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Toward Sustainable Machining: A Comprehensive Review of Surface Modification Techniques for Cutting Tools

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ABSTRACT: Cutting tools are subjected to severe wear during machining operations, especially when processing hard-to-machine materials. This wear primarily results from the intense friction and heat generated at the tool–chip–workpiece interfaces. To mitigate these effects and extend tool life, numerous strategies have been developed to modify the rake and flank surfaces of cutting tools. These include surface texturing and advanced coating techniques aimed at enhancing tribological properties, chemical stability, and resistance to mechanical stresses. This review provides a comprehensive analysis of such surface modification methods, highlighting their role in reducing friction, minimizing tool wear, and improving cutting efficiency. A detailed classification of cutting tool materials, such as ceramics, carbides, and polycrystalline cubic boron nitride used in recent studies for machining hard materials is presented. The paper also identifies current challenges and research gaps, particularly in the context of superalloy machining. Finally, it outlines promising future directions, including the development of functional tool surfaces, integration of data-driven optimization approaches, and the exploration of novel tool materials and geometries. The overarching aim is to promote sustainable, cost-effective, and high-performance machining practices aligned with modern manufacturing demands.

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1- Introduction

The durability and effectiveness of cutting tools encounter significant obstacles in the complex field of metal machining, especially when it comes to precisely cutting materials that are challenging to machine [1]. One of the main challenges facing cutting tools in this business is the extreme surface wear that they endure. High friction is primarily responsible for this wear at the tool-chip and tool-work interfaces [2]. As a result of producing a great deal of heat and abrasion, this friction is a severe hindrance to the longer tool life and the production of high-quality machined components [3]. Several strategies to alter the flank and rake faces of cutting tools have been implemented to solve these issues and herald in a new era of sustainability and efficiency for machining processes. The intricate relationship between difficult-to-machine materials and cutting tools is the source of the Nexus of Friction-Wear Tool wear. And also, Nanoscale textures alter the interfacial shear stress distribution primarily by introducing local stress concentrations and modulating the contact mechanics, with the dominant mechanism varying under different machining conditions such as lubrication regime, load, and material pairing. Under dry conditions, evidence generally points to mechanical interlocking and ploughing as dominating, whereas under lubricated or mixed regimes, changes in lubricant film formation and localized hydrodynamic effects can become more significant [4]. Friction at the tool-chip and tool-work interfaces becomes important when precise cutting is performed on these durable, hard, and thermally conductive materials. Frictional heat and abrasion from these interactions create a complex issue that reduces the life expectancy of cutting tools and reduces the precision and quality of machined components [5, 6]. Comprehending the relationship between wear and friction is crucial for identifying the root causes of tool wear and, eventually, developing innovative solutions that transform the metal machining industry [7]. Improving the cutting tool's performance in order to solve the issues brought on by friction-induced wear, this in-depth examination explores the subject of strategically altering cutting tool surfaces [8, 9]. Since solid lubricants like MoS_2 can degrade at elevated temperatures and interact differently with coatings, a dedicated section on coating–lubricant compatibility would

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add significant value. It would clarify performance trade-offs, guide material selection, and strengthen the review's relevance for high-temperature machining environments [10]. The major objective is to fortify cutting tools to make them more resilient to external loads, which will prolong their useful lives and enhance their tribological and chemical stability [11]. The core element of these tactical adjustments consists of surface texture and coating improvements on the rake and flank faces of cutting instruments.

Preventing friction and wear on cutting tools fur face coating appears to be a game-changing strategy, akin to putting a shield on cutting instruments to protect them from the constant barrage of wear and friction. TiN and TiAlN, two commonly utilized coatings serve as protective layers that accentuate the inherent properties of the materials used to create cutting tools and nano composite coatings like AlCrN/Si_3N_4 outperform them in high-temperature machining. Biomimetic textures enhance cutting tool performance by improving lubricant retention, reducing wear, and lowering friction, but face manufacturing and durability challenges for large-scale industrial adoption [12]. AI-driven adaptive tools significantly enhance wear prediction accuracy by analyzing complex signals and adjusting machining parameters in real time. Prioritizing smart coatings integrated with AI in the 'Future Scope' better reflects this technological revolution, enabling proactive wear management over passive surface modifications for improved machining efficiency [13, 14]. These coatings increase cutting instruments' resistance to abrasive contacts while minimizing friction, so offering a dual defensive mechanism. Reducing macroscopic difficulties with microscopic techniques surface texturing is a clever way of minimizing wear and friction by adding small movements that intentionally upset interfaces to the protective function of coatings [15, 16]. Cutting tool surfaces that have been purposefully micro texturized change the basic topography of the tools by forming reservoirs for efficient chip evacuation or channels for better lubrication. The investigation of surface texturing includes its theories, uses, and effectiveness in offering strategic moves that reinterpret the macroscopic problems caused by wear and friction [17].

Surface adjustments on Cutting Performance: A comprehensive analysis is conducted as the evaluation progresses to determine how surface adjustments affect cutting performance as a whole [18]. The analysis goes beyond theoretical foundations to explore real-world consequences, taking into account how these adjustments affect the effectiveness, accuracy, and caliber of machining operations [19]. This empirical investigation provides a link between theoretical developments and their concrete shop floor implementations, offering valuable perspectives on the applicability and feasibility of surface alterations in the context of metal machining [20]. Hard Material Machining delving deeper into the complex fabric of metal machining, the review identifies, groups, and highlights the state-of-the-art machining research horizons [21]. Based on the kinds of instruments that are employed, this classification separates the market into three segments: ceramics, polycrystalline cubic boron nitride and carbide. Every category reflects a different path of progress, where surface modification techniques and tool material developments come together to create new opportunities for hard material machining [22]. Refinement for Sturdiness and Accuracy Carbide, a stalwart in the arsenal of cutting tools, undergoes continual refinement in response to the demands imposed by hard materials [23]. Innovations in carbide formulations, accentuated by insights from surface modification techniques, shape the trajectory of research in this category. The investigation of carbide developments reveals how materials engineering is changing and how this has a significant impact on the accuracy and robustness of cutting tools used in hard material machining. A potential option for the precise machining of hard materials is the use of ceramic cutting tools, which are renowned for their inherent hardness and durability to high temperatures [24]. Fractal textures offer unpredictable friction reduction beyond conventional patterns, potentially surpassing current texture performance limits. Their complex geometry enhances tribological behavior differently, suggesting that exploring fractal designs could innovate tool surface engineering and break existing boundaries in cutting efficiency and tool life enhancement. You make a very valid point. Since tool materials respond differently to texturing, adding material-specific guidelines would significantly improve the practicality of the review. Highlighting distinct behaviors, such as crack propagation in ceramics and wear reduction in PCBN, would provide clearer insights for tailoring textured coatings in machining [25,26]. The investigation of ceramic tool research opens up a world of possibilities where the special qualities of ceramics allow hard material machining to be redefined. Ceramics are positioned to be a game-changer in the quest for previously unheard-of precision in the cutting of hard materials because of their resistance to wear and temperature [27, 28]. Establishing the forefront of hard material machining. The novel material known as polycrystalline cubic boron nitride (PCBN) is a specialized competitor for hard material machining. PCBN tools, with their exceptional hardness and thermal stability, represent a frontier where cutting-edge materials and surface modification techniques converge, offering an exciting opportunity for the development of hard material machining in the future [29]. The study of PCBN tools looks at their properties, applications, and the growing corpus of evidence that positions them as pioneers at the cutting edge of advanced hard material machining. Because of their intrinsic strength at high temperatures and corrosion resistance, superalloys have unique properties that make tool selection extremely important [30]. In the meantime, the intricacies of chip generation in superalloy machining emerge, offering a glimpse into the complex interplay between material properties and machining dynamics.

Novel materials, creative geometries, and optimization driven by data, the story takes off into the future as the review progresses, imagining the next phase in the development of cutting tools and machining techniques [31, 32]. This forward-looking viewpoint predicts a world molded by novel geometry, data-driven thorough optimization, and new materials.

Beyond conventional materials, the investigation explores the potential offered by cutting-edge tool designs that rewrite the accepted limits of machining [33, 34]. Furthermore, the assessment foresees the incorporation of functional surfaces designed to fulfil particular functions like better chip evacuation or lubrication into cutting tools. Single-component coatings like TiN is not suitable for improving the wear and corrosion resistance performance of cemented carbide tools due to oxidation at high temperatures. But the use of new generation coatings by adding elements such as Si, Al, and C by CVD technique exhibited a considerable improvement in the performance and tool life of these cutting tools due to their ultra-high hardness, wear and oxidation resistance, and excellent performance in the cutting/machining process. Nano composites coatings like AlCrN/Si3N4 outperform them in high-temperature machining [35, 36]. This section presents a paradigm shift in cutting tool design and reveals the potential of functional surfaces to change the cutting tool industry. The importance of data-driven holistic optimization is growing in the context of Industry 4.0 [37, 38]. Using data analytics and computational modelling, this section of the paper envisions a time when cutting tools are not only intelligent but also dynamically adapt to the intricacies of machining operations. This section discusses the benefits and challenges of data-driven optimization, which pave the way for a more efficient and adaptable machining ecosystem [38-40]. While the specialized analysis of super alloy machining stresses the unique opportunities and challenges present in this industry, the classification and assessment of recent research in the machining of hard materials highlights the boundaries of innovation [41-43].

The primary objective of this review is to present cutting tool surface modification state-of-the-art while concurrently promoting sustainable, affordable, and environmentally benign processes that have the potential to revolutionize metal machining [44-46]. As this exploration draws to a close, the need for a sustainable path in metal machining is heard, calling on academics, professionals, and industry stakeholders to work together to prepare for a time when efficiency and accuracy combine with environmental awareness to revolutionize the field of metal machining.

2- Tool Coatings

Each Tools can be made more functional, durable, and perform better by coating their surfaces with thin layers of materials such as TiN, TiCN, TiAlN, and DLC. It is possible to customize these coatings to reduce friction, boost wear and corrosion resistance, and enhance hardness [47]. They are widely utilized in drills, end mills, and cutting tools used in machining operations. These techniques consist of PVD and CVD. Longer tool life, increased cutting efficiency, reduced friction, corrosion resistance, and improved surface finishes on machined products are among the benefits [48]. Tool surface coatings are crucial for extending the life and effectiveness of tools across a range of industries. Additionally, they support the improvement of machining, manufacturing, and metalworking procedures [49, 50]. Because coated carbide tools are more resistant to wear than uncoated ones, they usually have a longer tool life. However, this isn't always the case if the incorrect coating and conditions are applied. Specifically, unless the depth of cut was more than 1.0 mm, the tool life of GC3015 grade coated tools was not longer than that of uncoated tools at different feed rates and cutting speeds [51].

In a study by Masooth et al. [52], the surface roughness of an Al6061-T6 alloy end mill was investigated using both uncoated and TiAlN-coated carbide tools. The outcomes demonstrated that using both coated and uncoated tools improved process efficiency and that the coated carbide end mill produced a superior surface polish. Tool wear was highlighted in a study by Ali et al. [53] conducted for varying cutting speed and findings revealed that coated tools exhibited improved surface quality compared to uncoated tools across all cutting conditions, as shown in Figure 1.

Where the functionality of a tool with and without PVD coating was investigated. The findings demonstrated that the uncoated tool exhibited superior resistance to chipping when it was utilized at a slower cutting speed of 25 m/min. In contrast, the TiN PVD-coated tools worked better at a quicker speed of 50 m/min due to the coating's outstanding wear resistance and low thermal conductivity. Martinho et al.'s study [54] examined how well-suited carbide inserts were for variously coated instruments. The coatings in question were PVD (monolayer) AlTiN and CVD (multilayer) TiN/TiCN/Al_2O_3. The primary goals of the experiment were to monitor wear, vibration, and the ultimate state of the machined surface during the cutting process. When PVD-coated inserts were compared to CVD-coated inserts, it was found that the former exhibited increased brittleness and failures. An intriguing aspect of the outcomes is that the machined surface was unaffected by the wear of the CVD-synthesized layer. In a similar vein, Bhatt et al. [55] discovered that using a tool coated with TiCN/Al_2O_3/TiN allowed for the faster achievement of optimal wear resistance. However, using an uncoated tool at a slower speed of 50 m/min resulted in better performance. Moreover, a carbide tool coated with TiN/TiCN/Al_2O_3/ZrCN via CVD demonstrated an advantage over its uncoated counterpart in terms of white layer thickness at low and medium cutting speeds. TiAlN's success at high speeds is real, but wear mechanisms shift sharply with Inconel 718, requiring careful tuning of coating properties and potentially composite or multi-layer approaches to manage adhesive wear and prolong tool life in these challenging machining conditions [56]. Choosing a coated tool appropriate for the workpiece's specific material will enable efficient cutting.

The experiment conducted by Hosokawa et al. [57] evaluated the cutting properties of tools coated with filtered arc deposition (FAD). During the experiment, this non-traditional deposition procedure produced two different types of films. TiCN and VN coatings were the main focus of the high-speed milling method used to apply the coatings on pre-hardened stainless steel. Specifically, the TiCN coatings showed remarkable adhesion to the substrate and hardness. Sharman et al. [58] found a 45% improvement in a milling

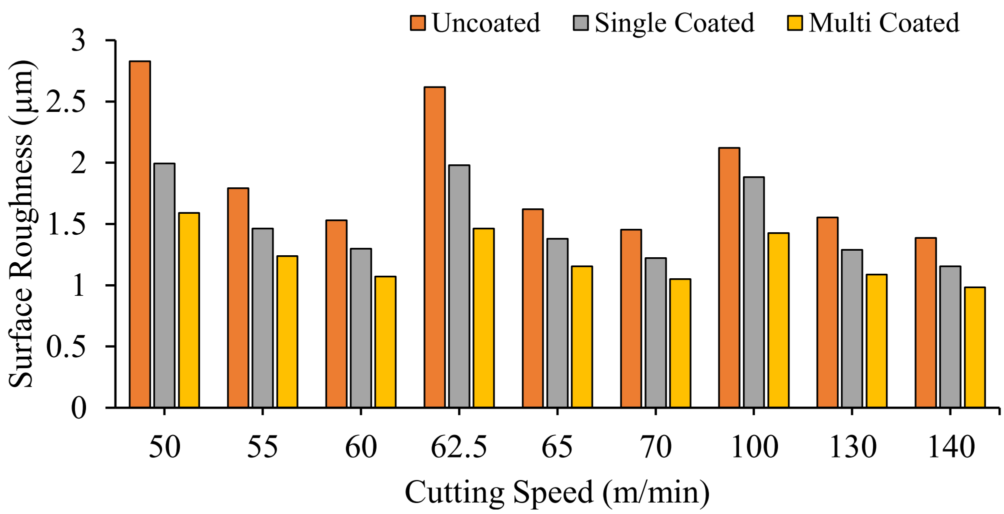

Fig. 1. Surface improvement for various cutting speed [54].

test, indicating the important role that tool coating plays in prolonging tool life. They used a carbide tool coated in CrN and a TiAlN tool. A $TiCN/Al_2O_3/TiN$-coated carbide demonstrated an astounding 100% longer tool life than an untreated tool when cutting Inconel 718 [59]. When it came to tool wear during Inconel 718 machining, AlTiN coating performed better than uncoated carbide [60]. Wang et al. [61] examined the cutting dynamics during high-speed machining of graphite moulds using tools coated with diamond. Throughout the experiment, the scratch resistance of various coatings—sub-microcrystalline diamond, microcrystalline diamond, nanocrystalline diamond, and micro/nanocrystalline composite diamond—was assessed. The choice of coating material has a significant impact on the tool's performance, especially with regard to wear resistance. When dry milling Inconel 718, it was found that a ball nose end mill coated with TiAlN performed better than one coated with CrN. This can be attributed to the enhanced hardness, reduced coefficient of friction, and resistance to oxidation of the TiAlN coating [62].

Hirata et al. [63] studied the characteristics of the sliding friction of carbon nanotubes (CNTs) on a range of substrates, such as silicon, silicon nitride, and cemented carbide. The results of their investigation demonstrated that on surfaces with increased porosity, CNT-coated substrates had notably enhanced lubricating and adhesion qualities. The study by Borkar et al. [64] demonstrates that pulsed electrode deposition of CNT coatings greatly boosts wear resistance in comparison to coatings composed completely of pure nickel. In a different investigation, Kamata and Obikawa [65] examined many coating materials under Minimum Quantity Lubrication (MQL) conditions while spinning Inconel 718 at high speeds. These materials included TiN/AlN superlattice (PVD), $TiCN/Al_2O_3/TiN$ (CVD), and TiAlN (PVD). Experimental results showed that during MQL cutting at 60 m/min, the $TiCN/Al_2O_3/TiN$ coating had the longest cutting length. Devillez et al. [66] examined two coatings in their study of tool wear resistance during the machining of Inconel 718: TiAlN + WC/C and TiAlN + MoST (MoS2 + Ti). According to their study, the best resistance to tool wear during machining was offered by an AlTiN coating.

Fig. 2 shows the many types of coating materials for cutting instruments. In order to evaluate the machining performance concerning crucial machinability parameters as cutting tip temperature, cutting forces, surface roughness, and tool wear and life, Chandru et al. [67] deposited carbon nanotubes (CNT) onto a High-Speed Steel (HSS) tool. Cutting tip temperature and cutting forces for the coated tools were significantly reduced by 70 to 80% as a result of the integration of carbon nanotubes (CNTs), which are well known for their exceptional mechanical and thermal qualities. In a related study, Chenrayan et al. [68] investigated the use of plasma-enhanced chemical vapor deposition (PECVD) to apply carbon nanotubes (CNT) onto an HSS tool. Temperature, cutting pressures, friction coefficient, mechanical performance, surface quality, and service life were all examined in this study to thoroughly assess the coated tool's mechanical capabilities. The tool coated with PVD nanocomposite demonstrated improved performance and outperformed the reference tool coated with AlTiN at cutting rates of at least 80 m/min. Yeadon et al. [69] integrated the effect of Icephobic coatings on surface roughness. The findings reported that Liquid Glass Shield and MG Silicone-coated coupons exhibited greater surface roughness on the roughened aluminum substrates than on the smooth substrates. The impact of a TiN coating produced using photovoltaic deposition (PVD) technology on the tungsten carbide insert machining performance during the dry hard turning of AISI 1040 steel was examined in a study by Tuffy et al. [70]. The TiN layer, at 3.5 mm thick, demonstrated the highest cutting

Fig. 2. Tool coating materials.

efficiency and produced a tool life that was around 40 times longer.

Sargade et al. [71] looked at the effects of a TiN coating thickness ranging from 1.8 to 6.7 mm on cementitious carbide tools composed of dry-turned, hardened C40 steel. When Biksa et al. [72] introduced an adaptive AlTiN/MexN PVD nano-multilayered coating, it outperformed nano-layered AlTiN coatings in terms of wear resistance during Inconel 718 machining. To provide a thorough physical and chemical surface characterization, Colombo et al. [73] created Inconel 718 (IN718) specimens using laser powder bed fusion (LPBF). These specimens were then PVD coated with TiN and AlTiSiN. In this context, glow discharge optical emission spectroscopy (GDOES) was used for chemical analysis and microhardness testing. Sugihara et al. [74] carried out an independent study on the topic of high-speed milling Inconel 718 with CBN cutting tools. Understanding tool wear behavior and extending tool life were the goals. The findings showed that high-speed Inconel 718 machining offers difficulties due to its elevated melting point, which causes a diffusion wear phase early in the cutting process. CBN tool wear is increased when a strong adhesion layer forms on the worn flank face. Since tool materials respond differently to texturing, adding material-specific guidelines would significantly improve the practicality of the review. Highlighting distinct behaviors, such as crack propagation in ceramics and wear reduction in PCBN, would provide clearer insights for tailoring textured coatings in machining. A later level of flaking and cracking results from this.

Fox-Rabinovich et al. [75] evaluated several Nano multilayered TiAlCrSiYN/TiAlCrN coatings and found a significant increase in tool life when milling Inconel 718. A nano-multilayered coating with 60 at.% Al enhances oxidation resistance and crack propagation resistance, improving machining of Inconel DA 718. For the tougher ME 16 superalloys, a 55 at.% Al variant provides better hardness, oxidation resistance, and plastic deformation resistance, delivering superior performance under high-temperature, thermally resistant machining conditions. In a follow-up study, they looked at an AlTiN/Cu coating that showed multifunctionality, including self-lubricating qualities meant to reduce heat conductivity [76]. Azineet et al. [77] used electroless nickel co-deposition to coat tools with cubic boron. The Ni-CBN surface coating was electrolessly coated with nickel, and ceramic CBN particles were added chemically. This electroless nickel approach has shorter coating process times and lower costs. These coatings are widely used in a variety of industries and are well-renowned for their resistance to corrosion, wear, and abrasion. The study specifically examined the surface tolerance of Ni-CBN-

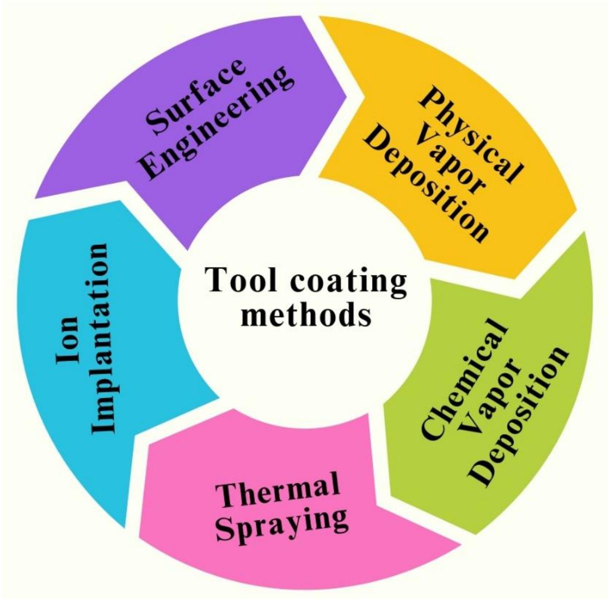

Fig. 3. Tool coating techniques.

coated High-Speed Steel (HSS) tool substrates during the cutting of aluminium alloy 7075 in comparison to uncoated HSS tool substrates.

Magnetron sputtering was used by Escobar et al. [78] to achieve HfN and VN film deposition. The elastic modulus caused a large difference in the plastic deformation resistance values: the HfN film registered 224 GPa, while VN registered 205 GPa. The HfN and VN films showed low friction coefficients, 0.44 for HfN and 0.62 for VN, in the tribological pair that included a steel pin and nitride film. The critical loads for HfN and VN films were approximately 41 N and 34 N, respectively. According to an examination using scanning electron microscopy (SEM), the two films displayed different wear mechanisms: adhesive wear in HfN and abrasive wear in VN. Ultimately, HfN films outperformed VN materials in mechanical properties and tribological traits such as friction coefficients, which were 18% superior, by 9%. Escobar [79, 80] carried out a comprehensive study on the tribological behavior and wear of [HfN/VN] n coatings. The hardness and elastic modulus of the coatings increased to 37 GPa and 351 GPa, respectively, as a result of the shortened bilayer durations. This sample had the lowest friction coefficient (0.15) and the highest critical load (72 N) of all the samples, with a bilayer number of n = 80 and a bilayer period of 15 nm. The WC inserts that were used as substrates enhanced the tribological and mechanical characteristics of the [HfN/VN] n coatings. By raising contact counts, this tactical approach sought to enhance coating performance and boost productivity in a range of industrial applications, such as machining and extrusion.

Fig. 3 shows several approaches to covering cutting implements. Improvements in tool quality have been the subject of research; Koseki et al.'s study [81] examined various coating methods for superalloy machining, including CVD, PVD sputtering, PVD arc ion-plating, and PVD hollow cathode approach. According to the data, there were the fewest flaws, including droplet formation, and the least amount of flank wear with the CVD and PVD sputtering techniques. In a related experiment, Koseki et al. [82] showed that plastic deformation and destruction are the main causes of defects in the PVD arc ion-plating TiN coating. Voids and droplets were among the issues caused by this when the deterioration initially started. The study underlined that rather than chemically adhering to the cutting edge, these imperfections had a mechanical or physical influence on the tool. Cryogenic treatment improves tool wear resistance, reduces residual stresses, and enhances microstructure for better durability. Its combination with texturing could significantly address high-temperature wear by merging structural strength with surface enhancements. The review missed exploring this promising synergy that could extend tool life effectively in machining. The study also discovered that applying cryogenic heat treatment improved the hard coatings' adhesion to the substrate material [83]. This treatment significantly extended the tool life when tested against a multilayer nanocomposite hard coated carbide cutting tool during the superalloy milling process at a cutting speed of 30 m/min. In particular, for untreated, TiN-, NC-, and TiAlN-coated tools, the tool life increased by 54%, 110%, 29%, and 30%, respectively. Moreover, it was shown that thinner PVD TiN coatings showed less damage morphology than their thicker counterparts when superalloys were subjected to interrupted machining.

A study on the tribological behavior of milling tools coated with HfN was carried out by Staia et al. [84]. WC was used as a tribological pair in laboratory friction and wear studies to record the early wear behavior of multilayer HfN coatings. To more thoroughly evaluate the mechanical characteristics of the coatings, such as the composite hardness of the coating-substrate system, Vickers micro indentation experiments were carried out. The findings showed that the wear volume of single-layer HfN coatings was approximately fifteen times more than that of HfN/TiCN coatings for a similar number of cycles. In order to generate unique multi-component raw materials, Yin et al.[85] combined FeAl powder, ZrO2 nanoparticles, and CeO2 additives during the spray-drying process. They then used plasma spraying to coat 1Cr18Ni9Ti stainless steel with FeAl, CeO2, and ZrO2 nanocomposite coatings. These nanocomposite coatings, along with pure FeAl coatings, were subjected to mechanical, frictional, and wear tests using Vickers micro indentation testers and ball disc sliding wear friction mills. With an emphasis on how the coatings wear, the study closely examined the microstructures and mechanical characteristics of the coatings. ZrO2 nanoparticle strengthening was found to be responsible for the increased hardness, fracture toughness, and wear resistance of nanocomposite coatings when compared to pure FeAl coatings. Fukumoto et al. [86] examined a (Ti,Cr,Al)N/(Al,Si)N nanolayer coating in a distinct study. The results of the investigation showed that the (Al,Si)N layer had a hexagonal structure while the (Ti,Cr,Al)N layer had a cubic structure. The coating's hardness increased as the nanolayer's thickness shrank, suggesting that it may survive temperatures as high as 1100 °C. The study by Chang et al. [87] examined cathodic-arc deposition of nanocrystalline CrAlSiN and CrTiAlSiN coatings produced with lateral rotating arc cathodes. Al89Si11, chromium, and titanium cathodes were used in the deposition process to create the CrAlSiN and CrTiAlSiN coatings.

3- Surface texture

Surface texturing on tools involves the deliberate creation of controlled micro- or nano-sized patterns, such as dimples or grooves, to enhance performance in various applications. These patterns play a crucial role in influencing friction, wear resistance, lubrication, and heat dissipation on tool surfaces. Applied to cutting tools, molds, and precision components, surface texturing has gained prominence due to its potential to reduce friction through a hydrodynamic effect, extend tool life, and improve surface finishes in machining processes. The implementation of surface texturing offers several advantages, including efficient chip evacuation, enhanced wear resistance, and positive effects on tribological properties. The technology proves particularly valuable in promoting effective lubrication, dissipating heat, and preventing material adhesion. Its applicability extends across diverse domains, ranging from metal cutting to high-speed machining, making it a versatile and impactful solution for optimizing tool performance.

In a study by Kim et al. [88], Electrical Discharge Machining (EDM) was used to construct parallel ridges on a tool's rake surface that matched the real direction of chip flow. By contrasting the textured tool with its non-textured equivalent, the goal was to investigate how the textured tool affected the primary cutting forces. On the rake surface of a cemented carbide insert, Arulkirubakran et al. [89] created linear texture in parallel, perpendicular, and cross patterns using the wire-cut EDM technique. Their findings indicate that reducing cutting pressures and improving the machinability of Ti–6Al–4V can be achieved efficiently by employing a micro-textured tool with perpendicular-direction patterns. Micro-Electrochemical Machining (ECM) was used by Patel et al. [90] to create a range of micro features, including micro dimples, micro channels, and linear micro channels, on the cylindrical surface of a hypodermic needle. They used both structured and non-textured needles in their investigation to better understand the effect of insertion force. V-tip diamond grinding wheel was used by Xie et al. [91] to micro-groove the rake face of a carbide tool. When turning Ti-6Al-4V alloy by dry turning, they assessed how the size and shape of these microgrooves affected the cutting forces and temperature. while emphasizing superalloys highlights key challenges, omitting titanium alloys indeed narrows applicability. Since texture–coating synergy plays a decisive role in titanium machining performance, including this material class would broaden relevance and enhance the review's value for diverse high-performance machining applications across industries. Conversely, in the study by Thomas et al. [92], micro-texture was applied to the high-speed steel (HSS) M42 Grade S200 rake face. Three different hardness testers-a Vickers, a Rockwell, and a diamond dresser -were among the instruments they used. Throughout the cutting process, the study aimed to determine how the textured tool affected temperature, cutting pressures, and surface roughness. The outcomes led to improvements in the temperature at the tool–chip contact, cutting forces, and workpiece surface roughness. In a follow-up study, Pal et al. [93] investigated the efficacy of abrasive water jet machining (AWJM) as an electrical discharge machining (EDM) tool on copper and brass sheets. This process can be used to mill titanium alloy and stainless steel without compromising the metallurgical or physical characteristics of the workpiece because it is non-chemical and non-thermal.

In the machining process, tool texturing offers several advantages, as seen in Fig. 4. Chang et al. [94] employed Focused Ion Beam (FIB) milling to create microstructures on the rake face of end milling cutters by inserting grooves with three different orientations: perpendicular, horizontal, and 45° sloping in. Afterwards, the writers examined how various textures affected the tool's ability to withstand wear. Jianxin et al. [95] used laser machining in a different study to create three different textures: elliptical, parallel to the main cutting edge, and linear, on the rake face of a tungsten carbide insert. They focused on analysing the effects of texturing on temperature, cutting forces, and coefficient of friction at the chip-tool contacts. The study by Thiyaguet al. [96] used MR fluid-based nano-texturing to add nanoscale texture to a cutting tool. Examining the machinability characteristics of a nano- and untextured cutting tool for duplex stainless steel turning was the main goal of the research project. The data

Table 1. Summary of coating materials and their advantages.

Aspect	Coatings	Texturing	Texturing + Coating
Mechanism	Deposition of hard, wear resistant thin films (ceramics, nitrides, carbon based) on tool surface.	Creation of micro,nano grooves, or patterns to alter tribological behavior.	Combination of textures and coatings to enhance adhesion, lubrication and wear resistance.
Benefits	High hardness, thermal stability, good wear resistance and enables high-speed cutting	Reduces friction, contact area, traps lubricants, improves chip breaking and enhances heat dissipation	Synergistic effect of reduced friction & high wear resistance, improved coating adhesion on textured surfaces, superior tool life and stability
Limitations	High processing cost, some coatings brittle, High temperature CVD can damage substrate	Fabrication complexity, weaken tool if over textured and effectiveness depends on pattern design	High fabrication cost, complexity and requires precise integration of methods
Suitable Applications	High speed machining of steels, superalloys, cast iron and nonferrous alloys	Machining of steels, Ti alloys, composites, applications with MQL or cryogenic cooling	Aerospace alloys, superalloys, hard to machine materials requiring both wear and friction control
Sustainability Impact	Extends tool life, reducing material waste, enables dry machining to reduce cutting fluids	Supports MQL machining lowers cutting forces & energy demand and reduces lubricant usage	Maximizes green machining benefits, longest tool life reduces replacement frequency, strong candidate for future ecofriendly machining

demonstrated superior tool rake and flank wear stability for the textured tool. Using a variety of lubrication techniques, including micro-pool lubrication and flood cooling, Lei et al. [97] used a different tactic. They created microscopic holes at the cutting edge of the turning insert. Based on the investigation, the total contact area decreased by 28% when micro-pool lubrication was applied as opposed to dry cutting operations.

This decrease was attributed to the rising temperatures that occur between the tool-chip contacts when working. When Koshy et al. [98] evaluated the effect of roughness on the primary cutting forces and feed forces, they found that the average cutting and feed forces were reduced by 13% and 30%, respectively. Because of the interplay between shear and friction processes during cutting, which resulted in smaller chips and a larger shear angle, cutting forces were found to have decreased. The behaviour of several textured tools, including single, conventional, and hybrid textured tools, was examined in a study by Sun et al. [99] while turning pure iron in the presence of MoS2 solid lubricant. With a 12.7% reduction in cutting force, the hybrid textured tool outperformed non-textured tools in cutting performance. Even with these results, it is still difficult to decide on the ideal size and placement of textures.

Jianxin et al. [100] investigated the impact of these self-lubricating tools on tool wear by creating micro-holes in the flank and rake face of cemented carbide and filling them with solid MoS2 lubricant. Using a diode-pumped Nd:YVO4 picosecond laser, Ling et al. [101] ground the drill bit edges into rectangular surface patterns to create titanium plates. Their findings indicated that texturing decreased chip adhesion and increased tool life, hence improving adherent chip shedding. Xie et al. [102] created orthogonal and diagonal micro-grooves on the tool rake face to investigate the impact of texture on tool wear. The results of the experiment showed that compared to non-textured tools, micro-grooved tools showed reduced wear on the rake and flank face.

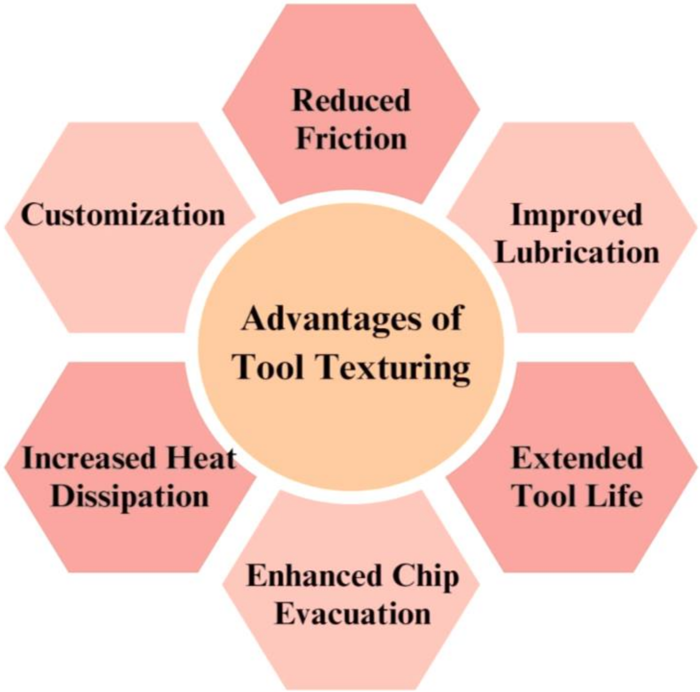

Fig. 4. Advantages of Tool texturing in machining process.

In order to investigate the impact of these textures on the adhesive capabilities of built-up edge creation on cutting tools, Kummel et al. [103] added dimple and channel textures to the rake surface of uncoated cemented carbide. Comparing their work to other textured cutting tools, they found that dimple-textured surfaces improved mechanical interlocking, which improved adhesive characteristics and decreased wear rates. Hybrid surface modifications require balanced thermal management. Strategies could involve optimizing texture geometry to minimize stress concentration, selecting coatings with higher thermal stability, and integrating coolant delivery techniques. A combined approach would help mitigate cracking risks while retaining benefits of both coatings and micro-texturing in machining

Using face milling on medium carbon steel, Sugihara et al. [104] produced micro-stripes on the rake face and flank of WC/Co carbide tools. Their investigations revealed that micro-stripes prevented flank and crater erosion by acting as microscopic traps for wear debris. Ti–6Al–4V alloy machinability was examined by Arulkirubakaran et al. [105] using coated, uncoated, textured, and untextured cutting tools. The tool coated with TiAlN and textured perpendicular to the chip flow was found to have the strongest resistance to flank wear. The machining process produced Al2O3, which reduced friction between contacting surfaces and improved the thermal stability of the cutting tool, and the greater wear resistance of the TiAlN coating explained this. Using solid lubricants including MoS2, CaF2, and graphite, Wenlong et al. [106] examined the impact of textured tools on friction at the tool-chip contact. By contrasting this textured tool with similar textured tools that were well lubricated, they discovered that the tool containing graphite had a reduced coefficient of friction without significantly changing the cutting speed. A study by Ze et al. [107] found that while converting Ti–6Al–4V alloy by dry cutting, the coefficient of friction decreased as cutting speed rose. Comparing the rake face textured tool to the flank face textured and conventional tools, the rake face textured tool showed a higher reduction in the coefficient of friction.

4- Challenges

Despite the promising benefits of cutting tool surface modifications, several challenges persist in their implementation. One key challenge is the complexity associated with optimizing the combination of surface coatings and texturing techniques for specific machining applications. A thorough understanding of material interactions and machining conditions is necessary to achieve the best possible balance between wear resistance, friction reduction, and other required qualities. Making sure the surface alterations are stable and durable during long periods of use-especially in high-stress environments-presents another issue. Additionally, the cost-effectiveness of implementing these techniques on a large scale and their environmental impact are areas that warrant careful consideration. Furthermore, the compatibility of surface modifications with evolving machining technologies and materials poses a continuous challenge in staying abreast of industry advancements.

5- Future scope

The future of cutting tool surface modifications holds promising avenues for exploration. Innovations in new materials and geometries are expected to redefine the conventional boundaries of machining, offering unprecedented precision and efficiency. A paradigm shift in tool design has occurred with the incorporation of functional surfaces into cutting tools that are intended for certain uses, including improved lubrication. Industry 4.0 presents the possibility of data-driven, all-encompassing optimization, in which cutting machines develop intelligence and instantly adjust to the complexities of machining processes. However, addressing challenges related to cost-effectiveness, environmental sustainability, and compatibility with evolving technologies remains crucial.

6- Conclusions

This comprehensive review underscores the significance of cutting tool surface modifications in addressing the formidable challenges posed by friction-induced wear in metal machining. The meticulous exploration of surface coating and texturing techniques reveals their transformative potential in extending tool life, improving cutting performance, and enhancing overall machining efficiency. The friction-wear nexus is highlighted as a critical factor, and strategic modifications to cutting tool surfaces emerge as key solutions to mitigate its impact. The empirical analysis of current research frontiers, with a focus on hard materials and superalloys, offers insights into ongoing innovations that refine precision and durability in machining. As the review transitions into the future scope, it envisions a landscape where new materials, innovative geometries, and data-driven optimization converge to shape the next era of cutting tools and machining processes.

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