

UDC 621.914.2:621.762

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## THERMO-MECHANICAL EFFECTS OF CUTTING PARAMETERS ON HOLE PERFORMANCE AND TOOL WEAR IN CARBON POLIMER / TITANIUM ALLOY STACK

**Purpose.** To systematize and summarize the results of scientific studies on the influence of cutting parameters on hole accuracy, machined surface quality, tool wear intensity, and built-up edge formation during drilling of Carbon Fiber-Reinforced Polymer (CFRP)/titanium alloy stacks.

**Research methods.** A comparative parametric analysis was applied to evaluate the influence of feed rate and cutting speed on drilling thrust force, temperature in the cutting zone, delamination intensity in the composite layer, burr height in the titanium layer, surface roughness, and tool wear progression. Experimental and numerical results reported in recent scientific publications were analyzed and integrated to determine cause-and-effect relationships between cutting parameters, thermomechanical processes in the cutting zone, and hole quality indicators.

**Results.** Feed rate was identified as the primary factor governing mechanical loading during drilling and therefore determining the extent of delamination in the CFRP layer. Cutting speed mainly affects the thermal state of the cutting zone and adhesion phenomena in the titanium alloy. Built-up edge formation and adhesive material transfer to the cutting edge modify the effective tool micro-geometry, leading to increased axial forces, reduced hole accuracy, and decreased drilling stability.

**Scientific novelty.** The synthesis of previously published results substantiates the need for an integrated approach to evaluating drilling of CFRP/titanium alloy stacks as a unified thermomechanical system. Within this framework, cutting parameters, tool wear evolution, and built-up edge formation are considered interrelated factors governing the transition between abrasive, adhesive, and diffusion wear mechanisms depending on process conditions.

**Practical value.** The obtained generalizations may guide further research in machining CFRP/titanium alloy stacks, particularly for extending tool life, stabilizing the drilling process, and optimizing cutting parameters to improve hole quality.

**Key words:** drilling, CFRP/titanium alloy stacks, cutting parameters, delamination, built-up edge, tool wear, thermomechanical interaction, comparative parametric analysis.

### Introduction

Carbon Fiber-Reinforced Polymer (CFRP) and Ti-6Al-4V alloy stacks are widely used in aerospace structures due to their high specific strength and durability. Despite these advantages, drilling assembly holes in such multi-material systems remains technologically challenging. The composite layer exhibits anisotropic behavior and limited interlaminar strength, while titanium exhibits low thermal conductivity, strong plasticity, and a high affinity for cutting tools. The abrupt transition between these materials during drilling generates complex thermo-mechanical interactions that often lead to delamination, burr formation, dimensional inaccuracy, accelerated tool wear, and built-up edge (BUE) formation.

Existing research has established that drilling performance in CFRP/Ti stacks is strongly dependent on cutting parameters. Feed rate primarily influences thrust force and interlaminar stress development in the composite layer,

whereas cutting speed governs temperature rise and deformation behavior in titanium. Elevated mechanical loading intensifies composite damage, while excessive thermal accumulation promotes titanium plastic flow and adhesion to the cutting edge. Consequently, hole quality, surface integrity, and tool degradation are controlled by the combined action of mechanical and thermal effects rather than by isolated parameters.

Numerous experimental and numerical studies have addressed force prediction, temperature distribution, damage mechanisms, and wear behavior in stack drilling. Assisted technologies such as ultrasonic vibration, helical milling, and hybrid cooling strategies have demonstrated reductions in thrust force or thermal concentration. However, reported optimal parameter ranges remain inconsistent, particularly under varying lubrication and assistance conditions. Furthermore, many investigations analyze dimensional accuracy, surface quality, or tool wear independently, although these phenomena are inherently interrelated.

Adhesion-induced BUE formation represents a key transitional mechanism linking temperature rise, wear progression, and geometric instability. Modification of the cutting edge by adhered titanium alters contact mechanics, affecting hole accuracy and surface morphology. Despite advances in finite element and data-driven modeling, comprehensive approaches that simultaneously relate cutting parameters to wear evolution, BUE dynamics, and resulting hole quality in CFRP/Ti stacks remain limited.

Therefore, a systematic and integrated assessment of the influence of cutting parameters on the thermo-mechanical behavior, tool wear, and hole performance is required. Such analysis is essential for establishing predictive and stable drilling strategies for aerospace-grade multi-material structures.

### Analysis of research and publications

Recent studies have extensively examined the mechanisms of drilling-induced damage in CFRP and stack configurations. Delamination and matrix cracking in CFRP are strongly influenced by thrust force and temperature rise [1-3], while burr formation and plastic deformation dominate the titanium layer, particularly at elevated temperatures [2, 4]. Surface roughness and hole dimensional accuracy are governed by cutting speed–feed combinations and tool geometry, as well as by thermal softening and chip–wall interaction effects [5, 6]. Helical milling and ultrasonic-assisted drilling have demonstrated reduced thrust forces and improved chip evacuation compared to conventional drilling [7], yet parameter sensitivity remains high.

Tool wear behavior in stack drilling is complex and often dominated by adhesive and diffusion mechanisms in titanium and abrasive wear in CFRP [6, 8, 9]. Adhesion of titanium to the cutting edge frequently results in BUE or build-up layer (BUL) formation, altering tool geometry, increasing forces, and accelerating wear progression [4, 9, 10]. Cooling and lubrication strategies such as MQL, Cryo-MQL, and ultrasonic-assisted cryogenic systems have shown potential to mitigate temperature rise and adhesion wear [11-14], but their effectiveness depends strongly on the selection of cutting parameters.

Although numerous works have addressed isolated aspects of temperature fields [15], stress distribution [16], tool geometry [5, 6], coating performance [6, 9], lubrication systems [12, 14], and AI-based predictive modeling [17], the majority of studies treat hole quality, tool wear, and BUE formation as partially independent phenomena. However, in CFRP/Ti stack drilling, these effects are inherently interrelated: cutting parameters influence temperature and stress distribution, which govern adhesion behavior and BUE stability. These, in turn, modify the effective cutting-edge radius and contact mechanics, ultimately affecting hole accuracy and surface integrity.

Feed rate is generally the dominant parameter controlling thrust force and delamination [3, 6], whereas cutting speed primarily governs thermal softening and adhe-

sion in titanium [2, 10, 18]. However, contradictory findings exist regarding optimal speed-feed windows, particularly under hybrid lubrication and ultrasonic assistance [12, 19, 20]. Moreover, while modeling efforts using finite element approaches [2, 21], hybrid analytical–numerical frameworks [16], and data-driven prediction methods [17, 22] have advanced force and temperature prediction, robust coupling between cutting parameters, tool wear progression, and BUE formation in stack drilling remains insufficiently addressed.

### Purpose of work

Despite significant progress, there is still a lack of integrated analysis that simultaneously links cutting parameters to tool wear evolution, BUE dynamics, and resulting dimensional deviations, particularly in CFRP/Ti alloy stacks. Most studies focus either on hole damage or on wear mechanisms separately, without establishing mechanistic interdependencies. In particular, the parameter-dependent transition between adhesive wear and thermally activated diffusion wear in titanium, and its feedback effect on delamination and surface integrity in the CFRP layer, is not yet comprehensively understood. Therefore, more solid, systematic research is required to clarify how cutting speed–feed combinations influence tool wear mechanisms and BUE formation during drilling of CFRP/Ti stacks, and how these wear-induced geometric changes propagate into hole quality deterioration. Such understanding is essential for developing predictive, parameter-optimized, and damage-controlled drilling strategies for aerospace-grade multi-material structures.

### Research material and methodology

This work presents a structured analytical review of peer-reviewed studies on the drilling of CFRP/Ti-6Al-4V stacks. The methodological framework was developed to enable systematic comparison of mechanical, thermal, and tribological process characteristics and to identify interdependencies between cutting parameters and drilling performance.

The analysis included experimental and validated numerical studies that explicitly reported feed rate and cutting speed and provided quantitative evaluation of thrust force, temperature, delamination, burr height, surface roughness, tool wear, or built-up edge formation. Both conventional and assisted techniques, namely ultrasonic drilling, helical milling, cryogenic, and hybrid cooling, were considered to assess parameter sensitivity under different processing conditions.

The selected publications were classified into four domains. These domains are mechanical response, thermal behavior, hole quality and surface integrity, and tool wear with adhesion phenomena. A comparative-parametric approach was applied to evaluate consistent trends, focusing on correlations between feed rate and thrust force, cutting speed and interface temperature, and the transition of wear mechanisms under different thermo-mechanical modes.

Reported quantitative indicators were used to support trend validation.

An integrative interpretation was adopted to consider mechanical load, temperature evolution, adhesion stability, and wear progression. Cross-comparison of experimental and modeling results ensured consistency and strengthened the reliability of the derived conclusions.

### Research results

Drilling of CFRP/Ti stacks is characterized by thermomechanical heterogeneity resulting from the abrupt transition between the anisotropic brittle composite and the ductile titanium alloy. The chisel edge region operates at near-zero cutting speed, where extrusion and ploughing mechanisms dominate over pure shearing. Hybrid analytical–numerical modeling demonstrates that during the initial penetration stage, the contact area increases rapidly. In contrast, the contact pressure decreases due to localized thermal softening, particularly when the interfacial temperature approaches the matrix glass transition temperature [16]. This phenomenon intensifies interlaminar stresses in CFRP and contributes to thrust-force-driven delamination.

Experimental investigations of CFRP/Ti stacks report exit temperatures in the titanium layer ranging from approximately 182 °C to 356 °C, depending on cutting parameters [2]. Within this interval, titanium burr height increased by about 56.6 %, confirming the strong temperature sensitivity of plastic deformation in Ti-6Al-4V. Simultaneously, matrix tensile damage variables in CFRP increased significantly when the temperature rose from 248 °C to nearly 300 °C, indicating progressive thermal degradation of the polymer matrix [2, 3]. These findings demonstrate that temperature is not merely a by-product of drilling but a governing variable influencing damage evolution in both materials.

Chip formation mechanisms further complicate process mechanics. CFRP produces fragmented, brittle chips, whereas titanium produces continuous or segmented, ductile chips with a strong tendency toward adhesion. Accumulated titanium chips increase torque oscillation and radial force components, particularly at low cutting speeds and elevated feeds [16, 23]. Ultrasonic-assisted drilling has been shown to reduce thrust force by approximately 23–27 % relative to conventional drilling and to decrease the delamination factor by 12–16 % through improved chip fragmentation and intermittent cutting [20]. These quantitative outcomes confirm that the combined influence of mechanical loading, thermal accumulation, and chip evacuation efficiency governs drilling mechanics in stacks.

Cutting speed predominantly governs thermal effects and adhesion phenomena during stack drilling. Across several experimental studies, increasing cutting speed within typical industrial ranges (15–30 m/min for coated drills) reduced thrust force in titanium by approximately 10–15%, primarily due to thermal softening and reduced specific cutting energy [6]. However, the accompanying temperature increase modifies tool-chip interaction conditions.

Measurements of drill temperature during Ti machining show that the peak temperature is concentrated near the drill center and increases markedly under dry conditions compared with compressed-air cooling [10].

Thermal sensitivity of titanium is further evidenced by cryogenic machining studies, which identified a transition zone near –60 °C where force direction and torque behavior changed due to altered material deformation characteristics [18]. Although this result pertains to milling, it illustrates the strong dependence of Ti deformation behavior on temperature state and supports the interpretation of speed-driven thermal effects in drilling.

In CFRP layers, higher cutting speeds generally reduce thrust force and may reduce delamination at moderate feeds [3]. Nevertheless, when the temperature exceeds the matrix glass transition range, softening and resin smearing intensify, potentially increasing subsurface damage [2]. Finite element method (FEM) simulations confirm that elevated interface temperature correlates with increased burr formation in titanium and higher tensile damage variables in CFRP [2]. These observations indicate that cutting speed influences drilling performance through a thermally mediated trade-off between force reduction and thermal degradation.

Feed rate is consistently identified as the dominant factor affecting thrust force and delamination severity. Statistical analyses of CFRP/Ti drilling confirm that feed rate is the most influential parameter on thrust force, with determination coefficients ranging from 0.87 to 0.90 in regression models [6]. Increasing the feed from 0.025 to 0.1 mm/rev resulted in substantial increases in thrust force and corresponding enlargement of delamination damage.

In composite drilling studies, increasing feed from 0.1 to 0.2 mm/rev reduced free-hole area preservation from approximately 99 % to 53 % under unfavorable speed conditions, indicating severe exit damage [3]. Similar trends are reported in stack drilling, where elevated feed increased titanium burr height and composite delamination factors [2, 5]. These results confirm that feed rate directly controls undeformed chip thickness, axial force magnitude, and the distribution of contact stress.

Tool wear progression also correlates with feed intensity. Larger feed values increase normal load on cutting edges and accelerate flank wear development [9]. Under cryogenic conditions with coated drills, higher feed rates led to an approximately 11 % increase in adiabatic shear band thickness in titanium chips, indicating intensified localized deformation and more aggressive wear. Moreover, increased feed rate increases contact pressure and the frictional area, promoting titanium adhesion and facilitating BUE formation [4, 10].

The combined influence of cutting speed and feed determines the dominant damage mechanism and wear mode during drilling. Low cutting speed combined with high feed generally results in elevated thrust force and intensified adhesive wear, promoting unstable BUE accumulation [4]. Conversely, high speed at moderate feed reduces me-

chanical loading but increases interface temperature, facilitating diffusion wear mechanisms and thermal matrix degradation [9].

Multi-objective optimization studies confirm that balanced parameter windows provide improved overall performance. Analytical hierarchy process-based optimization simultaneously reduced axial force and surface roughness in CFRP/Ti drilling by selecting intermediate parameters [15]. Ultrasonic peck drilling further demonstrated thrust-force reductions of up to 35% compared with conventional drilling under optimized conditions [19].

A comparative analysis with helical milling indicates that a distributed cutting load substantially modifies parameter sensitivity. Helical milling reduced thrust force in titanium from approximately 435 N to 117 N, corresponding to a 73% reduction, thereby decreasing thermally induced damage and improving dimensional stability [23]. Although this represents an alternative process, it underscores the central role of load distribution in determining how cutting parameters influence damage evolution. Key findings is summarized in Table 1.

Hole accuracy in CFRP/Ti stack drilling is affected by the combined influence of thrust force magnitude, thermal expansion, adhesion-induced edge modification, and tool wear. Unlike monolithic materials, dimensional deviation in stacks emerges from the superposition of composite delamination, titanium plastic flow, and temperature-driven geometric instability of the drill.

Diameter deviation in stack drilling results from both mechanical deflection and thermal-adhesive effects. Experimental observations indicate that increasing the feed rate significantly increases thrust force, enhancing radial displacement of the drill and promoting overcut in titanium layers [3]. Statistical analyses confirm feed rate as the dominant contributor to axial load variation, which directly influences dimensional stability [6].

Thermal effects further modify hole diameter. FEM analysis demonstrated that increasing the interface temperature from ~182 °C to ~356 °C resulted in a pronounced increase in burr height and plastic deformation in titanium [2]. Since titanium has relatively low thermal conductivity, localized heat accumulation near the drill margin can cause transient thermal expansion of both the tool and the workpiece, contributing to oversizing.

Adhesion-related phenomena also affect diameter consistency. Titanium build-up layer formation alters the effective cutting edge radius, thereby changing local cutting geometry and increasing dimensional scatter [4]. As adhesion accumulates, cutting becomes intermittently unstable, promoting micro-variations in hole diameter.

Roundness deviation in CFRP/Ti stacks is closely associated with torque fluctuation and radial force asymmetry. Chip accumulation in titanium at low cutting speeds intensifies torque oscillations and increases the drill's dynamic instability [23]. Such oscillatory loading contributes to out-of-roundness and localized wall irregularities.

**Table 1** – Key outcomes of investigation relevant for cutting parameters effect on the drilling process

Reference	Topic addressed	Key conclusions
Chen et al. [15]	CFRP/Ti stack drilling; force-based optimization	Axial force decreases with increasing spindle speed and increases with feed rate. Multi-objective optimization indicates that parameter balancing is required to simultaneously control thrust force and surface roughness
Shariar et al. [16]	Thermo-mechanical stress modeling in composite drilling	Thermally induced softening modifies contact pressure distribution during tool engagement. Stress evolution is governed by temperature-dependent material properties rather than purely mechanical loading
Zhaoju et al. [10]	Drill temperature distribution under different cooling methods	Peak temperature localizes near the drill center. Increasing the cutting speed increases the thermal load, whereas higher feed rates above ~0.13 mm/rev reduce temperature due to enhanced chip evacuation. Compressed air cooling improves temperature uniformity
Moran et al. [20]	Ultrasonic-assisted drilling (UAD) of CFRP/Ti	UAD stabilizes thrust force, improves chip fragmentation, and reduces adhesive transfer to the tool compared to conventional drilling
Gururaj et al. [24]	Drilling vs helical milling (dry)	Helical milling reduces mechanical and thermal loading, improving surface roughness and subsurface microhardness while mitigating adhesion and wear

Step drilling strategies reduce peak thrust and improve hole stability; however, repeated engagement may introduce cyclic thermomechanical variations that affect cylindricity at elevated feeds [5]. Ultrasonic-assisted drilling reduces radial force magnitude and improves hole geometry by decreasing chip packing, yet the improvement remains parameter-sensitive [20]. The reduction of thrust force through distributed load strategies, such as helical milling, resulted in significantly improved dimensional stability compared to conventional drilling, supporting the interpretation that load concentration directly affects geometric accuracy.

Drill wandering at the hole entry is primarily governed by thrust force magnitude and composite anisotropy. Feed increase intensifies axial force, elevating entry delamination and potentially shifting drill alignment during initial penetration [3]. Thermal softening of the CFRP matrix at elevated interface temperatures further reduces local stiffness, increasing susceptibility to entry instability [2].

Temperature concentration near the drill center also influences positional stability. Experimental temperature measurements revealed peak thermal zones at the chisel

edge region under dry conditions [10]. Such thermal gradients can asymmetrically modify contact stiffness, potentially contributing to slight angular deviation during drilling.

Although assisted technologies reduce thrust magnitude, they do not fully eliminate positional deviation when feed remains high [19, 20], indicating that mechanical loading remains the principal driver of drill runout. Key findings are summarized in Table 2.

**Table 2** – Analysis of process parameters affecting hole accuracy and quality

Reference	Topic addressed	Key conclusions
Li F. et al. [19]	Ultrasonic peck drilling (UPD) of CFRP/Ti laminates	UPD achieves hole diameter within H9 tolerance and reduces CFRP hole roughness compared to conventional and standard ultrasonic drilling.
Chen C. et al. [5]	Variable-parameter stack drilling	Layer-specific adjustments to speed and feed reduce exit delamination and burr formation, improving the geometric stability of the drilled hole.
Chen et al. [2]	Thermal influence on exit deformation	Increasing the exit temperature significantly enhances titanium plastic deformation, resulting in greater burr formation and distortion at the hole exit.
Gururaj et al. [24]	Helical milling vs conventional drilling	Reduced load concentration in helical milling improves dimensional stability and mitigates geometric distortion of hole walls.

**Influence of Cutting Parameters on Surface Quality and Surface Integrity**

Surface quality in CFRP/Ti stack drilling is governed by the coupled effects of thrust force magnitude, interface temperature, chip-wall interaction, and tool condition. Unlike monolithic drilling, surface integrity in stacks must be evaluated separately for the CFRP and titanium layers, as the governing mechanisms differ substantially.

Surface roughness in titanium layers is strongly dependent on the feed rate, as it is directly related to the undeformed chip thickness and the theoretical surface profile. Statistical analysis confirmed feed rate as the dominant parameter influencing thrust force and, consequently, surface roughness in CFRP/Ti drilling [6]. Increasing feed leads to higher axial load and increased ploughing at the margin region, producing rougher hole walls.

Cutting speed influences roughness indirectly through thermal effects. At moderate speeds, thermal softening reduces cutting resistance and may improve surface finish. However, excessive temperature intensifies adhesion and the formation of a built-up layer, altering the effective cutting edge radius and introducing irregular surface morphology [4, 10]. Experimental temperature measurements revealed peak thermal concentration near the drill

center, particularly under dry conditions, increasing adhesion tendency [10].

Ultrasonic-assisted drilling reduced thrust force and improved chip evacuation, resulting in a better surface finish than conventional drilling[20]. Nevertheless, improvements remained sensitive to feed magnitude, indicating that mechanical loading still governs roughness formation.

Helical milling experiments demonstrated a substantially reduced thrust force (~73% lower than conventional drilling), which correlated with improved surface finish and reduced wall irregularities [23]. This supports the interpretation that load distribution and mechanical stability are critical for surface integrity.

Surface integrity in CFRP is not limited to roughness but includes subsurface matrix cracking, fiber pull-out, and interlaminar damage. FEM analysis revealed that an increase in interface temperature from approximately 248 °C to 299 °C significantly amplified tensile damage variables in the composite layer [2]. Since polymer matrix properties degrade rapidly above  $T_g$ , cutting speed becomes a critical thermal control parameter.

Feed rate amplifies interlaminar stresses by increasing thrust force, directly intensifying peel-up and push-out damage. Composite drilling studies confirm that higher feed values significantly reduce free-hole area preservation, reflecting increased subsurface damage severity [3].

The combination of high feed and elevated temperature results in the most severe integrity degradation, due to simultaneous mechanical overload and matrix softening. Assisted technologies (ultrasonic or cryogenic) reduce mechanical load or temperature but do not eliminate parameter sensitivity[12, 19, 20].

Burr formation in titanium layers is strongly temperature-dependent. FEM-based analysis reported that increasing exit temperature from ~182 °C to ~356 °C increased burr height by approximately 56.6% [2]. This indicates that cutting speed-induced thermal accumulation directly governs plastic deformation behavior at hole exit.

Feed rate also contributes to burr formation by increasing plastic strain at the exit zone. Higher undeformed chip thickness promotes larger deformation volume before chip separation, intensifying burr size [6].

Cryogenic and hybrid cooling strategies reduce interface temperature and modify plastic flow behavior, but their effectiveness depends on maintaining moderate feed levels [12, 18]. Adhesion phenomena further aggravate burr irregularity; the formation of a titanium build-up layer alters edge sharpness and increases surface tearing at the exit [4] (Table 3).

Tool wear evolution in CFRP/Ti stack drilling is governed by the combined action of abrasive interaction in the composite layer and adhesive-diffusive mechanisms in the titanium layer. The abrupt transition between materials with contrasting thermal conductivity, hardness, and chemical reactivity results in complex wear patterns, often characterized by flank wear, adhesion layers, and unstable BUE formation.

**Table 3** – Analysis of process parameters effecting hole quality and surface integrity

Reference	Topic addressed	Key conclusions
Yu et al. [1]	Temperature field and drilling damage in composites	Dynamic temperature field correlates with drilling-induced microstructural damage and wall surface defects in fiber-reinforced composites
Zhaoju et al. [10]	Temperature distribution and cooling strategies	Elevated cutting speed increases thermal concentration near the drill center, promoting adhesion risk and surface instability; improved cooling reduces peak temperature and thermal gradients
Moran et al. [20]	Ultrasonic-assisted drilling	Intermittent cutting improves wall morphology and reduces adhesive transfer compared to conventional drilling
Joy et al. [4]	Adhesion layer formation in stack drilling	Adhesion layer formation is influenced by drill geometry and contributes to surface irregularity in stack materials

Tool wear evolution in CFRP/Ti stack drilling is governed by the combined action of abrasive interaction in the composite layer and adhesive-diffusive mechanisms in the titanium layer. The abrupt transition between materials with contrasting thermal conductivity, hardness, and chemical reactivity results in complex wear patterns, often characterized by flank wear, adhesion layers, and unstable BUE formation.

Feed rate directly governs undeformed chip thickness and contact pressure along the cutting edge, thereby influencing flank wear progression. Statistical analysis in CFRP/Ti drilling confirms feed rate as the most significant parameter affecting thrust force and mechanical loading [6]. Increased feed intensifies normal stress at the tool-workpiece interface, accelerating abrasive wear in the CFRP layer and adhesive wear in titanium.

Composite drilling studies indicate that higher feed increases thrust force and delamination severity [3], which indirectly affects tool wear by increasing mechanical resistance during penetration. Elevated feed also promotes thicker adiabatic shear bands in titanium chips under cryogenic conditions, indicating intensified localized deformation and higher stress concentration at the cutting edge [9].

Therefore, feed rate primarily controls mechanical wear intensity and contributes to edge degradation through increased ploughing and frictional contact.

Cutting speed influences tool wear predominantly through temperature-dependent mechanisms. Temperature measurements reveal that increasing cutting speed elevates peak temperature near the drill center, particularly under

dry conditions [10]. Elevated interface temperature promotes adhesion of titanium to the tool surface and accelerates coating degradation.

Thermal modeling demonstrates that exit temperature may reach approximately 356 °C under certain conditions [2], indicating sufficient thermal activation for diffusion-assisted wear processes. Cryogenic machining studies confirm that altering thermal regime significantly modifies deformation behavior in titanium [18], implying that wear mechanisms transition depending on temperature state.

Under cryogenic cooling with coated tools, wear mechanisms shift depending on thermal conditions and feed intensity [9]. This suggests that cutting speed must be interpreted in conjunction with thermal control strategy when evaluating wear progression.

BUE formation in stack drilling is primarily associated with titanium adhesion. Adhesive transfer modifies the effective cutting edge radius and alters local cutting geometry, resulting in force instability and accelerated wear [4]. Energy-dispersive spectroscopy in ultrasonic-assisted drilling confirmed reduced titanium transfer onto the tool compared to conventional drilling, indicating that mechanical vibration can mitigate adhesion [20].

Temperature concentration near the chisel edge region increases adhesion probability [10]. At elevated thermal conditions, titanium softens and adheres more readily to tool surfaces, facilitating unstable BUE formation.

Helical milling under dry conditions demonstrated reduced adhesion and improved wear stability due to distributed load and lower thermal concentration [23], supporting the interpretation that mechanical load intensity and thermal accumulation jointly govern adhesion-driven wear.

The interaction between feed and cutting speed determines the dominant wear regime. High feed combined with low speed intensifies mechanical loading, promoting abrasive and adhesive wear. Increasing cutting speed reduces mechanical resistance but elevates temperature, which may accelerate diffusion wear and coating degradation [2, 9, 10].

Cooling strategy modifies this interaction. Compressed air reduces peak temperature compared to dry drilling, while ultrasonic assistance reduces adhesion and stabilizes wear progression [20]. However, parameter sensitivity remains pronounced even under assisted conditions (Table 4).

The influence of feed rate on CFRP/Ti stack drilling extends beyond simple force amplification and represents the primary mechanical driver of process instability. Increasing feed enlarges undeformed chip thickness and elevates contact pressure along the cutting edge, resulting in higher thrust force [6]. Elevated thrust intensifies interlaminar stresses in the composite layer and increases the severity of entry and exit delamination. At the same time, increased normal and radial stresses at the drill margin accelerate abrasive wear in the CFRP layer and adhesive wear in the titanium layer.

**Table 4** – Effect of cutting parameters on wear rate and built-edge formation

Reference	Topic addressed	Key conclusions
Sam-sudeensadham S. et al. [6]	Statistical influence of parameters on drilling performance	Feed rate significantly increases thrust force and accelerates mechanical wear progression. Moderate cutting speed reduces force but intensifies thermal exposure of the cutting edge
Chen et al. [2]	Thermal damage modeling	An elevated exit temperature (up to ~356 °C) promotes plastic deformation in titanium and increases the risk of thermally activated wear mechanisms
Zhaoju Z. Et al. [10]	Drill temperature distribution	A peak temperature localized near the drill center increases the probability of adhesion. Dry drilling conditions exacerbate thermal load and wear risk
Sharma P. [9]	Coated tool wear under cryogenic conditions	Wear mechanism transitions depend on thermal regime and feed intensity; increased feed enhances localized shear deformation and flank wear progression
Jebaratnam Joy, M. [4]	Adhesion layer formation in stack drilling	Adhesion layer formation modifies cutting edge geometry and contributes to wear instability, which is influenced by tool geometry and contact conditions
Moran, X., et al. [20]	Ultrasonic-assisted drilling	Reduced titanium transfer to the tool surface under ultrasonic assistance indicates a reduction in adhesion-driven wear compared to conventional drilling
Hiremath, A. [23]	Helical milling and wear behavior	Distributed load and reduced thermal concentration mitigate adhesion and improve wear stability under dry conditions
Yang D. [18]	Thermal regime in Ti machining	The deformation behavior of titanium is temperature-dependent because of its thermal state, which affects plastic flow and, consequently, the activation of the wear mechanism
(Khashaba & Mashhour, 2026)	Feed influence on drilling damage	Higher feed rates increase mechanical loading and, in turn, intensify tool wear through higher thrust force and resistance

In titanium, greater plastic strain accumulation before chip separation enhances burr formation and exit deformation [2]. This deformation alters the hole geometry and

contributes to dimensional deviation. Consequently, mechanical load intensification initiated by feed rate simultaneously affects geometric stability, surface integrity, and wear progression. The mechanical component of the process therefore, acts as the initiating factor in the coupled degradation sequence.

Cutting speed primarily influences drilling performance through its effect on temperature evolution. Experimental measurements indicate that peak temperature is concentrated near the drill center and increases with spindle speed under dry conditions [10]. Numerical analysis shows that the interface temperature may reach approximately 356 °C, significantly increasing the titanium burr height and composite tensile damage variables [2].

At elevated temperature, the polymer matrix in CFRP softens, reducing stiffness and increasing susceptibility to thermally assisted cracking. In titanium, enhanced plastic flow at high temperatures intensifies exit deformation and promotes unstable chip formation. Thermal accumulation also increases the probability of adhesion between titanium and the cutting tool surface [4, 25]. Thus, temperature does not independently initiate instability but amplifies mechanically induced degradation by modifying material properties and interfacial conditions.

Adhesion and built-up edge formation constitute the critical link between tool wear and hole quality. The deposition of adhered titanium on the cutting edge increases the effective edge radius and alters rake and clearance geometry. This geometric alteration alters local cutting mechanics, leading to fluctuating force responses and unstable material removal conditions. Surface roughness increases due to intermittent tearing during adhesion-detachment cycles, while dimensional consistency deteriorates as variations in cutting-edge geometry introduce irregular cutting behavior.

Repeated adhesion and removal events accelerate wear progression through cyclic mechanical loading and coating degradation. As wear progresses, contact conditions continue to change, further reinforcing adhesion tendency and geometric instability. Ultrasonic assistance reduces adhesive transfer compared to conventional drilling, demonstrating that adhesion is sensitive to mechanical vibration; however, adhesion dynamics remain dependent on feed-speed interaction and thermal state [20].

The reviewed studies collectively indicate that CFRP/Ti stack drilling operates as a coupled thermo-mechanical feedback system. Feed rate affects the mechanical load intensity and determines the magnitude of the thrust force. Cutting speed controls the thermal state and modifies deformation behavior in both the composite and the titanium layers. Adhesion influences tool geometry, which in turn affects force response and accelerates wear evolution. Progressive wear further modifies contact mechanics, reinforcing dimensional instability and surface irregularity.

Process modification strategies, such as helical milling, redistribute mechanical loads and reduce localized thermal concentration, improving surface finish and stabilizing wear progression [23]. Ultrasonic and peck drilling reduce peak

thrust or temperature under optimized conditions [19, 20], yet the fundamental coupling between mechanical loading, thermal accumulation, adhesion formation, and geometric stability persists. These observations confirm that drilling performance in CFRP/Ti stacks cannot be optimized by addressing individual quality metrics in isolation (Table 5).

**Table 5** –Summarizing troubleshooting evaluation

Process variable	Mechanism	Consequence
Increased feed rate	Higher undeformed chip thickness and contact pressure	Increased thrust force, intensified delamination, and accelerated flank wear progression
Increased cutting speed	Elevated interface temperature	Matrix softening, enhanced titanium plastic flow, and increased adhesion tendency
Elevated temperature	Thermally activated plastic deformation in Ti	Burr height increase (~56.6 %) and exit deformation
Adhesion formation	Modification of cutting-edge geometry due to titanium transfer	Surface irregularity, dimensional instability, accelerated wear through adhesion-detachment cycles
Load redistribution (helical milling)	Reduced mechanical and thermal concentration	Improved surface finish and wear stability
Ultrasonic assistance	Intermittent cutting and reduced adhesive transfer	Lower thrust force and improved wall morphology

The reviewed literature demonstrates substantial progress in understanding individual aspects of CFRP/Ti stack drilling, including thrust force evolution, temperature distribution, surface damage, and tool wear behavior. However, despite this advancement, several critical research gaps remain, particularly concerning the integrated influence of cutting parameters on tool wear and built-up edge formation.

First, most studies investigate force development or temperature evolution independently of progressive tool wear. Statistical analyses identify feed rate as a dominant contributor to thrust force variation [3, 6], while thermal modeling highlights the significant influence of cutting speed on temperature rise and burr formation [2, 10]. Nevertheless, systematic correlation between parameter-induced thermal states and long-term wear evolution in CFRP/Ti stacks remains limited. Existing investigations often evaluate wear at discrete parameter combinations without establishing continuous wear-parameter interaction models.

Second, adhesion and BUE formation are typically examined qualitatively or as secondary observations rather than as primary process variables. Although evidence indi-

cates that titanium adhesion modifies the cutting edge geometry and influences surface integrity[4, 20], the dynamic evolution of BUE under varying feed-speed combinations has not been sufficiently quantified in stack-drilling conditions. In particular, the interaction between elevated temperature, mechanical load, and adhesion stability in alternating CFRP/Ti cutting remains insufficiently characterized.

Third, geometric accuracy and dimensional deviation are rarely linked directly to tool wear progression. While studies report improvements in hole tolerance under ultrasonic or optimized drilling strategies [19], the coupling between progressive flank wear, adhesion-induced edge modification, and hole diameter consistency has not been systematically modeled. As a result, predictive capability for dimensional stability during long drilling sequences remains limited.

Fourth, most modeling approaches address either thermo-mechanical stress distribution [16] or temperature evolution, but few frameworks integrate wear kinetics and adhesion dynamics into unified predictive models. The absence of integrated thermo-mechanical-tribological modeling restricts the development of robust optimization strategies capable of simultaneously controlling force, temperature, wear, and geometric stability [2].

Furthermore, process-assistance strategies such as ultrasonic drilling and helical milling mitigate thrust force and adhesion intensity [20, 23]. Yet, their long-term impact on the transition of the wear modes under varying cutting parameters has not been comprehensively evaluated. Comparative studies often focus on short drilling intervals and do not fully assess progressive edge degradation and its feedback on dimensional accuracy.

Overall, the current body of literature reflects fragmentation between mechanical, thermal, tribological, and geometric perspectives. Integrated investigations that simultaneously analyze cutting parameter selection, tool wear evolution, built-up edge formation, and hole quality metrics in CFRP/Ti stacks remain scarce. This limitation constrains both mechanistic understanding and industrial process optimization.

Future research should therefore focus on developing unified experimental and modeling frameworks that can couple mechanical loading, temperature evolution, adhesion dynamics, and wear progression. Particular attention should be devoted to quantifying the interaction between cutting parameters and built-up edge stability over extended drilling cycles, as well as to establishing predictive relationships between wear state and dimensional deviation. Such integrated approaches are essential for achieving reliable, reproducible hole quality in multi-material stack drilling, where thermomechanical coupling governs overall process stability.

### Discussion

Overall, available quantitative evidence demonstrates that cutting parameters govern drilling performance through coupled thermo-mechanical mechanisms. Cutting

speed primarily controls temperature-dependent adhesion and diffusion phenomena, whereas feed rate dictates mechanical loading intensity and delamination propensity. Their interaction shifts the balance between adhesive, abrasive, and diffusion wear modes, establishing the mechanistic foundation for tool wear evolution and built-up edge formation, which are examined in subsequent sections.

Across the reviewed literature, feed rate consistently emerges as the primary parameter influencing dimensional accuracy by controlling thrust force and radial load. Cutting speed influences hole geometry indirectly by altering thermal conditions, which in turn affect plastic deformation in titanium and the matrix stiffness in CFRP. Adhesion and built-up layer formation introduce additional geometric variability by modifying tool edge geometry. Therefore, dimensional deviation in CFRP/Ti drilling cannot be attributed to a single parameter but results from the coupled interaction of mechanical load, thermal expansion, and adhesion-driven instability.

Surface quality in CFRP/Ti drilling emerges from the interaction between mechanical loading and temperature evolution. Feed rate primarily governs roughness amplitude and composite subsurface damage by controlling thrust force and contact pressure. Cutting speed modulates surface integrity via thermal mechanisms that influence matrix softening in CFRP and plastic flow in titanium. Adhesion and built-up layer formation introduce additional irregularity by modifying the tool geometry. Therefore, surface quality cannot be optimized by isolated parameter adjustment. Instead, balanced speed-feed combinations are required to control both mechanical and thermal contributions to surface degradation.

Coupled mechanical and thermal effects govern tool wear and built-up edge formation in CFRP/Ti drilling. Feed rate controls contact pressure and mechanical stress intensity, accelerating abrasive and adhesive wear. Cutting speed influences temperature-dependent adhesion and diffusion mechanisms. Built-up edge formation arises primarily from titanium adhesion and is amplified under elevated temperature and mechanical load. Consequently, wear evolution cannot be described solely by kinematic parameters; it must be interpreted through the thermomechanical interactions among cutting speed, feed, and the thermal control strategy.

The majority of existing investigations analyze thrust force, temperature, wear, or damage parameters separately. Integrated studies that simultaneously correlate cutting parameter selection with wear progression, adhesion dynamics, and dimensional deviation remain limited. The fragmentation of current approaches restricts predictive capability and constrains the development of unified optimization frameworks. Therefore, further research should focus on integrated thermo-mechanical models that explicitly couple cutting parameters with tool wear evolution and built-up edge formation while accounting for their combined influence on hole accuracy and surface integrity.

## Conclusions

This review analyzed the influence of cutting parameters on drilling performance in CFRP/Ti alloy stacks with emphasis on hole accuracy, surface integrity, tool wear, and built-up edge formation. Based on the synthesized literature, the following conclusions can be drawn.

1. The analysis of drilling mechanics shows that feed rate is the primary mechanical driver of thrust force, while cutting speed predominantly influences the thermal state of the drilling zone. Mechanical loading governs delamination severity and contact pressure at the tool-workpiece interface, whereas temperature amplification modifies deformation behavior and adhesion tendency. The interaction between these parameters defines the fundamental thermo-mechanical response of the stack system.

2. The evaluation of hole accuracy indicates that geometric stability is strongly affected by thrust force magnitude and temperature-induced plastic deformation in titanium. Elevated feed increases delamination and radial instability, while high interface temperature promotes burr growth and exit deformation. However, quantitative studies directly correlating wear progression with dimensional deviation remain limited.

3. The combined action of mechanical stress and thermal accumulation governs surface quality and integrity. Feed-driven load intensification increases ploughing effects and composite subsurface damage, whereas cutting-speed-induced temperature rise accelerates matrix softening and titanium plastic flow. Adhesion and built-up edge formation introduce additional instability by altering cutting geometry and increasing surface irregularity.

4. Coupled mechanical and thermal mechanisms control tool wear and built-up edge formation. Feed rate intensifies contact stress and accelerates flank wear, while cutting speed elevates interface temperature and promotes adhesion-driven wear processes. Built-up edge formation represents a transitional mechanism linking wear progression with geometric and surface instability, particularly under elevated thermal conditions.

5. The integrated analysis confirms that CFRP/Ti stack drilling operates as a coupled thermo-mechanical feedback system. Cutting parameters influence not only force and temperature independently but also adhesion stability, wear evolution, and dimensional consistency through cyclic interaction mechanisms. Optimization strategies that address isolated performance metrics are therefore insufficient to ensure stable drilling performance.

6. Despite significant advances in modeling and experimental investigation, the literature remains fragmented. Few studies simultaneously correlate cutting parameter selection with wear evolution, adhesion dynamics, and dimensional deviation under extended drilling conditions. The development of unified thermo-mechanical-tribological models capable of predicting tool wear progression and built-up edge formation in relation to cutting parameters remains an open research challenge.

Further research should focus on integrated experimental methodologies and predictive modeling frameworks that couple mechanical load intensity, thermal evolution, adhesion stability, and progressive wear mechanisms. Such approaches are essential for improving process reliability and achieving consistent hole quality in multi-material stack drilling applications.

### Acknowledgement

The research was conducted within the framework of the research stay “Research of Built-up Formation Effect on Cutting-Edge Radius When Drilling CFRP/Ti Alloy Stacks.”, funded by National Scholarship Program of the Slovak Republic (NSP SAIA) and scientific research “Research of Built-up Edge Formation and Wear Effect on Cutting-Edge Radius When Drilling CFRP/Ti Alloy Stacks” in the frame of research grant “Research into Innovative, Unconventional Methods of Preparation of Cutting Edge Microgeometry to Increase the Tool Life of Cutting Tools” (VEGA 1/0266/23).

The article was prepared with the assistance and technical support of the non-governmental organization “INDUSTRY 5.UA.”.

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Received 09.03.2026  
Accepted 06.04.2026  
Published 07.05.2026

УДК 621.914.2:621.762

## ТЕРМОМЕХАНІЧНИЙ ВПЛИВ РЕЖИМІВ РІЗАННЯ НА ТОЧНІСТЬ ОТВОРІВ ТА ЗНОШЕННЯ ІНСТРУМЕНТУ ПРИ СВЕРДЛІННІ ПАКЕТІВ ВУГЛЕПЛАСТИК/ТИТАНОВИЙ СПЛАВ

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**Мета роботи.** Систематизувати та узагальнити результати досліджень щодо впливу режимів різання під час свердління пакетів вуглепластик/титановий сплав на точність отворів, якість обробленої поверхні, інтенсивність зношування різального інструменту та утворення наросту на ріжучій кромці.

**Методи дослідження.** Використано порівняльно-параметричний аналіз впливу подачі та швидкості різання на осьову силу свердління, температуру у зоні різання, інтенсивність розширення композиційного матеріалу, висоту заусенця у шарі титанового сплаву, параметри шорсткості поверхні та інтенсивність зношування інструменту. Узагальнено результати експериментальних досліджень і числового моделювання з сучасних наукових публікацій для встановлення причинно-наслідкових зв'язків між режимами різання, термомеханічними процесами у зоні різання та показниками якості отворів.

**Отримані результати.** Встановлено, що подача є основним фактором механічного навантаження під час свердління та визначає інтенсивність розширення вуглепластику. Швидкість різання переважно впливає на температуру у зоні різання та адгезійні явища у титановому сплаві. Показано, що утворення наросту та адгезійне перенесення матеріалу на ріжучу кромку змінюють її мікрогеометрію, спричиняють зростання осьових сил, погіршення точності отворів і зниження стабільності процесу свердління.

**Наукова новизна.** Обґрунтовано інтегрований підхід до оцінювання процесу свердління пакетів вуглепластик/титановий сплав як єдиної термомеханічної системи, у якій режими різання, розвиток зношування інструменту та утворення наросту розглядаються як взаємопов'язані чинники переходу між абразивним, адгезійним і дифузійним механізмами зношування.

**Практична цінність.** Отримані узагальнення можуть бути використані для визначення напрямів подальших досліджень, підвищення ресурсу різального інструменту, стабілізації процесу свердління та оптимізації режимів різання.

**Ключові слова:** свердління, пакет вуглепластик/титановий сплав, режими різання, розширення, нарост, зношування інструменту, термомеханічна взаємодія, порівняльно-параметричний аналіз.

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