confirmed that the cutting speed of 50 m/min and the



(a)



(b)

Fig. 8 **a** Interaction plot of surface roughness between cutting speed and point angle. **b** Surface plot of effect of cutting speed and point angle on surface roughness

Table 8 Response optimization solutions indicating the optimal parameter combination and composite desirability score to minimize Tool Wear, (μm)

Solution	Speed (m/min)	Point angle ($^{\circ}$)	Wear (μm) Fit	Composite desirability
1	50	118	85.7233	0.767249

Table 9 Analysis of variance (ANOVA) of Tool Wear, (μm)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Speed (m/min)	2	4136.05	2068.03	15.03	0.000
Point Angle ($^{\circ}$)	2	3184.66	1592.33	11.57	0.001
Speed (m/min) *Point Angle ($^{\circ}$)	4	99.03	24.76	0.18	0.946
Error	18	2476.20	137.57		
Total	26	9895.95			

point angle of 118° were the optimal parameter combinations, predicting a minimized steady-state average wear of $85.72 \mu\text{m}$. This optimized condition was in sharp contrast to the peak average wear of $140.23 \mu\text{m}$ recorded at the extreme parametric limits of 80 m/min and 140° . Two-Way Analysis of Variance (ANOVA) in Table 9 confirmed that, unlike surface roughness responses, tool wear was very sensitive to these machining parameters, revealing statistically significant main effects for both cutting speed ($p < 0.001$) and point angle ($p = 0.001$). The complete dataset of the tool wear results is tabulated in Appendix 3.

3.3.1 Validation of the optimized steady-state wear profile

To validate the tool life stages introduced above and confirm that the optimal machining parameters successfully

maintain a stable thermo-mechanical regime, a progressive tool life profile was constructed (Fig. 9). As outlined in the methodology, wear measurements were extracted at 10, 20, and 30 hole intervals to map the degradation trajectory before catastrophic failure.

Figure 9 illustrates this profile for an optimal cutting speed of 50 m/min . The data confirms the classic progressive wear regime. The 130° and 140° geometries exhibit a clear steady state between holes 20 and 30, where the wear rate effectively stabilized. Similarly, the optimal 118° geometry exhibits a very predictable linear wear progression without any exponential spikes that indicate catastrophic failure. Across all geometries at this optimal speed, the peak wear remains below $130 \mu\text{m}$. Since this value is far below the traditional failure threshold of $300 \mu\text{m}$ used in macro-scale machining, this profile conclusively confirms that the wear output analyzed in the subsequent sections represents the true steady-state degradation of the TiAlN coating. This progressive, non-catastrophic wear trajectory is consistent with established tool life literature, where cutting speed is identified as the most influential variable promoting acceleration of flank wear, particularly in difficult-to-machine alloys [43].

3.3.2 Main effect of cutting speed on tool wear

The main effects plot, shown in Fig. 10 illustrates a continuous and steep increase in tool wear as the velocity increases towards 80 m/min . As the cutting speed increases, the tool experiences high cutting forces, which transfer greater energy into the workpiece [44]. This kinetic energy is rapidly converted into heat, drastically increasing the temperature

Fig. 9 Progressive tool wear measurements at intervals of 10, 20, and 30 holes (cutting speed = 50 m/min), validating the steady-state wear regime of the TiAlN-coated micro-drills before catastrophic failure

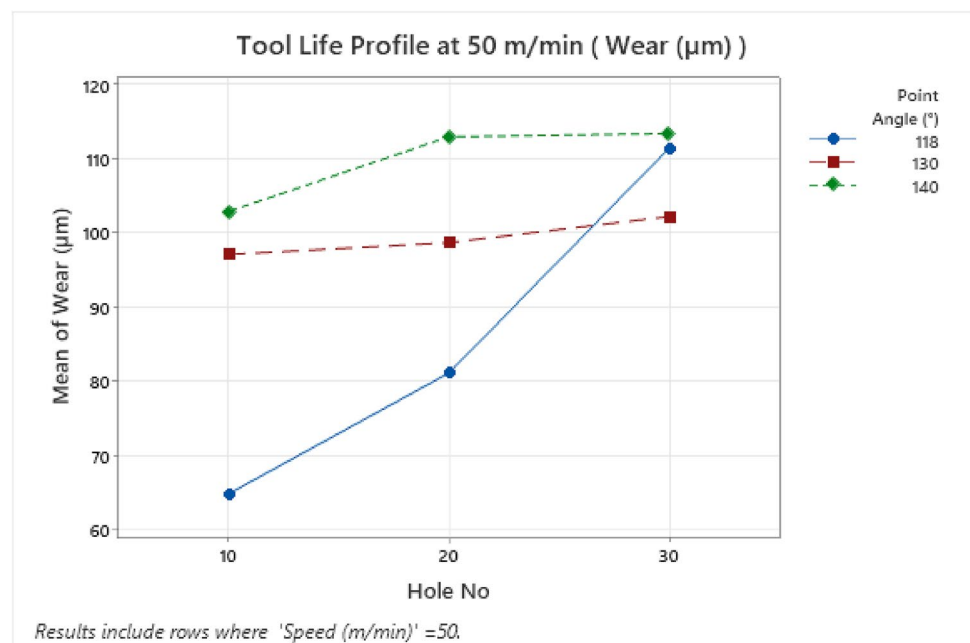
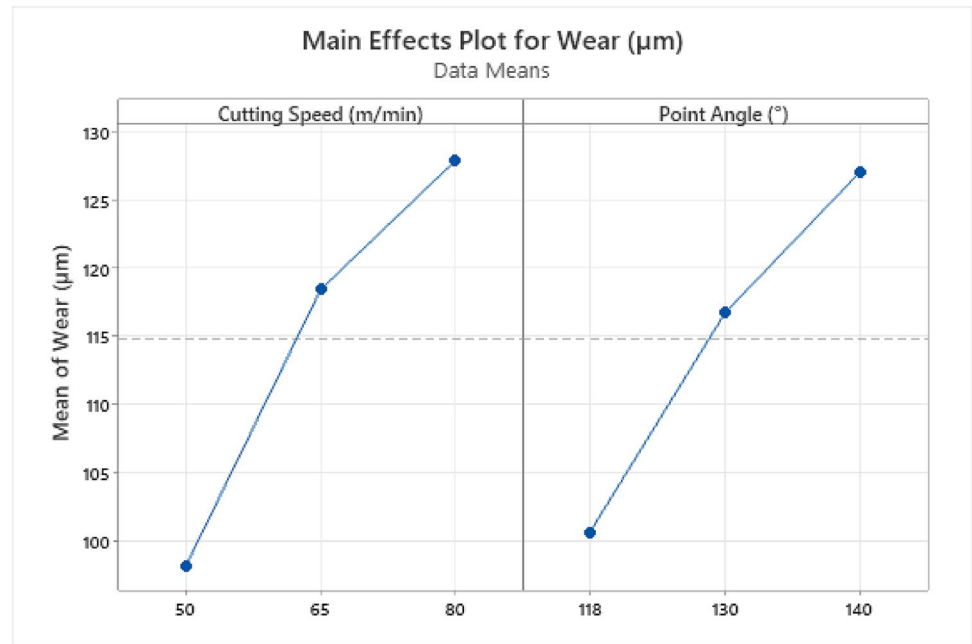


Fig. 10 Main effect plots for tool wear of cutting speed and point angle factors



within the localized cutting zone [44]. In micro-drilling of CoCrMo, this extreme thermal load eventually overcomes the protective TiAlN tribo-layer. The penetrating heat softens the underlying carbide substrate, making the cutting edge highly susceptible to plastic deformation, and accelerates severe wear mechanisms such as adhesion, diffusion, and abrasion [19]. In micro-drilling of nickel-based superalloys and CoCrMo alloys, the thermally driven progression of tool wear initiates with coating detachment, followed by chip adhesion and built-up edge (BUE) formation, leading to edge chips and a measurable increase in machining resistance [26]. Experimental studies have demonstrated that higher cutting speeds accelerate this thermal degradation, leading to a significant increase in the cutting-edge radius, which negatively impacts dimensional accuracy and intensifies tool wear through the size effect [14].

Crucially, this statistically significant acceleration of edge rounding at 80 m/min provides a mechanistic explanation for the cutting force observed in the Cutting Force section. While conventional machining theory suggests that cutting forces should decrease at high speeds due to thermal softening of the workpiece, the rapid degradation of the cutting edge observed here significantly increases the ploughing effect. This wear-induced ploughing mechanism, discussed in Section 3.1.3, indicates that the influence of thermal softening on cutting resistance is transient and is ultimately outweighed by the mechanical consequence of edge degradation.

3.3.3 Main effect of point angle on tool wear

In addition to the thermal velocity effect, the geometry of the drill point directly determines the wear rate ($p = 0.001$). Larger point angles, such as 140° , fundamentally change the cutting kinematics by reducing the effective rake angle. This flattens the rake surface relative to the workpiece plane, resulting in higher cutting resistance and requiring higher penetration forces to shear the material. This stress concentration along the cutting edge promotes aggressive abrasive and adhesive wear that facilitates material transfer between the CoCrMo and the tool substrate [45]. The optimized wear values recorded at 118° demonstrate that this sharper geometry successfully minimizes cutting resistance.

Furthermore, the preservation of this 118° point angle is entirely dependent on the specific EZ design of the micro drill. While conventional U-profile flutes suffer from severe chip compaction due to the fixed web thickness limiting the cross-sectional space for chip transfer [8], this trapped material results in strong secondary friction and trapped heat. To overcome this geometric compromise, the EZ design uses a modified C-flute geometry with a wider gullet. Complementing this extended C-flute, the EZ design incorporates a specialized chisel edge that features effective clearance and cutting. This structural enhancement actively reduces the thrust load on the drill tip and prevents the ploughing effect that typically destroys conventional sharp micro-drills [9, 13]. This specific shape actively forces the hard CoCrMo

chip to curve tightly and fracture, quickly transferring the hot chip from the cutting zone. By eliminating this secondary friction, the C-flute geometry works synergistically with the TiAlN coating to maintain a thermally stable environment, preventing the build-up of heat that would normally strip the coating and destroy the cutting edge. This synergistic benefit is consistent with CoCrMo high-speed end milling studies, which show that coated carbide tools consistently outperform uncoated tools in tool life at all cutting speeds, with higher speeds amplifying the performance gap as thermal protection becomes increasingly critical [46].

3.3.4 Interaction effect on tool wear

The evaluation of the interaction effect on average tool wear is visually mapped out in Fig. 11, which shows both the main 2D interaction plot (Fig. 11a) and the corresponding 3D surface topography (Fig. 11b). The 2D plot depicts the relationship between cutting speed and point angle as nearly parallel data lines across the experimental range. This visual parallelism is mathematically supported by the 3D surface plot, which displays a relatively flat and uniformly inclined plane surface without any severe topological curvature. Overall, this complementary visualization confirms the ANOVA results. The interaction between speed and angle on tool wear is not statistically significant ($p = 0.946$).

Mechanistically, this indicates a highly predictable tool wear profile across the parameter matrix. The rate of wear acceleration caused by flattening the point angle from 118° to 140° remains relatively constant, regardless of whether the tool is operating at 50 m/min or 80 m/min. Rather than indicating a lack of influence, this statistical independence reveals a highly decoupled thermo-mechanical system. The thermal degradation induced by high speeds operates completely independently of the geometric shear limitations of the point angle. Consequently, this confirms that the synergistic chip-evacuation benefits of the 118° C-flute architecture are reliably maintained across the speed matrix without the risk of unpredictable compound failure modes, thus enabling highly controlled process optimization.

3.4 Comparative performance and coating synergy

To definitively validate the thermo-mechanical benefits of the proposed tool architecture, these wear results were directly benchmarked against recent baseline data for uncoated EZ micro drills operating under similar kinematic conditions [22]. According to Patar's findings at 50 m/min, the uncoated 118° geometry experienced progressive wear reaching 122 μm by the 30th hole, while the flatter 140° geometry experienced severe degradation, culminating in wear of 274 μm . In contrast, the TiAlN-coated C-flute

design used in this study successfully suppressed the average steady-state wear to only 85.72 μm at the optimal 118° configuration.

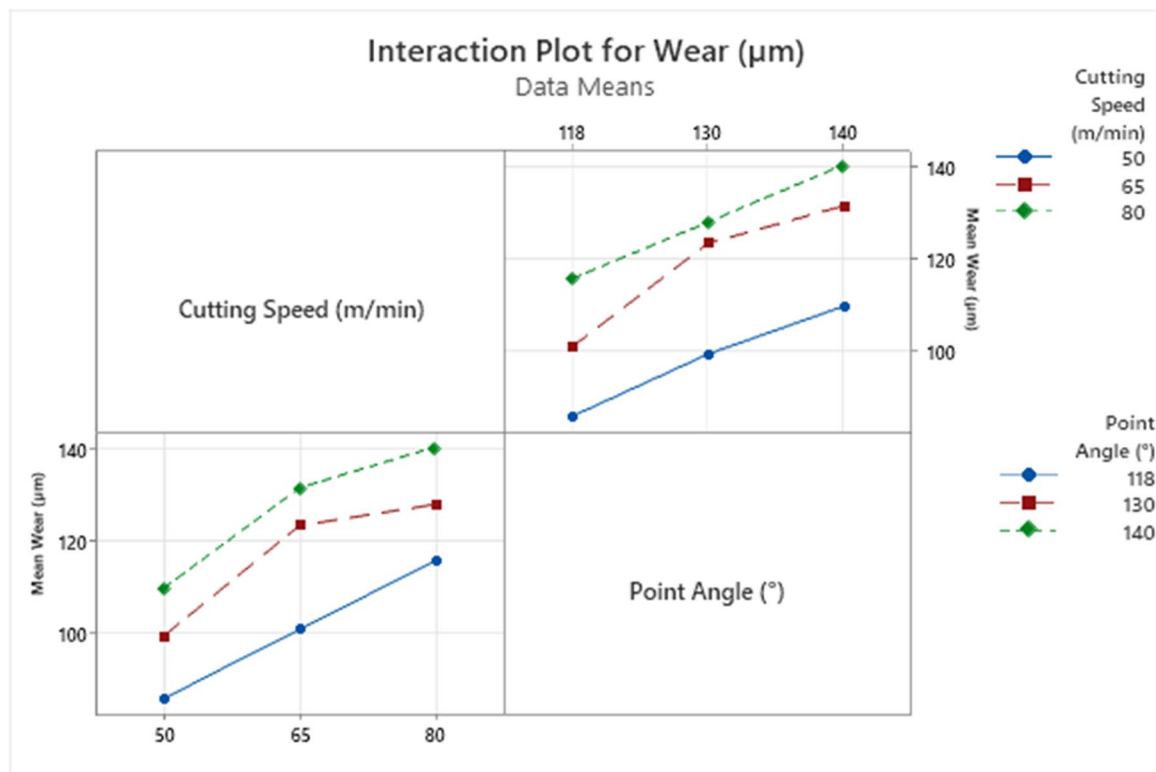
This direct comparison provides mechanistic evidence for the study's core hypothesis. While the EZ 118° geometry excels in mechanically distributing cutting forces and quickly transferring chips, it requires the thermal barrier properties of the TiAlN coating to withstand the severe localized heat generated by CoCrMo. This synergistic combination successfully reduces the thermal degradation that would quickly destroy uncoated tools, resulting in significantly longer tool life. This coating-driven performance advantage is generally consistent with comparative studies in Ti6Al4V milling, where TiAlN-coated tools demonstrated approximately 44% longer tool life and 31% lower surface roughness than uncoated equivalents under the same cutting conditions [47]. This shows a benefit that can be attributed to the suppression of adhesive chip transfer by the Al₂O₃ tribolayer.

3.5 Effect of cutting speed and point angle on tool wear mechanisms

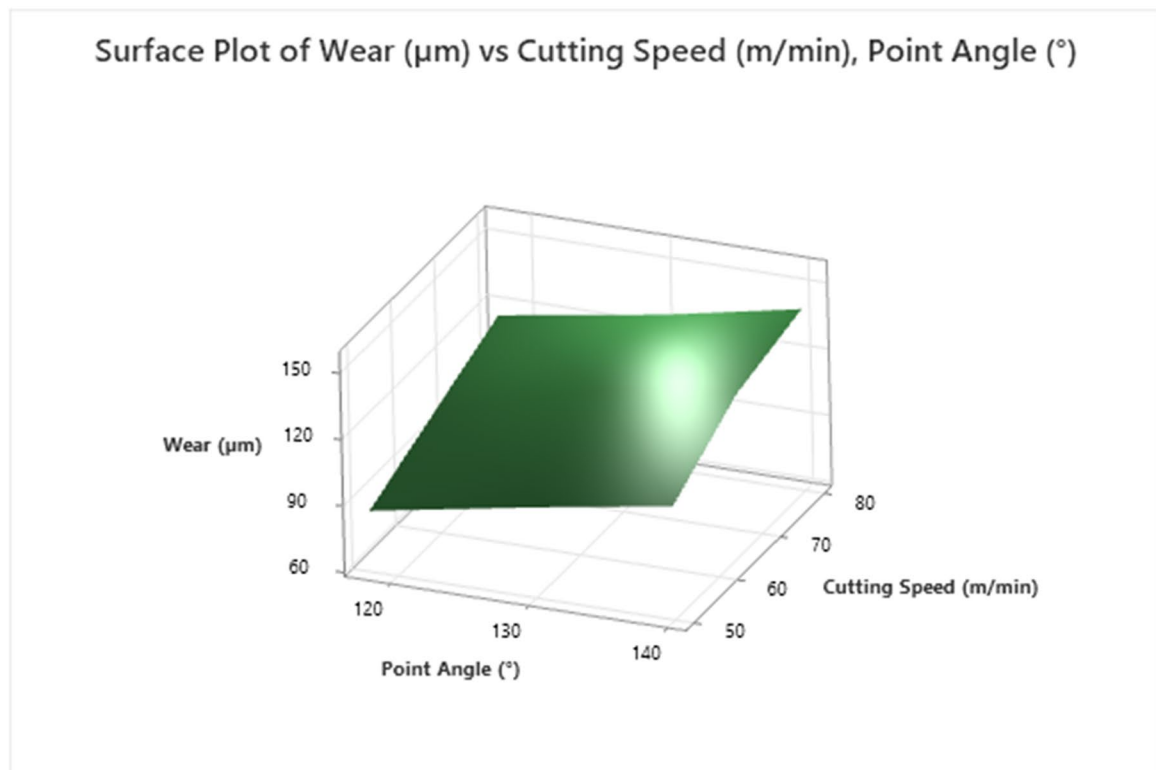
Optical evaluation of TiAlN-coated microdrills, summarized in Tables 10, 11, and 12, revealed distinct mechanistic transitions in tool degradation based on machining parameters. Rather than a uniform failure mode, the wear morphology shifted from a steady, progressive wear at the optimum speed (50 m/min) to a highly accelerated, thermally driven tertiary wear mechanism, such as edge cracking, aggressive built-up edge (BUE) formation, cratering, and notch wear, at the extreme velocity limit (80 m/min) [19].

3.5.1 The 118° geometry and active chip evacuation

At the optimized parameters of 50 m/min and 118°, flank wear appears to be very uniform and less severe (Table 10). The geometric justification for this preservation lies in the synergy between the sharper point angle and the C-flute architecture of the EZ micro drill. The 118° angle provides a very efficient effective rake angle, ensuring a clean shearing action that minimizes extreme stress concentrations along the cutting edge [22]. This is consistent with direct observations in micro-drilling of CoCrMo under flood-cooling conditions with the same point angle configuration, where crater and flank wear were identified as the dominant morphologies, with crater wear becoming more prevalent at higher speeds, highlighting the important role of cutting speed in determining the wear regime [48]. Furthermore, at this optimal velocity, the unique C-flute geometry and extensive wound clearance actively force the CoCrMo chip to curve and exit rapidly. By quickly clearing this hot chip from the cutting



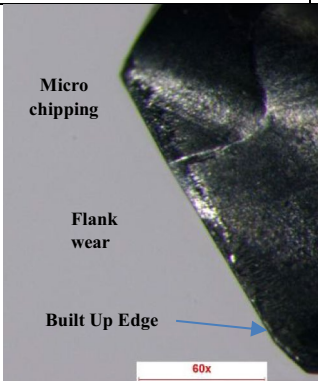
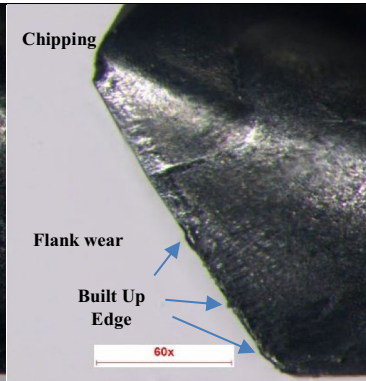
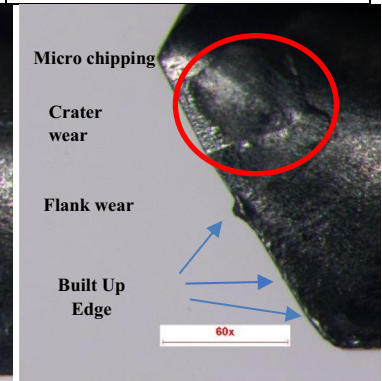
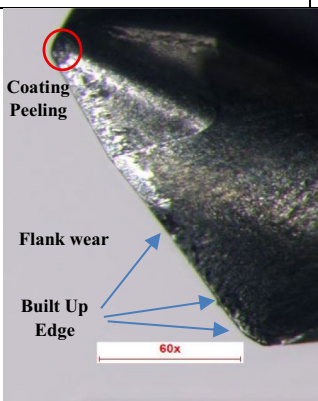
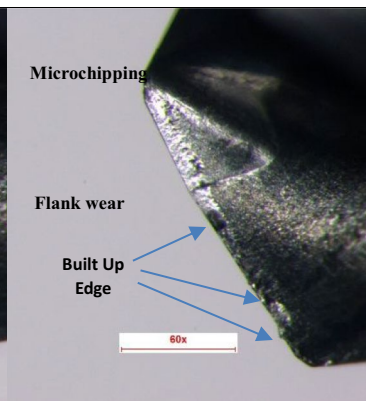
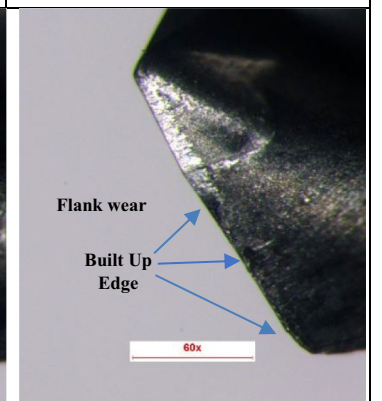
(a)



(b)

Fig. 11 **a** Interaction plot of tool wear between cutting speed and point angle. **b** Surface Plot of effect of cutting speed and point angle on tool wear

Table 10 Tool wear types of 118° point angle

Tool	Flute	Cutting Speed (m/min)		
		50 m/min	65 m/min	80 m/min
118°	1			
	2			

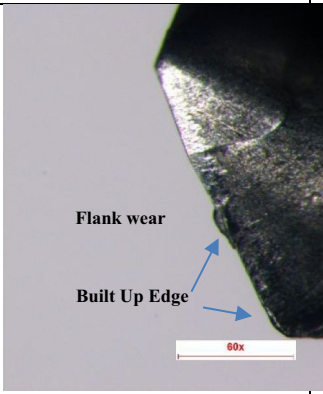
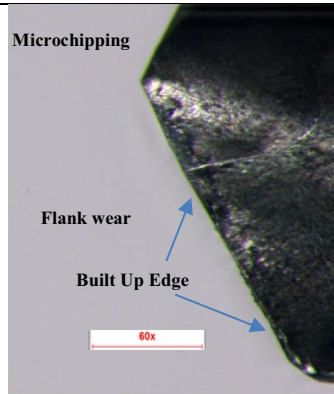
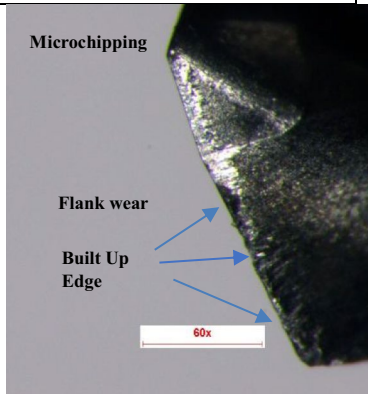
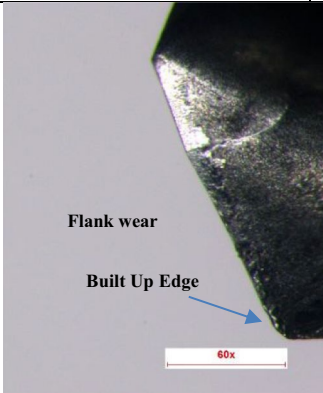
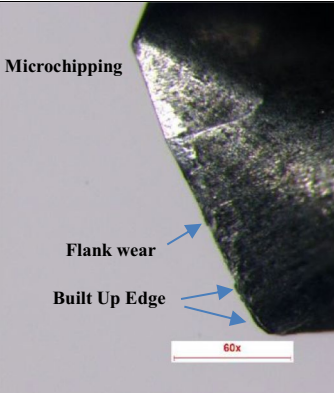
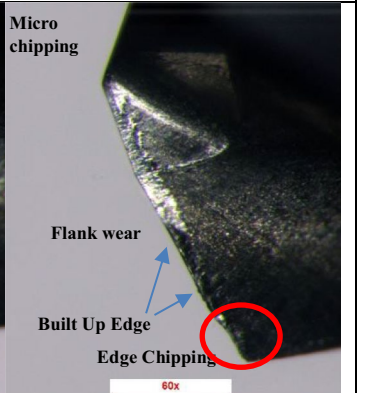
zone, the tool prevents the prolonged heat exposure required to trigger severe adhesion [22], allowing the TiAlN coating to successfully maintain its triboprotective layer.

3.5.2 Extreme velocity (80 m/min) causes crater wear at 118

At the extreme high-speed limit of 80 m/min, catastrophic failure mechanisms dominate all point angles. Notably, severe crater wear is observed at the 118° tool rake surface. This crater wear is mainly driven by thermally activated phenomena, such as adhesion and diffusion, which are caused by strong chemical interactions between the rake surface and the highly heated chip [13, 19]. In the machining of TiAlN-coated carbide tool superalloys, this thermally activated wear has been well documented, where high temperatures accelerate the diffusion of workpiece elements through the coating into the carbide

substrate, destabilizing the tool chip interface and initiating crater formation directly under the cutting edge [49]. Although the C-flute geometry efficiently clears the chip at moderate speeds, the thermal energy generation rate at 80 m/min far exceeds the physical heat dissipation capacity of the tool architecture. This extreme thermal load rapidly degrades the TiAlN coating and softens the underlying tungsten carbide substrate, allowing the superheated CoCrMo chip to chemically dissolve the crater directly onto the tool surface. At the same time, the extreme mechanical fatigue from high-frequency and high-impact loading at these velocities causes severe edge cracking, culminating in complete catastrophic tool failure [12, 13]. This failure sequence, which is from coating detachment to chip adhesion, edge chipping, and eventually fracture, has been systematically documented in microdrilling of nickel-based superalloys, where excessive thermal load cutting conditions consistently produce this degradation pattern [14].

Table 11 Tool Wear types of 130° Point angle

Tool	Flute	Cutting Speed (m/min)		
		50 m/min	65 m/min	80 m/min
130°	1			
	2			

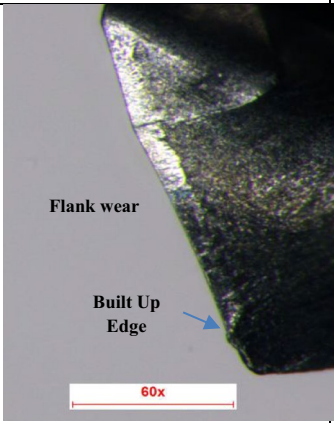
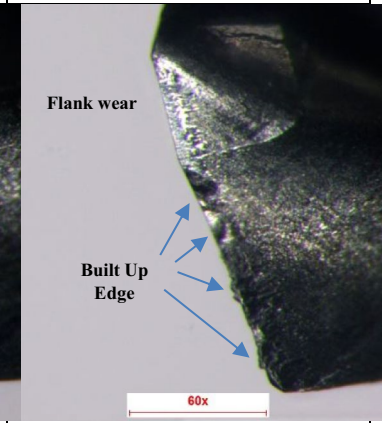
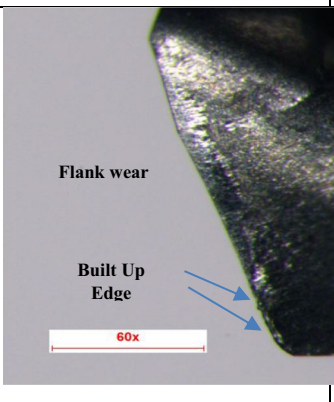
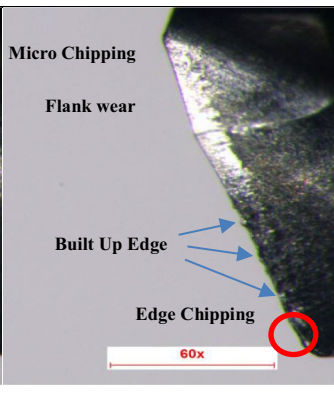
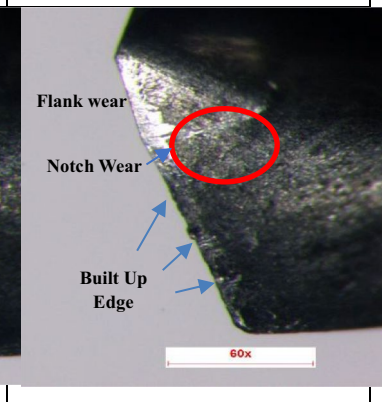
3.5.3 The 130° and 140° geometry caused BUE and notch wear

In contrast, the severity of edge cutting and built-up edge formation (BUE) increases drastically at larger point angles of 130° and 140°. Although flattening the point angle to 140° distributes the cutting load over a wider impact area, it critically reduces the shear efficiency and significantly increases the interfacial friction [45]. In this TiAlN-coated microdrilling, the combination of reduced shear efficiency and high friction accelerates the onset of adhesive wear, as the protective Al₂O₃ tribological layer is overwhelmed at localized stress concentration zones, exposing the carbide substrate directly to workpiece adhesion [4]. This increased friction generates immense localized heat. Because CoCrMo is highly adhesive and prone to extreme work-hardening, this trapped thermal energy accelerates diffusion wear, causing the workpiece material to micro-weld directly to the cutting edge, forming prominent BUE. As observed in Tables 11 and 12, this continuous

cycle of adhesive material welding and subsequent tearing of the tool forcibly extracts small carbide particles from the substrate, directly promoting aggressive edge chipping [13, 26]. This cyclic adhesion-tearing sequence in which micro-welded workpiece material is periodically pulled from the cutting edge, is identified by Hua and colleague [50] as one of the most destructive wear mechanisms in drilling difficult-to-cut alloys, especially when flute geometry limits hot chip transfer. Furthermore, the work-hardened cutting edge, which is poorly evacuated by this flatter geometry, drags aggressively against the major and minor cutting edges, resulting in the significant notch wear observed on the 130° and 140° micro drills.

In summary, this optical evaluation confirms that in CoCrMo microdrilling, tool failure is determined by thermal trapping rather than only mechanical forces. The 118° C-flute geometry emerged as the only configuration capable of clearing high-temperature chips fast enough to prevent the severe sticking and chemical wear mechanisms that would inevitably destroy the tool at higher speeds and flatter angles.

Table 12 Tool Wear types for 140° Point Angle

Tool	Flute	Cutting Speed (m/min)		
		50 m/min	65 m/min	80 m/min
140°	1			
	2			

4 Conclusion

This study successfully established a multi-objective and mechanistic optimization framework for precision microdrilling of biomedical CoCrMo alloys, using a custom TiAlN-coated microdrill featuring an active chip evacuation architecture. Based on extensive thermo-mechanical analysis and statistically validated ANOVA modeling, the following conclusions were drawn:

1. **The Optimal Thermo-Mechanical Envelope:** Multi-objective optimization mathematically identified a cutting speed of 50 m/min paired with a point angle of 118° as the absolute optimal machining condition. Operating strictly within this envelope resulted in the lowest thrust force (95.42 N), minimized surface roughness (0.52 μm), and successfully maintained cutting-edge integrity by limiting average tool wear to just 85.72 μm through 30 continuous holes.
2. **High-Speed Degradation and Parametric Inefficiency:** Conversely, operating at the extreme velocity limit (80 m/min) resulted in severe thermal gradients that completely overcame the local benefits of thermal softening. When paired with a flattened 140° geometry, this intense heat rapidly removes the protective coating and forces the blunt tool into a mechanical ploughing regime, resulting in maximum penetration resistance (125.35 N) and catastrophic tool wear (140.23 μm). Furthermore, at 80 m/min and 130°, stochastic micro-level chaos and slip vibrations attached to the tool-chip interface resulted in the worst surface finish recorded (0.70 μm).
3. **Circumventing Conventional Geometry Trade-offs:** This study demonstrates that the traditional geometry trade-offs associated with CoCrMo microdrilling are not absolute. By optimizing the cutting velocity to a thermally stable regime, at 50 m/min, the TiAlN coating successfully maintains its tribo-protective coating. This significant thermal stability allows the highly efficient 118° point angle, when synergistically coupled with the rapid chip evacuation dynamics of the C-flute, to actively shear the extremely abrasive superalloy

without experiencing catastrophic structural failure. Ultimately, the synergy of this specific coating geometry eliminates the reliance on extreme high-speed thermal softening, defining a robust and statistically validated operating window for CoCrMo implant manufacturing.

Appendix 1: Result of Thrust Force for microdrilling

Run	Cutting speed (m/min)	Point angle	Hole No	Thrust force (N)
1	50	140°	5	115.566
			10	119.588
			15	120.081
			20	122.001
			25	123.494
			30	125.068
2	65	140°	5	116.305
			10	118.907
			15	125.270
			20	121.711
			25	115.744
			30	117.629
3	80	140°	5	120.872
			10	123.412
			15	128.733
			20	128.824
			25	126.772
			30	123.495
4	50	130°	5	118.480
			10	119.342
			15	112.587
			20	111.258
			25	136.713
			30	116.798
5	65	130°	5	123.791
			10	120.824
			15	119.324
			20	121.441
			25	117.460
			30	116.172
6	80	130°	5	115.194
			10	118.591
			15	118.808
			20	118.909
			25	114.451
			30	117.150

Run	Cutting speed (m/min)	Point angle	Hole No	Thrust force (N)
7	50	118°	5	102.943
			10	98.172
			15	98.063
			20	94.550
			25	82.626
			30	96.178
8	65	118°	5	114.322
			10	117.082
			15	123.814
			20	121.001
			25	116.774
			30	117.517
9	80	118°	5	135.623
			10	101.711
			15	104.643
			20	113.403
			25	154.783
			30	108.603

Appendix 2: Result of Surface Roughness for microdrilling

Run	Speed (m/min)	Point Angle	Hole No	Ra (μm)			Average Ra (μm)
				1	2	3	
1	50	140°	5	0.805	0.871	0.869	0.848
			10	0.475	0.486	0.49	0.484
			15	0.423	0.37	0.3695	0.388
			20	0.586	0.581	0.584	0.584
			25	0.303	0.369	0.419	0.364
			30	0.765	0.777	0.753	0.765
2	65	140°	5	0.676	0.739	0.66	0.692
			10	0.632	0.644	0.641	0.639
			15	0.573	0.55	0.561	0.561
			20	0.642	0.727	0.748	0.706
			25	0.436	0.432	0.427	0.432
			30	0.761	0.76	0.763	0.761
3	80	140°	5	0.582	0.591	0.608	0.594
			10	0.865	0.868	0.882	0.872
			15	0.683	0.677	0.643	0.668
			20	0.918	0.946	0.996	0.953
			25	0.463	0.499	0.507	0.490
			30	0.441	0.471	0.465	0.459

Run	Speed (m/min)	Point Angle	Hole No	Ra (μm)			Average Ra (μm)
				1	2	3	
4	50	130°	5	0.551	0.539	0.565	0.552
			10	0.546	0.574	0.589	0.570
			15	0.678	0.739	0.745	0.721
			20	0.743	0.73	0.709	0.727
			25	0.676	0.682	0.699	0.686
5	65	130°	30	0.487	0.492	0.49	0.490
			5	0.403	0.404	0.417	0.408
			10	0.366	0.371	0.389	0.375
			15	0.425	0.435	0.43	0.430
			20	0.66	0.689	0.696	0.682
6	80	130°	25	0.698	0.733	0.705	0.712
			30	0.58	0.59	0.586	0.585
			5	0.775	0.763	0.729	0.756
			10	0.768	0.755	0.783	0.769
			15	0.774	0.71	0.627	0.704
7	50	118°	20	0.664	0.659	0.665	0.663
			25	0.596	0.631	0.652	0.626
			30	0.643	0.711	0.703	0.686
			5	0.486	0.489	0.459	0.478
			10	0.604	0.633	0.636	0.624
8	65	118°	15	0.447	0.446	0.457	0.450
			20	0.525	0.533	0.507	0.522
			25	0.631	0.525	0.533	0.563
			30	0.432	0.459	0.464	0.452
			5	0.551	0.57	0.537	0.553
9	80	118°	10	0.601	0.63	0.631	0.621
			15	0.906	0.9	0.936	0.914
			20	0.505	0.507	0.506	0.506
			25	0.724	0.725	0.729	0.726
			30	0.584	0.579	0.574	0.579
			5	0.94	0.968	0.989	0.966
			10	0.423	0.428	0.426	0.426
			15	0.656	0.681	0.685	0.674
			20	0.564	0.556	0.575	0.565
			25	0.374	0.335	0.342	0.350
			30	0.662	0.665	0.666	0.664

Appendix 3: Results of tool wear for microdrilling

Run	Hole No	Speed (m/min)	Tool	Wear (μm)	Average Wear (μm)
1	10	50	140°	102.76	109.60
	20			112.80	
	30			113.24	
2	10	65	140°	123.98	131.35
	20			127.58	
	30			142.48	
3	10	80	140°	122.35	140.23
	20			143.70	
	30			154.63	
4	10	50	130°	96.98	99.21
	20			98.58	
	30			102.08	
5	10	65	130°	112.47	123.18
	20			121.44	
	30			135.64	
6	10	80	130°	118.02	127.77
	20			127.18	
	30			138.10	
7	10	50	118°	64.82	85.72
	20			81.06	
	30			111.29	
8	10	65	118°	98.65	100.71
	20			99.01	
	30			104.47	
9	10	80	118°	109.74	115.55
	20			117.60	
	30			119.31	

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Data availability The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethical approval Not applicable.

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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