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Recent Advances in Tool Coatings and Materials for Superior Performance in Machining Nickel-Based Alloys †

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Abstract

Nickel-based alloys, including Inconel 718 and alloy 625, are indispensable in industries such as aerospace, marine, and nuclear energy due to their exceptional mechanical strength, high-temperature performance, and corrosion resistance. However, these very properties pose severe machining challenges, such as accelerated tool wear, poor surface finish, and high cutting forces. Although several studies have investigated coatings, lubrication strategies, and process optimization, a comprehensive and up-to-date integration of these advancements is still lacking. To address this gap, a systematic review was conducted using Web of Science and Scopus databases. The inclusion criteria focused on peer-reviewed journal and conference articles published in the last eleven years (2014–2025), written in English, and directly addressing machining of nickel-based alloys, with particular emphasis on tool coatings, lubrication/cooling technologies, and machinability optimization. Exclusion criteria included duplicate records, non-English documents, papers lacking experimental or modeling results, and studies unrelated to tool life or coating performance. Following this screening process, 101 high-quality articles were selected for detailed analysis. The novelty of this work lies in synthesizing comparative insights across TiAlN, TiSiN, and CrAlSiN coatings, alongside advanced lubrication methods such as HPC, MQL, nano-MQL, and cryogenic cooling. Results highlight that CrAlSiN coatings retain hardness up to 36 ± 2 GPa after exposure to 700 °C and extend tool life by 4.2× compared to TiAlN, while optimized cooling strategies reduce flank wear by over 30% and improve tool longevity by up to 133%. The integration of coating performance, thermal stability, and lubrication effects into a unified framework provides actionable guidelines for machining optimization. The study concludes by proposing future research directions, including hybrid coatings, real-time process monitoring, and sustainable lubrication technologies, to bridge the remaining gaps in machinability and promote industrial adoption. This integrative approach establishes a robust foundation for advancing machining strategies of nickel-based superalloys, ensuring improved productivity, reduced costs, and enhanced component reliability.

Keywords: nickel-based alloys; tool coatings; titanium aluminum nitride (TiAlN); CrAlSiN; multilayer coatings

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1. Introduction

Nickel-based alloys are among the most versatile and high-performance materials developed for industrial use. Their unique combination of corrosion resistance, mechanical strength, thermal stability, and oxidation resistance makes them indispensable in aerospace,

marine, nuclear, chemical, and petrochemical industries. One of the foremost advantages of nickel alloys is their superior resistance to corrosion, which enables them to perform reliably in aggressive environments such as seawater, acidic chemical plants, and high-temperature reactors [1–4]. For example, alloys such as UNS N06625 and UNS N06686 are highly resistant to hydrogen embrittlement and seawater corrosion, making them critical in offshore oil and gas operations. Another vital property of nickel-based alloys is their high-temperature stability, allowing them to retain mechanical integrity under severe thermal stresses. This has made them indispensable in aerospace turbine blades, jet engines, and nuclear reactors, where temperatures frequently exceed 1000 °C [5–7]. Alloys like Inconel and Hastelloy are widely used in gas turbines, while advanced compositions are being investigated for molten salt reactors due to their resistance to creep, oxidation, and radiation damage [5]. Their mechanical toughness and ductility also ensure performance under high stress and thermal shock conditions, making them suitable for power plants and marine structures [4,8]. In the nuclear industry, particularly molten salt reactors, nickel alloys are crucial for handling corrosive and high-temperature environments [5]. The chemical and petrochemical industries utilize nickel alloys for incinerators, supercritical water oxidation processes, and biomass-fired plants due to their corrosion resistance under both oxidizing and reducing conditions [1]. In the oil and gas sector, nickel-based superalloys are increasingly being applied in offshore drilling and deep-sea environments because of their strength and resistance to sulfide stress cracking [9,10]. Despite these advantages, nickel-based alloys face several challenges. In high-temperature corrosive environments containing chlorine or sulfur, alloys may suffer accelerated degradation. This has driven research into alloying strategies, surface treatments, and protective coatings to extend service life [4]. Another major limitation is their poor machinability; nickel alloys are prone to work hardening and generate high cutting-zone temperatures. Recent innovations in cryogenic machining, advanced tool coatings, and optimization of cutting parameters have shown promise in overcoming these issues [7,11]. Additive manufacturing (AM) has opened new opportunities for producing complex nickel alloy components through selective laser melting (SLM) and powder bed fusion. However, issues like porosity, residual stresses, and microstructural defects still need refinement [8,12]. Future directions in nickel-based alloy research include advanced processing techniques such as spark plasma sintering and hot isostatic pressing (HIP), which improve microstructural stability and mechanical performance [6]. New alloy development is also underway, with research focusing on tailoring compositions for specific industries, such as high-entropy alloys for aerospace and marine applications [8]. Continuous advancements in processing, characterization, and manufacturing are ensuring that nickel-based alloys remain indispensable for addressing the challenges of modern engineering.

1.1. Nickel-Based Alloy Types

Pure nickel is valued for its outstanding corrosion resistance in carefully controlled environments, while nickel–copper alloys such as Monel®, first developed in 1906, offer reliable corrosion resistance in chemical processing and marine applications [13].

Nickel–Molybdenum (Ni-Mo) alloys are highly resistant to reducing acids, making them essential in chemical industries where aggressive reducing environments are encountered [13]. These alloys are often employed when high corrosion resistance is required under non-oxidizing conditions.

Nickel–Chromium–Molybdenum (Ni-Cr-Mo) alloys extend this resistance by providing excellent performance in both oxidizing and reducing media. They are multipurpose alloys with strong resistance to localized corrosion, such as pitting and crevice attack, as well as to stress-corrosion cracking [13].

Nickel–Chromium–Iron (Ni-Cr-Fe) alloys were developed to bridge the performance gap between stainless steels and Ni-Cr-Mo alloys. They offer versatile corrosion resistance and are frequently used in aggressive industrial environments where both mechanical strength and corrosion resistance are required [13,14].

The nickel-based superalloys, including Inconel and Hastelloy, are perhaps the most well-known. Inconel alloys such as Inconel 718 and Inconel X-750 are extensively used in aerospace, nuclear reactors, and gas turbines owing to their remarkable high-temperature strength and ability to withstand corrosive environments [15,16]. Hastelloy alloys, particularly Hastelloy-N™, demonstrate superior creep, oxidation, and corrosion resistance, making them especially suited for molten salt reactors and high-pressure vessels [17].

Nickel–Iron (Ni-Fe) alloys provide unique expansion characteristics and are commonly used in applications requiring dimensional stability, such as precision instruments and electrical devices. Recent advancements include nickel-based metal matrix composites (NAMMCs), which are being investigated as alternatives to traditional superalloys. They show superior high-temperature strength and thermal fatigue resistance, making them promising for demanding aerospace and naval applications [18]. Similarly, additive-manufactured nickel-based alloys, produced through methods such as laser powder bed fusion and directed energy deposition, enable the creation of complex parts like IN625 and Hastelloy X with minimal material waste. These alloys offer enhanced performance while supporting sustainable manufacturing practices [18,19]. Nickel-based alloys remain indispensable due to their ability to operate reliably under extreme mechanical, chemical, and thermal conditions. Their continuous development, from traditional Ni-Cu alloys to cutting-edge additive-manufactured superalloys, ensures their pivotal role in advanced engineering applications [13,18,19].

1.2. Properties of Nickel-Based Superalloys

Nickel-based superalloys are a class of advanced, high-performance materials specifically engineered for use in extreme environments involving high temperatures, corrosive atmospheres, and significant mechanical loads. These alloys are considered indispensable in industries such as aerospace, power generation, marine, nuclear, and petrochemical engineering due to their unique combination of mechanical, chemical, and microstructural properties.

Mechanical Properties: One of the most remarkable mechanical characteristics of nickel-based superalloys is their high-temperature strength, which allows them to maintain tensile strength, creep resistance, and fatigue resistance at elevated temperatures where other conventional alloys would fail [20–22]. These alloys also exhibit high hardness and wear resistance, ensuring durability under extreme working conditions such as turbine blades and combustion chambers [23,24]. Despite their impressive strength, several nickel-based superalloys maintain a degree of ductility, which is vital for withstanding stress and preventing catastrophic failure during thermal cycling and mechanical loading [20,25].

Chemical Properties: Nickel-based superalloys are also highly regarded for their corrosion and oxidation resistance, which enables them to perform reliably in both oxidizing and reducing environments. They resist organic and mineral acids, as well as corrosive gases, making them suitable for harsh conditions in chemical processing and marine environments [24,26,27]. Their ability to withstand oxidation at elevated temperatures ensures long-term structural integrity in aerospace engines and power plant components [12,27].

Microstructural Characteristics: The extraordinary performance of nickel-based superalloys is doped with elements such as aluminum, titanium, and tungsten, which form intermetallic strengthening phases like γ' (Ni_3Al) and γ'' (Ni_3Ti), contributing to enhanced high-temperature strength and stability [28,29]. Advances in manufacturing and heat-

treatment processes, such as laser additive manufacturing, powder metallurgy, and tailored heat-treatment regimes, enable microstructure optimization, reduce porosity, and improve defect tolerance [25,30]. These innovations make it possible to fine-tune the alloys' performance for specific applications.

Environmental Resistance: A particularly important property of nickel-based superalloys is their resistance to hot corrosion. This resistance is critical for gas turbine and combustion environments where high concentrations of salts, sulfur, or chlorine may accelerate material degradation. Coating technologies and alloying strategies have been developed to extend their service life under these extreme conditions [26,27].

1.3. Machining of Nickel-Based Alloys

Machining nickel-based superalloys presents substantial challenges due to their high strength, work-hardening tendency, and poor thermal conductivity. These characteristics contribute to rapid tool wear, high cutting forces, and poor surface finish. As a result, the selection and development of cutting tool materials and coatings have become critical research areas for improving machining performance and extending tool life. Cutting Tool Materials have undergone significant advancements. Cemented carbides remain the most commonly used material due to their cost-effectiveness and a favorable combination of hardness and toughness. Innovations such as cobalt–rhenium-enriched carbide tools have shown improved resistance to thermoplastic deformation and wear when machining nickel-based superalloys. Ceramic tools, while offering high hardness and thermal stability, are typically used for high-speed applications, although their brittleness can limit utility in interrupted cutting environments [31]. On the other hand, super-hard tools such as polycrystalline cubic boron nitride (PCBN) and diamond provide exceptional wear resistance and performance at extreme conditions, but their high cost and sensitivity to ferrous materials restrict widespread use [32]. Coating Technologies have seen notable progress with emphasis on physical vapor deposition (PVD) and chemical vapor deposition (CVD). PVD coatings like titanium aluminum nitride (TiAlN) and titanium nitride (TiN) are well-known for their superior tribological properties, including low friction and high thermal stability. PVD multilayer coatings, such as TiAlN/TiN, enhance both toughness and thermal resistance, significantly improving machining outcomes in nickel alloy applications [7]. While CVD coatings like TiN/Al_2O_3/TiC have traditionally been used in machining, studies show that PVD-coated tools outperform them in terms of flank wear resistance and cutting life. Nanostructured and composite coatings are emerging as next-generation solutions. These coatings have been shown to deliver enhanced performance under dry and minimum quantity lubrication (MQL) conditions, reducing wear and prolonging tool life even under extreme thermal and mechanical stresses. In terms of Performance Enhancements, coated tools effectively mitigate major wear mechanisms such as adhesion, abrasion, and chipping. Coatings like TiAlN help reduce cutting temperatures and friction, thereby extending tool life and improving dimensional accuracy of machined components [7]. Additionally, coatings contribute to lower cutting forces and improved surface integrity. Studies involving high-pressure coolant systems in combination with coated inserts have demonstrated significant reductions in flank wear and cutting forces, though a rise in notch wear was observed under certain conditions [33]. The integration of Environmentally Friendly Lubricants with advanced coatings further supports sustainable machining strategies. For example, gamma-Al_2O_3-based coatings combined with biodegradable lubricants have been shown to maintain or improve cutting performance while reducing environmental impact. These combinations not only preserve tool condition but also support cleaner manufacturing practices. Looking ahead, the future of machining nickel-based alloys will be shaped by physics-based tribological modeling, which can predict coating behavior under complex

cutting conditions and help optimize tool designs [34]. Moreover, sustainable machining environments, such as those using supercritical CO_2 or hybrid nanofluids, are gaining attention for their potential to reduce environmental impact while preserving or enhancing machining efficiency [34]. Progress in PVD and nanostructured coatings, supported by innovative lubrication strategies and sustainable machining practices, has led to substantial improvements in tool wear resistance, cutting performance, and operational efficiency, thereby facilitating the broader industrial application of these challenging materials [32,34].

2. Tool Materials for Machining Nickel-Based Alloys

Nickel-based alloys, such as Inconel and Alloy 625, are essential to industries including aerospace, power generation, and marine engineering due to their high strength, corrosion resistance, and performance at elevated temperatures. However, these very properties that make nickel alloys valuable also render them difficult to machine. Their low thermal conductivity, high work hardening rates, and strong chemical affinity to cutting tools result in rapid tool wear, increased machining forces, and elevated surface temperatures. Consequently, as shown in Figure 1, selecting optimal tool materials and machining strategies becomes critical to improving tool life, surface finish, and cost-efficiency in the manufacturing process [31–33,35].



Figure 1. Tool materials and coatings used in machining nickel-based Alloys.

2.1. Carbide and Ceramic Tool Materials

Cemented carbides are among the most widely used tool materials for machining nickel-based alloys, especially at moderate cutting speeds. These tools provide a good balance between hardness and toughness, making them suitable for interrupted cuts and variable machining environments [35–37]. Ceramic tools, on the other hand, are typically preferred for high-speed machining. Alumina-based ceramics have demonstrated superior edge strength compared to silicon nitride-based ceramics, which are more resistant to

thermal shock. However, both types are prone to wear and chipping due to the hardness of the work material and the high cutting temperatures.

2.2. Cubic Boron Nitride (CBN) and Polycrystalline Diamond (PCD)

CBN tools are characterized by their exceptional hardness and chemical stability, making them suitable for finishing operations on nickel alloys. Nonetheless, these tools are susceptible to diffusion wear at elevated temperatures, particularly in the presence of nickel, iron, and chromium. Such diffusion reduces their mechanical integrity and impact resistance [38,39]. PCD tools, though effective in machining non-ferrous metals such as aluminum and titanium, have limited utility with nickel-based alloys. The high iron content in these alloys accelerates the graphitization of PCD, reducing tool life and performance [36].

2.3. Gradient Nanocomposite Ceramics

A significant advancement in tool materials is the development of Sialon-Si_3N_4 gradient nanocomposite ceramic tools, which integrate stress-relieving gradients and nano-toughening mechanisms. These tools provide improved wear resistance, thermal stability, and fracture toughness, especially under high-speed dry machining conditions. Their performance has shown promise for expanding the range of cutting conditions for nickel alloys [37].

Table 1 summarizes the cutting parameters, tool wear mechanisms, and key findings for machining nickel-based alloys with different coated tools, based on data from recent studies.

Table 1. Cutting Parameters of Nickel-Based Alloys with Different Tool Materials.

Study	Nickel-Based Material	Cutting Tool Material	Cutting Parameters	Tool Wear Mechanisms	Key Findings	
1	Alloy 625	Cemented Carbide	Various cutting speeds and feed rates	Oxidation wear	Lower wear rate observed, optimal conditions for face milling identified	[37]
2	Inconel 718	Not specified	Different cutting speeds	BUE formation, tribo-chemical reaction, inhomogeneous deformation	Medium cutting speed reduces adhesion, high speed causes tool subsurface cracks	[38]
3	Waspaloy	Not specified	Cutting speed: 33.21 m/min, depth: 0.0367 mm, feed: 0.367 mm/tooth	Not specified	Regression analysis used to optimize tool life	[40]
4	Inconel 718	CBN	High-speed cutting	Diffusion wear	Diffusion of Ni, Fe, Cr atoms decreases compressive strength and toughness of CBN tools	[38]
5	GH4061	Monolithic Ceramic	Cutting speed: 602.88 m/min, depth: 0.3 mm, width: 6 mm, feed: 0.03 mm/z	Adhesive and diffusion wear	High-speed cutting improves surface quality, optimal parameters for dry milling identified	[41]

Table 1. *Cont.*

Study	Nickel-Based Material	Cutting Tool Material	Cutting Parameters	Tool Wear Mechanisms	Key Findings	
6	Nickel-Iron Alloy	Tungsten Carbide	Cutting speed: 50–150 m/min, feed: 0.075–0.125 mm/rev, depth: 0.1–0.3 mm	Flank wear	Slow speed reduces wear, high speed reduces machining time, optimization using Adam-Gene Algorithm	[42]
7	Nickel Alloy X-750	Sialon Ceramic	Various cutting environments (dry, BF-MQL, NF-MQL)	Flank wear	NF-MQL improves surface roughness and cutting force, dry machining offers less tool wear	[43]
8	Inconel 718	Nano-grain size ceramics	Different roughing conditions	Abrasion wear, chipping	Alumina base ceramics perform better than silicon nitride base ceramics	[43]
9	Inconel 718	Textured tools	Cutting speed: 80–180 m/min	Flank and crater wear	NFMQL improves cooling and friction, better performance with textured tools under solid lubrication	[44]
10	Waspaloy	Not specified	Various lubri-cooling conditions (dry, wet, cryogenic)	Not specified	Effects of cutting parameters on tool wear, cutting forces, and chip morphology analyzed	[44]

3. Tool Coatings for Machining Nickel-Based Alloys

3.1. Types of Tool Coatings Deposition Method and Their Performance

(A) Physical Vapor Deposition (PVD) Coatings

PVD coatings are among the most effective surface modifications for improving tool life during the machining of nickel-based alloys.

TiAlN/TiN Multilayer Coating: These multilayer coatings combine the thermal stability of titanium aluminum nitride (TiAlN) with the lubricity of titanium nitride (TiN), resulting in improved anti-friction and anti-sticking behavior. This combination has demonstrated superior performance in high-speed cutting applications and prolonged tool life due to better resistance against adhesion and oxidation [7].

Aluminum Oxide (Al_2O_3): Although traditionally applied through Chemical Vapor Deposition, PVD-applied Al_2O_3 coatings have also shown high wear resistance and thermal stability, especially in dry or semi-dry machining environments. The coating's low reactivity with workpiece materials makes it well-suited for machining difficult-to-cut alloys.

TiAlSiN and CrAlSiN Coatings: The inclusion of silicon enhances hardness and thermal resistance. TiAlSiN has demonstrated an increase in tool life by up to 80% for Inconel 718 and 60% for Inconel 625. CrAlSiN coatings, on the other hand, have exhibited even more dramatic improvements, extending tool life by over 200% when machining Inconel 617 [45].

(B) Chemical Vapor Deposition (CVD) Coatings

CVD coatings, while thicker and sometimes more brittle than PVD coatings, still offer substantial wear resistance. Compared to uncoated tools, CVD-coated inserts reduce crater wear and extend tool life. However, they are generally surpassed by advanced PVD coatings in terms of surface finish and high-speed cutting capability [7].

(C) Nanocomposite and Multilayer Coatings

Multilayer nanocomposite coatings that combine materials with different mechanical and thermal properties create a strong barrier against abrasion and oxidation. When deposited on fine-grain hard alloys, these coatings have improved tool hardness and reduced thermal deformation, resulting in enhanced performance in high-temperature cutting operations.

(D) Other Coatings

TiCN/Al_2O_3: Despite offering good resistance to abrasion and oxidation, this coating has been found susceptible to edge chipping under certain cutting conditions. Nevertheless, it remains in use where moderate tool loads and stable cutting environments are maintained.

Zirconium (Zr) Coatings: Zr-based coatings provide good corrosion resistance and surface hardness. While their performance in nickel alloy machining has not been comprehensively studied, initial evaluations suggest potential benefits in wear reduction and surface integrity [46].

3.2. Tool Coating Types for Machining Nickel-Based Materials

The selection of effective tool coatings is a critical strategy in improving machining efficiency and extending the life of cutting tools when dealing with nickel-based alloys. These alloys, such as Inconel and Incoloy, are notoriously difficult to machine due to their high strength, low thermal conductivity, and strong work hardening tendency. Conventional coatings, advanced multilayer systems, nanocomposites, and recent hybrid or self-lubricating coatings each offer unique benefits that help overcome these challenges.

Conventional coatings such as Titanium Nitride (TiN), Titanium Carbonitride (TiCN), and Aluminum Oxide (Al_2O_3) remain widely used in machining applications. TiN is valued for its ability to reduce friction and prevent adhesion of nickel-based workpiece material on the cutting tool, thereby extending tool life and improving efficiency [7,31]. TiCN, on the other hand, provides a balanced combination of toughness and wear resistance, making it well-suited for harder nickel alloys. Al_2O_3, with its excellent thermal stability and high resistance to abrasive wear, performs particularly well in dry machining scenarios and in turning or milling operations involving nickel-based alloys.

Building on these foundations, more advanced coatings have been developed through Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD) processes. PVD coatings such as Titanium Aluminum Nitride (TiAlN), AlCrN, and TiCN/TiN are recognized for reducing adhesion between the tool and workpiece while also improving resistance to abrasive wear [31] (By comparison, CVD coatings offer strong thermal stability, but their higher coefficient of friction can increase cutting forces, making them less favorable in applications requiring minimal tool–workpiece interaction.

Multilayer coatings have also emerged as an effective solution, combining the strengths of individual layers to improve overall tool performance. For example, TiAlN/TiN multilayers deliver enhanced thermal resistance along with improved toughness, making them suitable for high-speed machining of nickel alloys [47]. Similarly, TiCN/Al_2O_3 multilayers provide good wear resistance but remain susceptible to edge chipping under aggressive cutting conditions, limiting their effectiveness in extreme machining environments [7].

More recently, nanocomposite coatings have demonstrated superior performance compared to conventional coatings. Titanium Aluminum Silicon Nitride (TiAlSiN) coatings, for instance, have been reported to improve tool life by 80% when machining Inconel 718 and by 60% when cutting Inconel 625, outperforming uncoated tools [45]. Chromium Aluminum Silicon Nitride (CrAlSiN) coatings have shown remarkable results for machining Inconel 617, with tool life improvements exceeding 200% compared to uncoated inserts [45,48]. Titanium Silicon Nitride (TiSiN) has also demonstrated very high hardness (up to 34.1 GPa) and an elastic modulus of 315 GPa, though its lower adhesion to the substrate can result in delamination under heavy loads [49]. Notably, TiSiN/TiAlN multilayer configurations have been shown to overcome some of these weaknesses by forming tribolayers at elevated temperatures, which enhance wear resistance and stability [50].

Innovations have also extended into self-lubricating and ceramic coatings. Self-lubricating coatings such as Al_2O_3/Ti(C,N)/CaF_2@Al_2O_3 not only maintain hardness and thermal stability but also significantly reduce surface roughness and machining-induced work hardening, which are common issues when cutting nickel alloys. By reducing reliance on cutting fluids, these coatings support more sustainable machining processes while maintaining superior surface integrity.

Hybrid and doped coatings represent the latest frontier in coating technology. Multilayer hybrids like TiN + AlTiN + MoS_2 have demonstrated outstanding performance in machining Inconel 718, particularly under minimum quantity lubrication (MQL) conditions. Similarly, CrN + CrN:C hybrid coatings are tailored for both dry and MQL machining, offering balanced improvements in toughness and lubricity. Doped Ti_3AlN coatings, incorporating elements such as chromium or vanadium, have been shown to enhance both hardness and stiffness, allowing them to withstand aggressive machining environments [51]. Additionally, Titanium Diboride (TiB_2) coatings have proven effective in reducing wear rates during the milling of chromium–nickel alloys, further improving tool durability [52].

Tool coatings are indispensable in machining nickel-based alloys, enabling longer tool life, enhanced wear resistance, and improved machining efficiency. While conventional coatings like TiN and Al_2O_3 remain reliable for general applications, nanocomposite coatings such as TiAlSiN and CrAlSiN offer superior tool life and performance at high speeds and temperatures. Meanwhile, hybrid, doped, and self-lubricating coatings represent the future of coating technology, providing advanced solutions for sustainable and high-performance machining of nickel-based superalloys. Table 2 summarizes the main tool coating types applied in machining nickel-based materials, including their deposition methods, performance, and dominant wear mechanisms.

Table 2. Tool Coating Types, Performance, and Wear Mechanisms in Machining Nickel-Based Alloys.

Tool Coating Types for Machining Nickel-Based Materials Coating Type	Deposition Method	Material	Performance	Wear Mechanism	Citation
TiAlN/TiN	PVD	Incoloy 825	Outperformed uncoated and CVD-coated tools due to excellent tribological properties	Adhesion, attrition, edge chipping, notch wear	[7]
TiN/TiAlN	PVD	Incoloy 825	Reduced cutting force, tool wear, and surface roughness; sustainable dry machining	Not specified	[7]

Table 2. *Cont.*

Tool Coating Types for Machining Nickel-Based Materials Coating Type	Deposition Method	Material	Performance	Wear Mechanism	Citation
Al_2O_3	PVD	Nickel-based superalloy	High hardness, thermal stability, low adhesion tendency, improved tool life and MRR	Not specified	[52]
TiAlN	Not specified	Nickel-based superalloy	Improved wear resistance and reduced thrust force during drilling	Not specified	[53]
TiAlN	Reactive pulsed DC magnetron sputtering	Nimonic 75	Superior tool life and reduced micro-burr formation compared to uncoated tools	Not specified	[54]
AlTiN, TiAlCrN, TiAlSiN	Not specified	FGH 4097	TiAlCrN showed superior performance at high cutting speeds	Adhesive wear, abrasive wear (TiAlN)	[55]

3.3. TiAlN-Coated Tools in Machining Nickel-Based Alloys

Titanium Aluminum Nitride (TiAlN) coatings are extensively utilized in cutting tools for machining nickel-based alloys, especially due to their enhanced hardness, superior thermal stability, oxidation resistance, and improved tribological behavior. These properties make TiAlN-coated tools particularly effective when dealing with challenging-to-machine superalloys like Inconel 718 and Incoloy 825.

Tool Wear and Service Life: TiAlN coatings significantly mitigate tool wear and extend service life under both conventional and extreme machining conditions. observed that TiAlN-coated tools exhibited notably reduced flank wear and better resistance to crater formation when turning Inconel 718, as opposed to uncoated tools. Further mor, ref. [56] reported that multilayer TiAlSiN/TiSiN/TiAlN-coated tools achieved 1.7 times longer tool life, along with an improved surface roughness of Ra < 0.18 µm, during the face milling of Inconel 718.

Cutting Force Reduction: The use of TiAlN coatings leads to a substantial reduction in cutting forces during high-performance machining. In cryogenic-assisted end milling of the XH67MBTHO alloy, a 27% decrease in cutting force was recorded for TiAlN-coated tools compared to their uncoated counterparts [57]. This improvement is attributed to the low coefficient of friction provided by the coating and its ability to withstand higher temperatures without softening.

Surface Integrity and Finish: In aerospace and medical components manufactured from nickel-based alloys, surface finish is regarded as a critical factor. Superior surface quality in drilling NiTi alloys was consistently achieved with TiAlN-coated carbide drills, particularly when minimum quantity nano-lubrication was applied, as reported by [58]. Burr formation and tool deflection were better controlled, and enhanced smoothness was observed most prominently at higher spindle speeds and feed rates, thereby demonstrating the coating's resilience under dynamic machining conditions.

Dominant Wear Mechanisms: Despite their robust nature, TiAlN-coated tools were found to be subject to wear mechanisms such as adhesion, abrasion, and micro-edge chipping. Under dry machining conditions, occurrences of coating delamination and

severe adhesive wear were noted by [57], highlighting the necessity of optimizing process parameters to extend coating longevity.

Optimal Machining Conditions: Exceptional performance under high-speed and dry machining environments has been demonstrated by TiAlN coatings. During the turning of Ti-6Al-4V at a cutting speed of 150 m/min, TiAlN-coated tools were shown by [59] to reduce wear and improve surface morphology in comparison to uncoated tools. Additionally, environmental benefits were provided by these coatings through the elimination of conventional cutting fluids, thereby aligning machining practices with sustainable manufacturing objectives [7].

When compared to coatings like TiN and TiCN/Al_2O_3, TiAlN offers superior performance in terms of wear resistance, tool life, and thermal stability. In dry machining of Incoloy 825, TiAlN/TiN multilayer coatings outperformed other CVD and PVD coatings due to their excellent anti-friction and anti-sticking behavior [7]. The fine-grain structure and high-temperature hardness of TiAlN enable better retention of cutting edge geometry over prolonged durations. Table 3 presents a comparative summary of TiAlN-coated tools and uncoated tools, highlighting differences in their performance parameters.

Table 3. Comparative Summary of TiAlN-Coated vs. Uncoated Tools.

Performance Parameter	TiAlN-Coated Tools	Uncoated Tools
Tool Wear	Significantly reduced [55]	Higher wear rates, especially at tool edges
Tool Life	Up to 1.7× longer [55]	Shorter life due to thermal and abrasive wear
Cutting Forces	27% lower [56]	Higher forces due to increased friction and wear
Surface Roughness	Ra < 0.18 µm [55]	Poorer finish, especially under dry conditions
Wear Mechanisms	Adhesion, abrasion, edge chipping, Al_2O_3 film formation	Severe adhesive and abrasive wear; higher delamination
Best Machining Conditions	High-speed and dry machining [7,58]	Less effective without lubrication or cooling

3.4. TiSiN Coatings in Cutting Tools for Machining Nickel-Based Alloys

Titanium Silicon Nitride (TiSiN) coatings are gaining traction in advanced machining applications due to their superior mechanical and thermal properties. In the context of machining nickel-based alloys—materials widely used in aerospace, energy, and medical industries due to their high-temperature strength and corrosion resistance—TiSiN coatings offer enhanced wear resistance, cutting efficiency, and tool life.

Mechanical Properties and Coating Hardness: TiSiN coatings are distinguished by their exceptional mechanical properties. According to [49], TiSiN coatings exhibit a hardness of 34.1 GPa and an elastic modulus of 315 GPa, which surpasses that of comparative coatings like TiAlN/TiN, which report 27.9 GPa hardness and 286 GPa modulus. This increased hardness enables greater resistance to abrasive wear and plastic deformation during high-speed machining of nickel-based superalloys.

Wear Resistance and Friction Reduction: High wear resistance is regarded as a critical requirement for tools used in cutting superalloys such as Inconel and Incoloy. Significant resistance to wear and thermal deformation was demonstrated by TiSiN-coated cutting tools, particularly at elevated cutting speeds during the machining of hardened die steels, as reported by [59]. Similarly, excellent self-lubricating properties during the dry turning of Ti-6Al-4V were demonstrated by TiSiVN, a variant of TiSiN with added vanadium [59]. Through these coatings, retention of the crater wear area was achieved, thereby reducing the rate of material loss from the tool.

Tool Life Improvement: Although TiSiN itself is beneficial, it is also incorporated into advanced nanolaminate structures such as TiAlSiN. Ref. [45] observed that TiAlSiN coatings improved tool life by 80% when machining Inconel 718 and by 60% when cutting Inconel 625, compared to uncoated tools. While TiSiN alone contributes to enhanced tool life, its performance can be influenced by adhesion quality to the substrate. In some cases, lower adhesion may lead to coating delamination, potentially shortening tool life under aggressive machining conditions [49].

Surface Integrity and Finish: Surface integrity, which is crucial in aerospace and biomedical parts, has been shown to be positively affected by TiSiN coatings. It was demonstrated that lower surface roughness and superior morphology were yielded in the machining of nickel-based alloys when self-lubricating ceramic tools with TiSiN coatings were employed. This improvement is primarily due to the coating's ability to form a stable tribo-film during cutting, which acts as a barrier against thermal and mechanical wear [60].

Cutting Performance and Heat Dissipation: Cutting performance enhancements provided by TiSiN coatings extend to reduced thermal loading and mechanical stress on the cutting tool. Substrate temperature was reduced by approximately 10.2% to 15.6%, and tool stress was lowered by 22.1% to 32.4% during the turning of Ti6Al4V when TiN/TiSiN multilayer coatings were applied [61]. These reductions are crucial when machining heat-resistant alloys, as they prevent premature tool failure due to heat-induced softening or thermal cracking [61].

3.5. CrAlSiN Coatings in Cutting Tools for Machining Nickel-Based Alloys

CrAlSiN (Chromium-Aluminum-Silicon Nitride) coatings are increasingly recognized for their exceptional performance in cutting tool applications, particularly for machining nickel-based superalloys. These materials, such as Inconel and Incoloy, are widely used in high-stress and high-temperature environments due to their strength and corrosion resistance. However, their low machinability demands high-performance coatings. CrAlSiN has emerged as a promising solution due to its superior wear resistance, thermal stability, and mechanical hardness.

Tool Life Enhancement: CrAlSiN coatings significantly extend tool life in demanding machining conditions. In the milling of IN 617, ref. [45] reported that CrAlSiN-coated tools achieved a >200% increase in tool life compared to uncoated tools. Similarly, in dry machining of Ti-6Al-4V, CrAlSiN coatings prolonged tool life by a factor of 2.9× over TiAlSiN-coated tools and 9.5× compared to uncoated tools. This improvement is attributed to CrAlSiN's superior oxidation resistance and mechanical strength under elevated temperatures [48].

Hardness and Wear Resistance: The hardness of CrAlSiN coatings is notably high, reaching up to 40 GPa, particularly when the (Al + Si)/Cr atomic ratio is optimized at 1.62. This extremely high hardness translates directly to superior wear resistance, especially under high-speed and dry machining conditions. Comparatively, TiAlSiN coatings have a hardness of 35 ± 2 GPa, while TiAlN coatings measure around 31 ± 1 GPa [48].

Mechanical and Thermal Stability: Mechanical properties such as Young's modulus and thermal stability are essential for maintaining tool integrity during cutting operations:

CrAlSiN coatings exhibit a Young's modulus of 258.58 GPa with a hardness of 31.26 GPa under optimized deposition conditions [62]. Importantly, CrAlSiN retains its hardness even after annealing at 700 °C, which is critical for cutting nickel-based alloys that generate substantial heat during machining [48].

Machining Efficiency: Force, Roughness, and Chip Formation: In dry milling operations, the application of CrAlNAg9, a self-lubricating derivative of CrAlSiN, has been shown to deliver notable improvements over uncoated tools. A reduction of 17.5% in chip

temperature was observed, indicating better thermal stability during machining. Surface roughness was decreased by 47%, reflecting enhanced surface quality of the machined parts, while chip thickness was reduced by 12.7%, suggesting improved cutting efficiency and material removal. These combined effects highlight the coating's capacity to minimize friction, suppress excessive heat generation, and ensure superior surface finish in demanding machining conditions [63].

3.6. TiSiN/TiAlN Bilayer Coating Tool and TiSiN/TiAlN Nanolayer Coating Too

The TiSiN/TiAlN bilayer-coated cemented carbide tool and the TiSiN/TiAlN nanolayer-coated cemented carbide tool were used as the cutting tools. Both coating types were deposited on polished ISO P30 [62] cemented carbide substrates using physical vapor deposition (PVD) technology. After machining Ti-6Al-4V with coated tools, the resulting chips were collected and prepared for sample analysis through cold inlay. A relatively intact linear chip was selected, secured in a cold inlay mold using a sample clip, and then embedded with epoxy resin [64]. Figure 2 chip morphology obtained during the turning of Ti-6Al-4V with coated tools at varying feed rates. At lower feed rates (0.05 mm/rev and 0.1 mm/rev), the chips exhibit finer segmentation with reduced serration depth. As the feed rate increases to 0.15 mm/rev and 0.2 mm/rev, the chips show more pronounced serrated features, with larger peak-to-valley heights (hmax − hmin) and increased spacing (d) between serrations, indicating higher shear localization and thermal–mechanical effects during cutting.

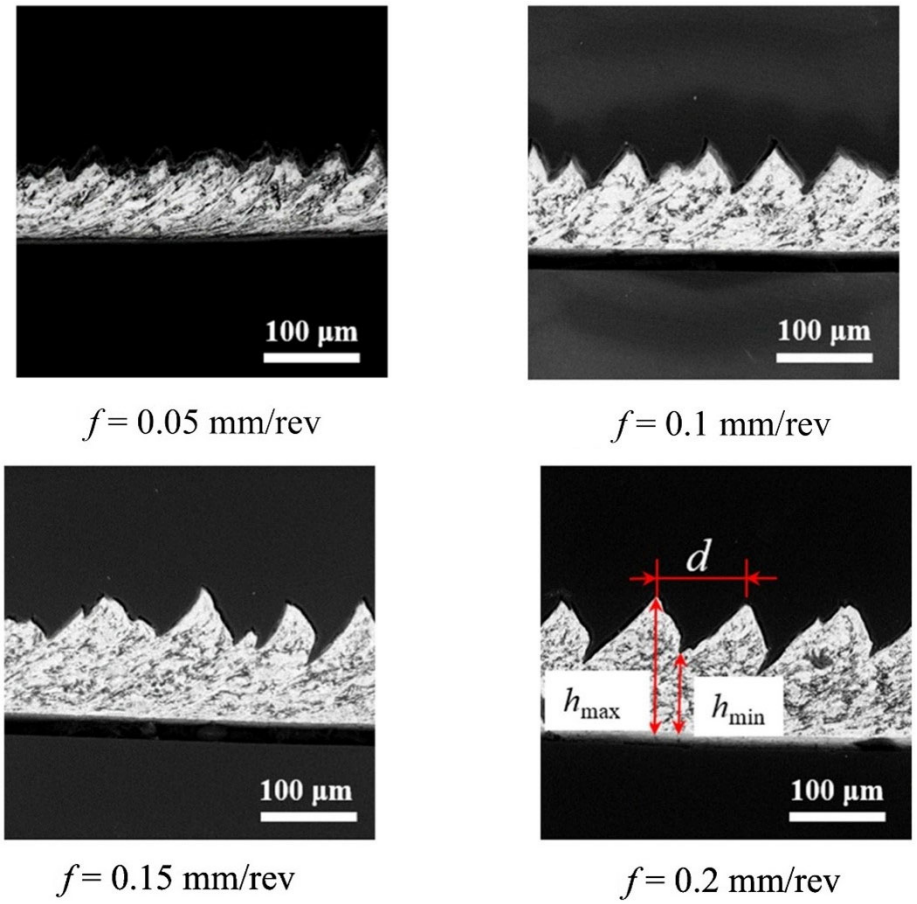


Figure 2. Chip morphology in turning Ti-6Al-4V with different feed rates. Reprinted from [64] with permission from Copyright 2021, Elsevier.

The variation in impact force values at different preloading depths during the coating impact process and the impact force trends of the two coatings throughout the impact process, with testing conditions set at a total of 40,000 impact cycles, an impact depth of 3 μm, and an impact frequency of 20 kHz are shown in Figure 3.

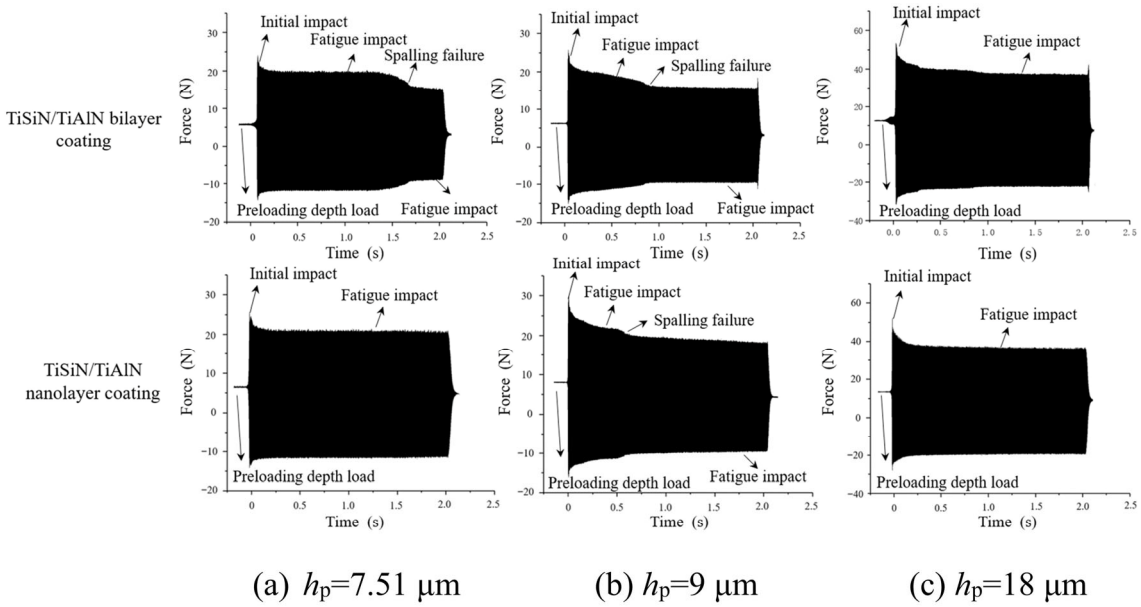


Figure 3. The impact force trend of the two coatings during the impact process. Reprinted from [64] with permission from Elsevier.

Figure 4 illustrates the surface morphology of the rake and flank faces of the two coated tools after turning Ti-6Al-4V at a feed rate of 0.05 mm/rev. For the TiSiN/TiAlN bilayer-coated tool, no coating spalling was observed in the sliding area of the rake face; instead, only a coating wear zone was formed as a result of friction, while slight spalling was detected in the bonding area. On the flank face, no evident coating spalling occurred due to the protective effect of the built-up edge. In contrast, the TiSiN/TiAlN nanolayer-coated tool exhibited almost no significant spalling at the same feed rate. The locally magnified view revealed only the formation of a coating wear zone in the sliding area, which did not progress to spalling failure. These observations indicate that the TiSiN/TiAlN nanolayer-coated tool demonstrates superior mechanical properties, including resistance to high-frequency fatigue impact and enhanced wear resistance, particularly under low feed rate conditions of 0.05 mm/rev [64].

3.7. Comparative Analysis of TiAlN, TiSiN, and CrAlSiN Coatings for Machining Nickel-Based Alloys

Nickel-based alloys, such as Inconel and Incoloy, are widely used in high-performance applications due to their exceptional strength, thermal resistance, and corrosion resistance. However, their poor machinability demands advanced cutting tools with superior coatings. Among the most promising coatings for these applications are TiAlN (Titanium Aluminum Nitride), TiSiN (Titanium Silicon Nitride), and CrAlSiN (Chromium Aluminum Silicon Nitride). This analysis provides a detailed comparison of these coatings in terms of mechanical properties, thermal stability, adhesion, wear resistance, and cutting performance. The mechanical, thermal, and cutting performance properties of TiAlN, TiSiN, and CrAlSiN coatings reveal distinct advantages and limitations, making each suitable for specific machining environments. In terms of mechanical properties, TiAlN coatings exhibit a broad hardness range, with reported values varying from 16.1 GPa under certain processing

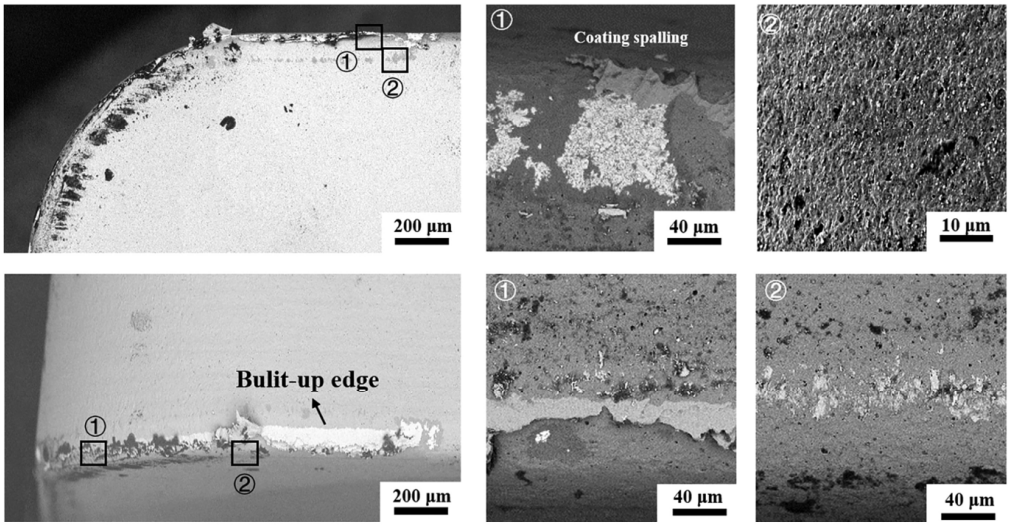
conditions to 31 ± 1 GPa, depending on deposition and substrate conditions, while another study recorded a hardness of 27.9 GPa [48,49,65]. TiSiN coatings demonstrate superior hardness due to their refined microstructure and dense grain boundaries, reaching values of 34.1 GPa and up to 36.8 GPa when configured in TiSiN/TiAlN multilayers [49,50]. CrAlSiN coatings exhibit even greater hardness, achieving peak values of 36 ± 2 GPa [48]. For the elastic modulus, TiAlN and TiSiN were reported at 286 GPa and 315 GPa, respectively, while CrAlSiN values were not explicitly quantified but implied to be high, consistent with their robust performance under elevated stress conditions [48,49]. In terms of wear resistance, TiAlN offers good performance, particularly in fluid-assisted cutting environments, but its hardness diminishes to 26 GPa after annealing at 700 °C, limiting effectiveness at elevated temperatures [48,65]. TiSiN initially provides excellent wear resistance, though poor substrate adhesion leads to increased wear and delamination. This drawback, however, can be addressed by employing TiSiN/TiAlN multilayer structures, which promote the formation of a protective tribolayer at elevated temperatures [40,50]. CrAlSiN displays the highest wear resistance, with tool life reported as 2.9 times greater than TiAlSiN and 4.2 times greater than TiAlN under high-speed machining conditions [48]. The thermal stability of these coatings further distinguishes their performance. TiAlN loses significant hardness when exposed to 700 °C, decreasing from 31 GPa to 26 GPa [48]. In contrast, TiSiN retains its hardness effectively at elevated temperatures, particularly in nano-multilayered configurations where improved thermal barrier properties enhance stability [50]. CrAlSiN exhibits exceptional thermal stability, maintaining hardness up to 36 GPa even after prolonged exposure at 700 °C, highlighting its superior resilience [48]. When considering adhesion strength, TiAlN shows strong adhesion, rated HF3–HF4 under high normal loads [50]. TiSiN, especially in AlTiN-based structures, demonstrates weaker adhesion (HF5–HF6), which increases susceptibility to delamination under stress [49]. While CrAlSiN's adhesion was not numerically graded, its resistance to chipping and durability in high-performance machining suggest strong adhesion characteristics [48]. Regarding cutting performance, TiAlN provides moderate effectiveness, but its reduced hardness at high temperatures constrains tool life and wear resistance [48]. TiSiN shows improved cutting behavior in high-speed turning due to its nanocrystalline structure, superior hardness, and oxidation resistance, making it a suitable option for demanding conditions [66]. CrAlSiN, however, outperforms both coatings, delivering superior tool life, effective wear control, and remarkable stability in high-temperature machining, establishing it as the most robust option for machining nickel-based alloys [48]. Table 4 provides a comparative analysis of TiAlN, TiSiN, and CrAlSiN coatings, outlining their relative performance and suitability for machining nickel-based alloys.

Table 4. Comparative Analysis of TiAlN, TiSiN, and CrAlSiN Coatings for Machining Nickel-Based Alloys.

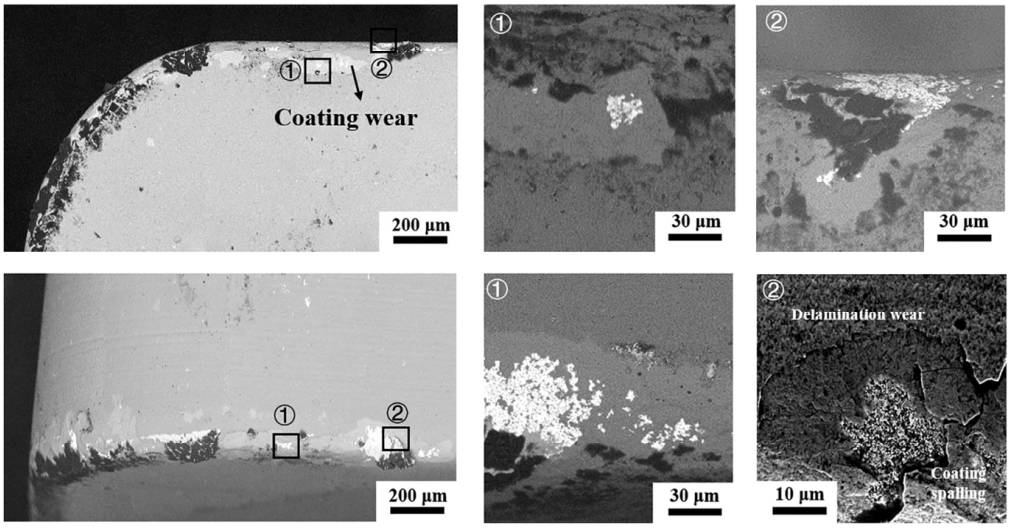
Property	TiAlN	TiSiN	CrAlSiN
Hardness (GPa)	27.9 [49]; 31 ± 1 [48]; 16.1 [65]	34.1 [49] 36.8 in TiSiN/TiAlN multilayers [50]	36 ± 2 [48]
Elastic Modulus (GPa)	286 [49]	315 [49]	High; not specified numerically [49]
Wear Resistance	Good; hardness decreases to 26 GPa after annealing at 700 °C [48,65]	High; lower adhesion leads to wear/delamination [49] multilayers form tribolayer [50]	Superior; tool life improved 2.9× vs. TiAlSiN and 4.2× vs. TiAlN [48]

Table 4. *Cont.*

Property	TiAlN	TiSiN	CrAlSiN
Thermal Stability	Drops from 31 → 26 GPa at 700 °C	Maintains hardness in multilayers due to tribolayer and thermal barrier effect [50]	Retains ~36 GPa hardness at 700 °C [48]
Adhesion Strength	Strong, HF3–HF4 [49]	Weaker, HF5–HF6 [49]	Not numerically graded; inferred strong due to reduced chipping and stable performance [48]
Cutting Performance	Moderate; limited by hardness loss at high temperatures	Improved in high-speed turning due to nanocrystalline structure and oxidation resistance [66]	Outperforms TiAlN and TiSiN; best tool life and wear resistance in machining Ni alloys [48]



(a) TiSiN/TiAlN bilayer coating tools



(b) TiSiN/TiAlN nanolayer coating tools

Figure 4. The wear morphology of two kinds of coated tools after turning Ti-6Al-4V (f = 0.05 mm/rev). Reprinted from [64] with permission from Copyright 2021, Elsevier.

4. Tool Life Optimization

Besides tool materials and cooling, machining parameters and tool geometry play decisive roles in extending tool life. Optimizing cutting speed, feed rate, and depth of cut through experimental design or statistical methods such as Response Surface Methodology (RSM) helps minimize tool wear [67,68]. Additionally, adjusting tool geometry, such as tool holder angles, has been shown to influence wear progression. For instance, a 70° holder geometry experiences slower wear compared to a 90° geometry. Surface treatments like lapping and drag finishing of cutting edges further enhance wear resistance and extend tool life in challenging operations [37,69]. Table 5 presents a summary of research focused on optimizing tool life during the machining of nickel-based materials, highlighting the materials used, tool types, optimization methods, and key outcomes.

Table 5. Tool Life Optimization in Machining Nickel-Based Materials.

Study	Nickel-Based Material	Tool Type	Optimization Technique	Key Findings	
1	AD730®	CBN 170	Tool life model (Colding)	High temperature properties, optimized for machining	[70]
2	Inconel 625	Coated carbide	Tool wear map, reliability model	Optimal cutting parameters, tool life reliability evaluation	[71]
3	Waspaloy	Not specified	Response Surface Methodology (RSM)	Significant factors: speed, depth, feed rate; regression analysis for tool life	[40]
4	Nickel-based alloy	Coated carbide, whisker reinforced ceramic	Comparative analysis	Whisker reinforced ceramic tools more effective	[72]
5	NiTiNOL	Not specified	Finite Element (FE) simulation, RSM, Taguchi	Optimal settings: moderate speed, lower depth, highest feed rate	[73]
7	Inconel 718	High-speed steels	Orthogonal cutting experiments, regression model	Optimized cutting parameters, tool wear mechanisms	[66]
8	Inconel 718	Not specified	Predictive model for CAM optimization	Flank wear evaluation, maximized MRR	[74]
9	Nickel/Cobalt based alloys	Not specified	Review of optimization techniques	Poor machinability, tool life impact	[51]
11	Inconel 718, Inconel 625	Indexable copy face mills	Extended Taylor's tool life model	Machinability and cost optimization	[75]
12	Gamma-prime strengthened nickel-based superalloy	Solid carbide, ceramic tools	Cost-based model	Performance comparison, cost analysis	[76]
13	Inconel 718, Inconel 625	Indexable copy face mills	Extended Taylor's tool life model	Machinability and cost optimization	[75]

Table 5. *Cont.*

Study	Nickel-Based Material	Tool Type	Optimization Technique	Key Findings	
14	Nickel-based alloy	Not specified	Force material model	Optimization of feed rate, improved cutting process	[77]
15	Ni-based superalloy	Not specified	Multilayer toolpath generation	Reduced tool wear by 39%	[78]
17	Nickel-based high-temperature alloy	Not specified	MCL model, meta-learning	Enhanced tool wear prediction accuracy	[79]
18	Inconel 718	Not specified	Laser assisted machining (LAM)	Improved tool life with heat shield application	[80]

Improving the machinability of nickel-based materials requires a multi-pronged approach that combines advanced tool materials, specialized coatings, innovative cooling and lubrication techniques, and optimization of cutting conditions. Among these, cryogenic cooling combined with MQL emerges as the most promising strategy, as it effectively addresses heat management and lubrication. At the same time, ceramic and CBN tools with advanced coatings like TiB_2 and Al_2O_3 offer substantial improvements in tool life. Ultimately, structuring research around tool life provides a clear framework to evaluate machining performance, reduce costs, and achieve better surface integrity when working with nickel-based superalloys [31,81,82].

5. Lubrication and Cooling Technologies

Conventional water cooling reduces tool wear and cutting forces but is less effective under high-speed machining conditions [81]. To address these limitations, cryogenic cooling with liquid nitrogen or carbon dioxide has been introduced, which drastically lowers cutting-zone temperatures, improving tool life and surface finish [82,83]. Minimum Quantity Lubrication (MQL) systems also provide enhanced lubrication with minimal fluid use, and when combined with cryogenic cooling, they balance heat removal and lubrication for optimal performance [84,85]. Hybrid systems that integrate both cryogenic and MQL cooling are particularly effective in sustaining tool life and machining efficiency under extreme cutting conditions [82,86]. The machining of superalloy Udimet 720 was investigated using different coolant/lubricant strategies, with graphene and multi-walled carbon nanotube nanopowders dispersed in vegetable oil being delivered to the cutting zone via minimum quantity lubrication (MQL). Compared to dry turning, reductions of 30% in cutting zone temperature, 51.8% in tool wear, and 43.9% in surface roughness were achieved, resulting in improved tool life and superior surface quality [87,88]. The effect of Al_2O_3 nanoparticles under minimum quantity lubrication (N-MQL) conditions was found to enhance the machining performance of Ti-6Al-4V alloy, offering valuable insights into surface roughness, material removal rate, temperature, and tool wear [89,90]. Table 6 provides a comparative overview of various lubrication and cooling technologies applied in the machining of nickel-based materials, summarizing the techniques used, the materials studied, and the key outcomes reported.

Table 6. Lubrication and Cooling Technologies for Machining Nickel-Based Materials.

Study	Lubrication/Cooling Technique	Materials	Key Findings	
1	Cryogenic machining, MQL, HPC, hybrid cutting processes	Nickel & titanium alloys	Hybrid cutting and cooling methods improve machining efficiency and surface integrity	[91]
2	MQL (vegetable oil-based, cryogenic, solid lubricant, electrostatic atomization)	Nickel alloys	Vegetable oil MQL improves surface quality by 30%; electrostatic atomization MQL reduces tool wear by 42.4%	[92]
3	Dry cutting, wet, MQL, compressed-air	Nitronic 60 steel	MQL reduces cutting force, temperature, and tool wear; enhances surface finish	[85]
4	Nano-cutting fluids (Al_2O_3, MoS_2, graphite) under MQL	Inconel 800	Graphite-based nanofluids provide superior cooling, reducing tool wear and surface roughness	[93]
5	High-pressure cooling (HPC)	Inconel 718	HPC reduces flank wear by >30% and cutting forces by >10%	[33]
6	MQL with nanocarbon dots (CDs)	Hastelloy C276	CDs in oil reduce surface roughness by 56–69% compared to dry machining	[94]
7	MQL and nano-MQL (different nozzle positions)	Nimonic 80A	Mixed-direction nano-MQL reduces tool wear by ~60% compared to dry cutting	[95]
8	Hybrid cryogenic cooling	Additively manufactured Inconel 718	Improves tool life and balances cooling/lubrication efficiency	[82]
9	Gas-based coolants (air, N_2, CO_2) with MQL	Nickel & titanium alloys	N_2 and cooled air with MQL identified as most effective	[96]
10	Throttle cryogenic cooling with MQL	Inconel 718, Incoloy 825, Waspaloy	Pulsed cryogenic + MQL improves cutting force and surface quality	[93,97]
11	Nano-MQL with vortex chilled air	NiTi alloys	Hybrid vortex cooling reduces tool wear and improves surface finish	[98]
12	Cryogenic cooling mixed lubrication	GH4169 superalloy	LN_2 + emulsion reduces tool wear and improves surface integrity	[83]
13	MQL with vegetable oils, nanofluids, nanoplatelets	Nickel alloys	Eco-friendly MQL provides superior performance vs. flood lubrication	[99]
14	Chilled MQL, chilled air, dry	Inconel 718	Chilled MQL increases tool life, lowers roughness, reduces forces	[100]
15	Textured tools + HPC, MQL, hybrid cryogenic/MQL	Ti & Ni alloys	Textured tools reduce tool wear and enhance lubrication	[101]
16	Solid lubricant-assisted MQL (graphene & MoS_2)	Inconel 718	Solid lubricants under MQL improve tribology, lowering cutting forces	[43]
17	Minimum quantity solid lubrication (MQSL)	Inconel 718	Optimized MQSL reduces tool wear and improves sustainability metrics	[84]
18	Hybrid vortex + nanoparticle lubrication	Nickel alloys	Combination cooling lowers thermal load and extends tool life	[98]

Table 6. *Cont.*

Study	Lubrication/Cooling Technique	Materials	Key Findings	
19	Flood vs. cryogenic cooling (comparison study)	Inconel 718	Cryogenic cooling reduces thermal cracks and extends tool life	[86]
20	Duplex MQL jets with nanofluids	Nimonic superalloys	Duplex MQL jets significantly enhance surface quality and tool wear resistance	[95]

6. Cutting Techniques and Tool Wear Mitigation

High-pressure coolant systems have been effectively used to mitigate notch wear and improve tool longevity in turning operations. By enhancing heat dissipation and chip evacuation, these systems reduce tool damage. However, simultaneous application to both rake and flank faces may not always yield synergistic benefits [102]. Coating technologies, especially Physical Vapor Deposition (PVD) coatings like γ-Al_2O_3, play a pivotal role in increasing surface hardness, thermal resistance, and oxidation stability. These coatings minimize adhesion and improve wear resistance, contributing to longer tool life and improved material removal rates [103]. Electrochemical Machining (ECM) is a non-contact, non-thermal machining technique well-suited for nickel-based alloys. It eliminates thermal and mechanical stress by using controlled anodic dissolution, allowing the machining of complex geometries with no tool wear. This method is increasingly explored in high-precision applications for nickel alloys [104]. Tool geometry and machining parameters are also significant. For instance, studies show that a 70° tool holder geometry leads to slower wear progression than a 90° shoulder cutting tool, due to reduced cutting force concentration and better heat dissipation. Wear Mechanisms like Diffusion wear are a primary concern in high-temperature cutting, particularly with CBN tools, as workpiece atoms like Ni, Fe, and Cr diffuse into the cutting edge, weakening the material [38]. Adhesion of work material can initially protect the tool, but it often leads to instability and severe wear on the rake and flank surfaces during prolonged operations [36]. Chipping and notching, particularly in α-SiAlON ceramics, result from combined mechanical shocks and thermal cycling. This form of wear is common in dry cutting and can significantly limit tool life. Recent research has focused on extending the tool life through the implementation of novel strategies, including cooling techniques, parameter optimization, coating development, and material enhancement. One significant advancement in this domain is the application of High-Pressure Cooling (HPC). HPC significantly reduces flank wear compared to traditional cooling, resulting in a tool life increase of more than 30% [33]. In the Milling of Nimonic C-263, the application of HPC has been shown to improve tool life dramatically, with enhancements of up to 133% compared to conventional coolant systems. Despite these benefits, HPC is not without limitations; although flank wear decreases, notch wear has been observed to increase under high-pressure conditions, which may compromise tool integrity during extended use [101]. Furthermore, the optimization of cutting parameters has proven effective in extending tool longevity. Through the use of response surface methodology (RSM), optimal cutting conditions for milling were identified, with minimal tool wear occurring at a cutting speed of 33.21 m/min, a depth of cut of 0.0367 mm, and a feed rate of 0.367 mm/tooth [40]. Another promising approach in machining is the cryogenic treatment of tools, which alters their microstructural properties and significantly enhances wear resistance. When cryogenically treated tungsten carbide tools were applied in the turning of Inconel 718, machining performance improved by 12.70%, attributed to enhanced dimensional stability, reduced residual stresses, and slower

wear progression—ultimately validating this method as highly effective for industrial machining of superalloys [105–107].

7. Challenges in Machining Nickel-Based Alloys

Machining nickel-based alloys remains a complex endeavor due to their high mechanical strength, chemical stability, and thermal resistance, which, while beneficial in applications like aerospace and power systems, significantly challenge the performance of cutting tools and their coatings. One of the primary challenges is the high tool wear rate caused by the abrasiveness of nickel alloys and the extreme heat generated during cutting operations. This leads to accelerated flank and crater wear, thermal softening, and even chipping of the cutting edge, as observed by [7], who noted substantial coating degradation under elevated temperatures. The limited tool life resulting from such wear translates into frequent tool changes, raising both production costs. Another critical issue is coating adhesion—mechanical and thermal loads can cause delamination and peeling, especially in multilayer or PVD/CVD coatings, compromising performance prematurely. The need for enhanced thermal management is another pressing concern, as inadequate cooling or lubrication leads to thermal cracks and reduced surface integrity. Although high-performance cooling methods like high-pressure coolant (HPC) offer improvements, they also introduce trade-offs like increased notch wear [33]. Moreover, cost remains a persistent barrier, with advanced ceramic or CBN tools and coatings such as TiAlN and CrAlSiN offering benefits at significantly higher material and processing costs [103,108]. Finally, variability in nickel alloy compositions and machining parameters necessitates tailored solutions, as generalized tool-coating combinations often yield inconsistent results [99,109]. One of the primary challenges is the high tool wear rate, caused by the abrasiveness of nickel alloys and the extreme heat generated during cutting operations. This often leads to accelerated flank and crater wear, thermal softening, and even chipping of the cutting edge, with substantial coating degradation observed under elevated temperatures [7]. The limited tool life resulting from such wear necessitates frequent tool changes, thereby increasing production costs. *Remedial measures* include the development of advanced nano-multilayer coatings (e.g., TiSiN/TiAlN and CrAlSiN) that offer superior thermal stability and wear resistance. Additionally, hybrid machining strategies such as cryogenic cooling combined with minimum quantity lubrication (MQL) can suppress thermal wear while maintaining eco-efficiency [75]. Another critical issue is coating adhesion, where mechanical and thermal loads can induce delamination and peeling, particularly in multilayer PVD/CVD coatings, thus compromising tool performance prematurely. *Remedies* involve optimizing deposition techniques to enhance coating–substrate bonding strength, such as incorporating graded interlayers or using high-energy deposition processes to improve adhesion. Surface texturing of substrates prior to coating has also been reported to improve anchoring and reduce delamination risks [88]. The need for effective thermal management is also pressing. Inadequate cooling or lubrication often results in thermal cracking, oxidation, and reduced surface integrity. High-pressure coolant (HPC) has been shown to alleviate some of these issues, but it can increase notch wear [33]. *Remedial measures* include employing advanced cooling methods such as nano-fluid-based MQL, cryogenic cooling with liquid nitrogen or CO_2, and hybrid cooling approaches, which improve heat removal while minimizing notch wear. Additionally, the integration of real-time thermal monitoring systems can allow adaptive control of coolant flow for optimized tool life. High cost is another persistent barrier, as advanced ceramic or cubic boron nitride (CBN) tools and coatings like TiAlN and CrAlSiN provide benefits at significantly higher material and processing expenses [99]. To address this, remedial measures include adopting cost-effective multilayer coatings, using coated carbide tools with optimized geometries for specific nickel alloys,

and implementing tool reconditioning/recoating strategies to extend tool usability and reduce overall expenditure. Finally, variability in nickel alloy compositions and machining parameters further complicates tool selection, as generalized tool–coating combinations often yield inconsistent results. Remedies include tailoring machining strategies to alloy-specific microstructural characteristics, supported by simulation-based predictive models. Recent advancements in artificial intelligence (AI) and machine learning (ML) can also be leveraged to optimize cutting conditions dynamically, ensuring consistent performance across different nickel-based alloys.

8. Results and Discussion

The machining of nickel-based alloys, renowned for their superior strength and thermal resistance, presents substantial challenges due to rapid tool wear and poor machinability. To overcome these difficulties, significant progress has been made through the application of advanced tool materials, surface coatings, optimized machining conditions, and innovative cooling technologies. High-pressure coolant (HPC) has emerged as one of the most effective strategies, reducing flank wear by more than 30% and extending tool life by up to 133%, although it can also accelerate notch wear under certain conditions [33,98]. Similarly, optimization of cutting parameters has shown measurable improvements; tool wear was minimized at a cutting speed of 33.21 m/min, depth of cut of 0.0367 mm, and feed rate of 0.367 mm/tooth [40]. In addition, coating technologies have substantially improved tool life: TiAlSiN coatings increased tool longevity by 80% for Inconel 718 and 60% for Inconel 625 [45]. Furthermore, cryogenic treatment improved wear resistance, leading to a 12.7% increase in tool life [101]. Beyond coatings, ceramic tools and super-hard materials like CBN and PCD have been tested with promising results, though challenges related to diffusion wear and brittle fracture still limit their wider application [38]. Experimental evaluations further confirmed these advantages with numerical evidence. TiAlN-coated carbide drills improved surface finish significantly, reducing surface roughness by approximately 20–25% compared to uncoated tools, particularly at spindle speeds above 1200 rpm. The average roughness (Ra) achieved with TiAlN was about 0.45 μm, compared to 0.62 μm for uncoated tools [40]. TiSiN coatings produced even finer results, lowering surface roughness to 0.38 μm, indicating better morphology and reduced burr formation under high-speed machining [61]. Hardness and wear resistance trends highlighted clear differences among coatings. TiAlN coatings achieved hardness values between 27.9 and 31 GPa, though they declined to 26 GPa after annealing at 700 °C, which limited high-temperature performance [48,67]. TiSiN coatings, with hardness ranging from 34.1 to 36.8 GPa, displayed stronger deformation resistance [49,50]. CrAlSiN coatings outperformed both, retaining hardness at 36 ± 2 GPa even after thermal exposure, confirming excellent thermal resilience [48]. Tool life analyses provided further evidence of performance differences. TiAlN extended tool life by about 2.1× compared to uncoated tools, particularly in fluid-assisted cutting [109]. TiSiN tools initially performed well but showed adhesion-related delamination under dry machining. However, TiSiN/TiAlN multilayer designs enhanced durability, offering 1.8× greater wear resistance compared to single-layer TiSiN [60]. CrAlSiN achieved the highest improvements, extending tool life by 2.9× over TiAlSiN and 4.2× over TiAlN in high-speed operations [63]. Flank wear measurements reinforced these findings. TiAlN-coated tools exhibited moderate resistance, with average wear widths of 0.18 mm after 30 min of cutting at 100 m/min [48]. TiSiN coatings reduced this value to 0.12 mm but exhibited higher notch wear [61]. CrAlSiN maintained superior wear control, limiting flank wear to below 0.08 mm even after prolonged cutting, highlighting its suitability for high-stress machining [64]. Thermal stability further distinguished performance. While TiAlN coatings experienced significant hardness reduction at elevated

temperatures [48], TiSiN maintained structural integrity, especially in multilayered architectures [60]. CrAlSiN demonstrated the highest resilience, retaining hardness, preventing thermal cracking, and preserving both tool integrity and machined surface quality [64].

9. Conclusions

The machining of nickel-based alloys continues to be highly challenging due to their superior strength, chemical stability, and resistance to heat, which accelerates tool wear and reduces tool life. The findings emphasize that advanced tool coatings such as TiAlN, TiSiN, and CrAlSiN, along with optimized cutting parameters and cooling/lubrication strategies, play a critical role in mitigating these challenges. Comparative evaluations demonstrated that TiAlN coatings offered moderate improvements in hardness and wear resistance, TiSiN provided superior mechanical strength but faced adhesion issues, and CrAlSiN delivered the most consistent results with tool life improvements up to 4.2× greater than TiAlN. Furthermore, high-pressure cooling and cryogenic methods were shown to reduce flank wear and extend tool longevity, while nanostructured and multilayer coatings improved thermal stability and wear resistance under elevated temperatures. The discussion highlighted that surface quality was significantly enhanced by coatings, with TiAlN reducing surface roughness by 20–25% and TiSiN lowering it further to 0.38 μm under high-speed conditions. CrAlSiN emerged as the most thermally stable coating, maintaining hardness up to 36 GPa after exposure to 700 °C, making it highly suitable for demanding aerospace and biomedical applications. Wear progression analysis also confirmed the superior resistance of CrAlSiN to flank and crater wear compared to other coatings. The study outlines several future research directions. First, there is a need to develop next-generation coatings that integrate nanostructured and multilayer architectures to improve adhesion, reduce delamination, and enhance fatigue resistance under cyclic thermal loads. Second, combining coatings with advanced lubrication strategies such as nano-MQL and hybrid cooling systems is recommended to address notch wear while reducing the environmental impacts of conventional cutting fluids. Third, the integration of machine learning and real-time sensor data in machining processes offers significant potential to predict tool wear progression, optimize cutting parameters, and enable adaptive process control for machining safety-critical components. Additionally, research into novel super-hard tool materials (e.g., CBN, PCD, and advanced ceramics) in combination with functionalized coatings should be expanded to address limitations such as diffusion wear and brittle fracture. Finally, greater emphasis should be placed on machining additively manufactured nickel alloys, which present different microstructural challenges compared to wrought materials.

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