

# A Review on Turning of Titanium Alloys: Recent Advances, Challenges and Future Trends

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## **Abstract**

Titanium alloys, particularly Ti-6Al-4V, are extensively used in aerospace, biomedical, and energy applications due to their superior strength-to-weight ratio, corrosion resistance, and thermal stability. However, their poor machinability poses significant challenges in turning operations, primarily due to low thermal conductivity, high chemical reactivity, and severe strain hardening behavior. These characteristics lead to elevated cutting temperatures, rapid tool wear, unstable chip formation, and compromised surface integrity. This review paper provides a comprehensive and critical analysis of recent advances (2020–2025) in the turning of titanium alloys. Key aspects discussed include machinability characteristics, tool wear mechanisms, cooling and lubrication strategies, surface integrity, and modeling and optimization approaches.

The review highlights that tool wear in titanium turning is dominated by adhesion, diffusion, abrasion, and notch wear, strongly influenced by thermal and chemical interactions at the tool–chip interface. Advanced cooling techniques, particularly minimum quantity lubrication (MQL), cryogenic machining, and hybrid approaches, have shown significant potential in improving tool life and surface quality while addressing sustainability concerns. Furthermore, emerging assisted machining techniques such as ultrasonic vibration-assisted turning and laser-assisted machining offer promising solutions to enhance machinability.

In addition, the integration of artificial intelligence (AI) and optimization algorithms, including artificial neural networks (ANN) and genetic algorithms (GA/NSGA-II), has enabled more accurate prediction and multi-objective optimization of machining performance. Despite these advancements, challenges remain in developing unified predictive models and understanding the complex interactions among process parameters, tool materials, and cooling strategies. This review identifies key research gaps and provides future directions toward intelligent, sustainable, and high-performance machining of titanium alloys.

**Keywords:** Titanium alloy; Ti-6Al-4V; Turning; Tool wear; MQL; Cryogenic machining; Optimization

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## **I. INTRODUCTION**

Titanium alloys, particularly Ti-6Al-4V, have become indispensable in advanced engineering applications owing to their exceptional combination of high specific strength, corrosion resistance, and biocompatibility. These properties make them highly suitable for demanding sectors such as aerospace, biomedical implants, marine engineering, and energy systems. In aerospace applications, titanium alloys are extensively used in structural components, turbine blades, and landing gear due to their ability to maintain mechanical integrity under elevated temperatures. Similarly, in biomedical engineering, their superior biocompatibility and resistance to body fluids enable their widespread use in orthopedic implants and prosthetics (Sun et al., 2020; Umbrello et al., 2021). Despite these advantages, titanium alloys are widely recognized as one of the most difficult-to-machine materials, particularly in turning operations.

The poor machinability of titanium alloys arises from a combination of unfavorable physical, chemical, and mechanical properties. One of the most critical factors is their low thermal conductivity, typically around 6–7 W/m·K, which is significantly lower than that of steels. As a result, the heat generated during machining is not effectively dissipated through the chip but is instead concentrated at the tool–chip interface. This localized heat accumulation leads to extremely high cutting temperatures, often exceeding 800°C, which accelerates tool wear and reduces tool life (Shokrani et al., 2020). In addition, titanium alloys exhibit high chemical reactivity at elevated temperatures, promoting strong adhesion between the workpiece and cutting tool. This adhesion results in the formation of built-up edge (BUE), which periodically detaches and causes surface damage, dimensional inaccuracies, and tool chipping (Guo and Eynian, 2021).

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Another important characteristic influencing machinability is the relatively low elastic modulus of titanium alloys, which is approximately half that of steel. This property leads to significant elastic deformation during machining, resulting in increased tool–workpiece contact length and higher frictional forces. Consequently, the cutting process becomes less stable, and issues such as chatter and vibration are more likely to occur. Furthermore, titanium alloys exhibit pronounced strain hardening behavior, meaning that the material becomes harder and stronger as it undergoes plastic deformation. This phenomenon increases cutting resistance and further exacerbates tool wear during prolonged machining operations (Pervaiz et al., 2021).

In turning processes, these characteristics manifest in several distinct phenomena. One of the most notable is the formation of serrated or segmented chips, which is a hallmark of titanium machining. This chip morphology is primarily attributed to adiabatic shear localization in the primary deformation zone. As the cutting speed increases, thermal softening competes with strain hardening, leading to cyclic shear instability and the formation of saw-tooth chips. This segmented chip formation results in fluctuating cutting forces, which can adversely affect surface quality and tool stability (Sun et al., 2020). Moreover, the intermittent nature of chip formation contributes to dynamic loading on the cutting tool, accelerating fatigue wear and potential tool failure.

Over the past five years, significant research efforts have been devoted to addressing the challenges associated with turning titanium alloys. One major area of focus has been the development of advanced cutting tool materials and coatings. Coatings such as AlTiN, TiAlN, and nano-multilayer structures have been widely investigated to improve thermal stability, oxidation resistance, and wear performance (Zhang et al., 2023). Although these coatings have demonstrated improvements in tool life, their effectiveness is still limited under extreme cutting conditions, highlighting the need for further innovation in tool design.

Another critical research direction involves the optimization of cooling and lubrication strategies. Conventional flood cooling has been widely used in machining; however, it poses environmental and economic concerns due to excessive fluid consumption and disposal requirements. As a result, alternative approaches such as minimum quantity lubrication (MQL), cryogenic cooling, and hybrid cooling techniques have gained increasing attention. MQL utilizes a small amount of lubricant delivered in the form of an aerosol, reducing friction and improving chip evacuation while minimizing environmental impact (Pervaiz et al., 2021). Cryogenic machining, on the other hand, employs liquid nitrogen or carbon dioxide to significantly reduce cutting temperature, thereby enhancing tool life and surface integrity (Shokrani et al., 2020; Dhar et al., 2023). More recently, hybrid approaches combining MQL with cryogenic cooling or nano-fluid additives have been proposed to achieve synergistic improvements in machining performance (Zhang et al., 2023).

In addition to cooling strategies, advanced and assisted machining techniques have emerged as promising solutions for improving the machinability of titanium alloys. Among these, ultrasonic vibration-assisted turning (UVAT) has received considerable attention due to its ability to reduce cutting forces and improve surface finish. By superimposing high-frequency vibrations onto the cutting tool, UVAT introduces intermittent cutting conditions, which reduce tool–chip contact time and facilitate chip breakage (Li et al., 2022). Similarly, laser-assisted turning (LAT) has been explored as a means of locally preheating the workpiece, thereby reducing its strength and improving machinability. While these techniques have shown significant potential, their industrial adoption is still limited due to complexity, cost, and process control challenges.

Another emerging trend in recent years is the machining of additively manufactured (AM) titanium alloys. Additive manufacturing technologies, such as selective laser melting (SLM) and electron beam melting (EBM), enable the fabrication of complex geometries that are difficult to achieve using conventional methods. However, AM titanium alloys often exhibit anisotropic microstructures, residual stresses, and porosity, which significantly influence their machining behavior. Studies have shown that the machinability of AM titanium alloys differs substantially from that of wrought materials, necessitating the development of tailored machining strategies (Singh et al., 2024).

Furthermore, the integration of artificial intelligence (AI) and data-driven approaches into machining processes has opened new avenues for optimization and control. Techniques such as artificial neural networks (ANN), genetic algorithms (GA), and multi-objective optimization methods (e.g., NSGA-II) have been increasingly used to predict machining responses and optimize cutting parameters (Kumar et al., 2022). These approaches enable the simultaneous consideration of multiple objectives, such as minimizing surface roughness, tool wear, and cutting forces, thereby improving overall machining performance. In parallel, the concept of digital twins has emerged as a powerful tool for real-time monitoring and predictive maintenance, allowing for more efficient and intelligent manufacturing systems.

Despite these advancements, several challenges and research gaps remain. For instance, there is still a lack of unified models that can accurately predict tool wear and surface integrity under varying machining conditions. Additionally, the interactions between different machining parameters, tool materials, and cooling strategies are not yet fully understood. The machining of AM titanium alloys also requires further investigation, particularly in terms of microstructure–machinability relationships. Moreover, the integration of sustainable machining practices with high-performance requirements remains a critical challenge (Dhar et al., 2023).

Therefore, this review aims to provide a comprehensive and critical analysis of recent developments in the turning of titanium alloys, with a particular focus on studies published between 2020 and 2025. The review covers key aspects including machinability characteristics, tool wear mechanisms, cooling and lubrication strategies, advanced machining techniques, and modeling approaches. In addition, emerging trends such as additive manufacturing and AI-based optimization are discussed. Finally, research gaps and future directions are identified to guide further studies in this important field.

## II. MACHINABILITY CHARACTERISTICS OF TITANIUM ALLOYS IN TURNING

Titanium alloys are widely recognized as difficult-to-machine materials, and their machinability in turning operations has been extensively investigated over the past decades, with significant advancements reported in recent years. The poor machinability of titanium alloys is primarily attributed to their unique thermo-physical and mechanical properties, which strongly influence chip formation, heat generation, cutting forces, and tool–workpiece interactions (Sun et al., 2020; Shokrani et al., 2020). A comprehensive understanding of these characteristics is essential for improving machining performance and enabling the development of advanced cutting strategies.

One of the most critical factors governing machinability is the thermal behavior of titanium alloys. Due to their low thermal conductivity, typically around  $6\text{--}7\text{ W/m}\cdot\text{K}$ , heat generated during machining is not effectively dissipated through the chip but is instead concentrated near the cutting zone, particularly at the tool–chip interface. This localized heat accumulation leads to extremely high cutting temperatures, often exceeding  $800^\circ\text{C}$  under moderate cutting conditions, which significantly accelerates tool wear and limits tool life (Shokrani et al., 2020). Although elevated temperatures can induce thermal softening of the workpiece material and reduce cutting forces, this effect is generally outweighed by the detrimental impact on tool integrity. Consequently, thermal management remains a critical challenge in titanium machining.

Another defining feature of titanium alloy turning is the formation of serrated or segmented chips, which distinguishes it from the continuous chip formation observed in more ductile materials such as aluminum alloys. This phenomenon is primarily attributed to adiabatic shear localization within the primary deformation zone. During cutting, the competition between strain hardening and thermal softening leads to periodic instability, resulting in the formation of shear bands and a characteristic saw-tooth chip morphology (Sun et al., 2020). Figure 1 illustrates the typical segmented chip morphology and shear band formation observed during titanium turning. The degree of chip segmentation is strongly influenced by cutting speed, with higher speeds promoting more pronounced thermal softening and thus more distinct segmentation. While segmented chips facilitate chip breakage and evacuation, they also introduce cyclic variations in cutting forces, which can negatively affect process stability and surface quality.



Figure 1. Chip formation in titanium turning: (a) Serrated chip morphology; (b) Adiabatic shear band formation observed under high-speed imaging, Adapted from Li et al. [6] and Sun et al. [1].

The behavior of cutting forces in titanium turning further reflects the complex nature of its machinability. Titanium alloys typically exhibit higher specific cutting energy compared to conventional steels, indicating greater resistance to plastic deformation. However, the relationship between cutting speed and cutting force is non-linear. At lower cutting speeds, strain hardening dominates, resulting in higher cutting forces, whereas at higher speeds, thermal softening reduces the cutting forces but simultaneously increases tool wear rates (Guo and Eynian, 2021). Additionally, the relatively low elastic modulus of titanium alloys leads to increased tool–workpiece contact length, which enhances frictional interactions and contributes to higher energy consumption during machining.

The tool–chip interface plays a crucial role in determining machinability, particularly due to the high chemical reactivity of titanium alloys at elevated temperatures. This reactivity promotes strong adhesion between the workpiece material and the cutting tool, resulting in the formation of built-up edge (BUE). The BUE is inherently unstable and undergoes repeated formation and detachment during the cutting process, leading to

fluctuations in cutting forces and degradation of surface finish. Moreover, the adhesion of titanium to the tool surface accelerates wear mechanisms and can cause micro-chipping of the cutting edge (Guo and Eynian, 2021). Recent studies emphasize that reducing friction and adhesion at the tool–chip interface is essential for improving machinability, which has driven the development of advanced coatings and lubrication techniques (Pervaiz et al., 2021).

Microstructural characteristics also significantly influence the machinability of titanium alloys. In conventional wrought titanium alloys, the distribution of  $\alpha$  and  $\beta$  phases governs deformation behavior and chip formation mechanisms. However, the increasing adoption of additive manufacturing technologies has introduced new complexities. Additively manufactured titanium alloys often exhibit anisotropic microstructures, residual stresses, and internal defects such as porosity, which affect their machining response. Several recent studies have reported that these materials tend to produce more irregular chip morphology and exhibit higher tool wear rates compared to wrought counterparts (Singh et al., 2024). Furthermore, the orientation of the build layers has been shown to influence cutting forces and surface quality, highlighting the need for process-specific optimization strategies.

The influence of cutting parameters on machinability has also been extensively studied. Cutting speed, feed rate, and depth of cut collectively determine machining performance, but their effects are often interdependent. Increasing cutting speed generally reduces cutting forces due to thermal softening but significantly increases cutting temperature and tool wear. Feed rate has a dominant influence on surface roughness and cutting force magnitude, as it directly affects chip thickness. Depth of cut primarily influences material removal rate and cutting force but has a relatively limited effect on surface integrity (Sun et al., 2020). The complex interaction among these parameters necessitates the use of advanced optimization techniques, such as multi-objective algorithms, to achieve an optimal balance between productivity and tool life.

When compared to other engineering materials, titanium alloys exhibit a unique combination of properties that make them particularly challenging to machine. Their low thermal conductivity results in higher cutting temperatures, their high chemical reactivity leads to severe adhesion and tool wear, and their low modulus of elasticity contributes to process instability. Additionally, their ability to retain strength at elevated temperatures increases cutting resistance, further complicating machining operations (Shokrani et al., 2020; Pervaiz et al., 2021). These characteristics necessitate the use of specialized machining strategies, including advanced tool materials, optimized cutting conditions, and enhanced cooling/lubrication techniques.

Overall, recent literature (2020–2025) consistently highlights that the machinability of titanium alloys is governed by a complex interplay of thermal effects, chip formation mechanisms, material properties, and process parameters. Despite significant progress in understanding these phenomena, challenges remain in achieving stable and efficient machining performance. In particular, the simultaneous control of cutting temperature, tool wear, and surface integrity continues to be a major research focus. Future studies are expected to further explore the integration of advanced machining techniques and intelligent optimization methods to overcome these limitations.

### **III. TOOL WEAR MECHANISMS IN TURNING OF TITANIUM ALLOYS**

Tool wear is widely recognized as the primary limiting factor in the turning of titanium alloys, significantly affecting machining performance, dimensional accuracy, and surface integrity. Compared to conventional engineering materials, tool wear in titanium machining is characterized by rapid progression, complex wear modes, and strong dependence on thermal and chemical interactions at the tool–workpiece interface. Recent studies (2020–2025) consistently emphasize that the unique combination of low thermal conductivity, high chemical reactivity, and high strength at elevated temperatures leads to severe tool degradation mechanisms (Sun et al., 2020; Guo and Eynian, 2021).

A dominant feature of tool wear in titanium turning is the strong coupling between thermal effects and material transfer processes. Due to localized heat accumulation at the cutting zone, the tool–chip interface experiences extremely high temperatures, which facilitate diffusion and adhesion phenomena. Under such conditions, adhesive wear becomes one of the most prevalent mechanisms. Titanium has a strong affinity for tool materials, particularly carbide-based tools, resulting in the formation of adhered layers on the rake face. These layers, often referred to as built-up edge (BUE), are inherently unstable and undergo repeated formation and detachment during machining. The cyclic nature of BUE formation induces micro-chipping and edge fracture, thereby accelerating tool failure and degrading surface quality (Guo and Eynian, 2021).

In addition to adhesion, diffusion wear plays a critical role, particularly at high cutting speeds. At elevated temperatures, chemical elements from the cutting tool, such as cobalt and tungsten in cemented carbides, diffuse into the titanium workpiece. This process weakens the tool's microstructure and leads to the formation of crater wear on the rake face. Diffusion wear is strongly temperature-dependent and becomes increasingly dominant as cutting speed increases, which explains the rapid tool degradation observed in high-speed machining of titanium alloys (Shokrani et al., 2020). Recent experimental investigations have highlighted that diffusion wear can significantly reduce tool life even when cutting forces appear relatively stable, indicating that thermal effects are

more critical than mechanical loading in certain regimes. Typical wear modes observed in titanium turning are presented in Fig. 2.

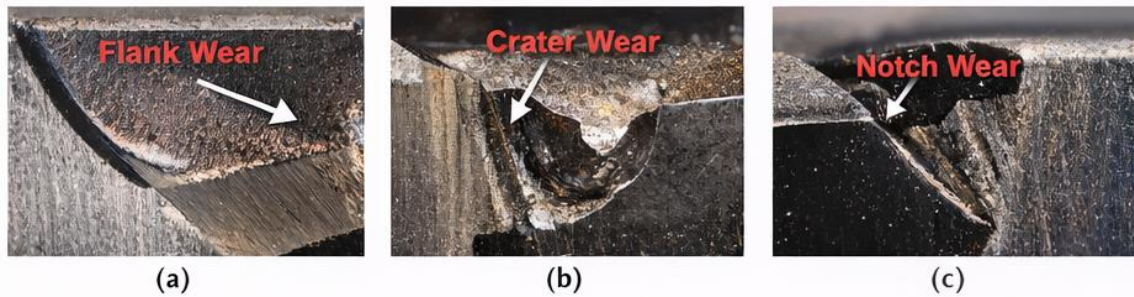


Figure 2. Tool wear mechanisms in titanium turning: (a) Flank wear; (b) Crater wear; (c) Notch wear at depth-of-cut line. Adapted from Guo and Eynian [3].

Abrasive wear is another important mechanism contributing to tool degradation. Although titanium alloys are not traditionally classified as highly abrasive materials, the presence of hard  $\alpha$ -phase constituents and potential oxide layers can lead to mechanical abrasion along the flank face of the tool. This results in the gradual development of flank wear (VB), which is commonly used as a criterion for tool life evaluation. Abrasive wear is particularly pronounced under conditions of insufficient lubrication or when machining additively manufactured titanium alloys, where microstructural heterogeneity can enhance abrasive interactions (Singh et al., 2024).

Notch wear represents a localized but critical form of tool degradation that frequently occurs at the depth-of-cut line. This phenomenon is associated with the combined effects of work hardening, oxidation, and stress concentration at the boundary between the machined surface and the uncut material. The repeated exposure of this region to high temperature and mechanical stress leads to accelerated material removal, forming a distinct notch on the cutting edge. Notch wear is particularly problematic because it can act as an initiation site for catastrophic tool failure, especially under interrupted or unstable cutting conditions (Sun et al., 2020).

The interaction between these wear mechanisms is complex and often interdependent. For instance, adhesive wear can facilitate diffusion by increasing the contact temperature, while abrasive wear can expose fresh tool material, making it more susceptible to chemical interactions. Recent literature suggests that tool wear in titanium machining should be considered as a multi-mechanism process rather than being dominated by a single wear mode. This perspective has led to increased interest in integrated modeling approaches that account for the combined effects of thermal, mechanical, and chemical phenomena (Umbrello et al., 2021).

Tool material and coating technology play a crucial role in mitigating wear mechanisms. Cemented carbide tools remain the most widely used in titanium turning due to their balance of hardness and toughness. However, their performance is often limited by thermal softening and diffusion wear. To address these challenges, advanced coatings such as AlTiN, TiAlN, and nano-multilayer coatings have been developed to enhance thermal stability and oxidation resistance. These coatings act as thermal barriers, reducing heat transfer to the substrate and improving wear resistance under high-temperature conditions (Zhang et al., 2023). Nevertheless, coating failure, including delamination and cracking, can occur under severe cutting conditions, particularly when adhesion and thermal stresses are high.

Alternative tool materials, such as cubic boron nitride (CBN) and ceramic tools, have also been investigated for high-speed machining of titanium alloys. While these materials offer superior hardness and thermal resistance, their application is often limited by their brittleness and susceptibility to thermal shock. As a result, their use is typically restricted to specific machining conditions where stability can be maintained. Recent studies have explored hybrid tool designs and functionally graded materials to overcome these limitations, although their industrial adoption remains limited.

Cooling and lubrication strategies have been shown to significantly influence tool wear behavior. The application of minimum quantity lubrication (MQL) reduces friction at the tool–chip interface, thereby mitigating adhesive wear and lowering cutting temperature (Pervaiz et al., 2021). Cryogenic cooling, on the other hand, effectively suppresses diffusion wear by reducing the temperature in the cutting zone. However, excessive cooling may increase tool brittleness, leading to chipping under certain conditions (Shokrani et al., 2020). Hybrid cooling approaches combining MQL and cryogenic techniques have demonstrated promising results in balancing thermal control and lubrication, thereby extending tool life (Dhar et al., 2023).

Another emerging area of research is the influence of machining techniques on tool wear. Advanced methods such as ultrasonic vibration-assisted turning (UVAT) have been shown to reduce tool–chip contact time, thereby decreasing friction and wear rates. The intermittent cutting mechanism in UVAT facilitates chip breakage and reduces heat generation, leading to improved tool life compared to conventional turning (Li et al., 2022).

Similarly, laser-assisted machining reduces cutting forces by preheating the workpiece, although it may introduce additional thermal effects that influence wear behavior.

Despite significant progress, several challenges remain in fully understanding and controlling tool wear in titanium turning. One major limitation is the lack of predictive models capable of accurately capturing the complex interactions among wear mechanisms under varying cutting conditions. Additionally, the machining of additively manufactured titanium alloys introduces new variables, such as anisotropy and porosity, which further complicate wear behavior. These challenges highlight the need for integrated experimental and modeling approaches to develop more robust tool life prediction methods.

In summary, tool wear in the turning of titanium alloys is governed by a complex interplay of adhesion, diffusion, abrasion, and notch wear mechanisms, all of which are strongly influenced by thermal and chemical interactions at the cutting interface. While advancements in tool materials, coatings, and cooling strategies have contributed to improved performance, achieving a balance between tool life, productivity, and surface quality remains a significant challenge. Future research should focus on developing integrated solutions that combine advanced materials, optimized machining conditions, and intelligent monitoring systems to effectively control tool wear in titanium machining.

#### IV. COOLING AND LUBRICATION STRATEGIES IN TURNING OF TITANIUM ALLOYS

Cooling and lubrication strategies play a pivotal role in determining the machinability of titanium alloys, primarily due to their strong influence on cutting temperature, tool wear, and surface integrity. Given the severe thermal conditions inherent in titanium machining, effective control of heat generation and dissipation is essential for achieving stable and efficient cutting performance. Over the past five years, significant research efforts have been directed toward developing advanced cooling and lubrication techniques that not only improve machining performance but also address environmental and sustainability concerns.

Conventional flood cooling has long been employed in machining processes to reduce temperature and flush away chips. However, its effectiveness in titanium turning is limited due to the poor thermal conductivity of the material, which restricts heat transfer away from the cutting zone. Moreover, the use of large volumes of cutting fluids raises environmental, economic, and health concerns, prompting a shift toward more sustainable alternatives. As a result, recent studies have increasingly focused on dry machining, minimum quantity lubrication (MQL), cryogenic cooling, and hybrid approaches as viable solutions (Pervaiz et al., 2021; Dhar et al., 2023). A comparison of different cooling strategies is shown in Fig. 3.



*Figure 3. Comparison of cooling and lubrication strategies in titanium machining: (a) Dry cutting; (b) Minimum quantity lubrication (MQL); (c) Cryogenic cooling; (d) Hybrid cooling/lubrication. Adapted from Dhar et al. [9] and Zhang et al. [8].*

Dry machining represents the most environmentally friendly approach, as it eliminates the use of cutting fluids altogether. However, in the context of titanium alloys, dry cutting is generally associated with excessively high cutting temperatures and rapid tool wear. The absence of lubrication increases friction at the tool–chip interface, exacerbating adhesive wear and promoting built-up edge formation. Consequently, dry machining is typically unsuitable for titanium alloys unless combined with advanced tool coatings or assisted machining techniques that can compensate for the lack of cooling (Sun et al., 2020).

Minimum quantity lubrication (MQL) has emerged as a promising alternative that balances performance and sustainability. In MQL, a small amount of lubricant is delivered in the form of an aerosol directly to the cutting zone, providing both lubrication and limited cooling. The primary advantage of MQL lies in its ability to reduce friction at the tool–chip interface, thereby lowering cutting forces and mitigating adhesive wear. Recent studies have demonstrated that MQL can significantly improve tool life and surface finish compared to dry machining, while drastically reducing fluid consumption (Pervaiz et al., 2021). However, the cooling capacity of MQL is relatively limited, which may restrict its effectiveness under high-speed or high-temperature conditions.

To address the limitations of conventional lubrication techniques, cryogenic cooling has gained considerable attention in recent years. Cryogenic machining typically employs liquid nitrogen (LN<sub>2</sub>) or carbon dioxide (CO<sub>2</sub>) to rapidly extract heat from the cutting zone. This approach is particularly effective in titanium machining, where temperature control is critical for reducing tool wear. By lowering the cutting temperature,

cryogenic cooling suppresses diffusion wear and oxidation, thereby extending tool life. Additionally, reduced thermal softening of the tool material helps maintain its mechanical integrity during cutting (Shokrani et al., 2020). Nevertheless, cryogenic cooling also presents certain challenges. Excessive cooling can increase the brittleness of the cutting tool, making it more susceptible to chipping, particularly under interrupted cutting conditions. Furthermore, the infrastructure and cost associated with cryogenic systems may limit their widespread industrial adoption.

In recent years, hybrid cooling and lubrication strategies have emerged as a highly effective approach to overcoming the limitations of individual techniques. By combining the advantages of MQL and cryogenic cooling, hybrid systems aim to provide both efficient lubrication and enhanced heat dissipation. For example, the integration of nano-fluid MQL with cryogenic cooling has been shown to significantly improve heat transfer and reduce friction simultaneously. Nanoparticles such as Al<sub>2</sub>O<sub>3</sub>, MoS<sub>2</sub>, and graphene are commonly used to enhance the thermal conductivity and tribological properties of the lubricant. These hybrid approaches have demonstrated superior performance in terms of tool life, cutting force reduction, and surface quality compared to standalone methods (Zhang et al., 2023; Dhar et al., 2023).

Another important development in this area is the application of high-pressure coolant (HPC) systems. High-pressure coolant delivery improves penetration into the tool–chip interface, facilitating chip breakage and enhancing heat removal. In titanium machining, HPC has been shown to reduce tool wear and improve chip evacuation, particularly at high cutting speeds. However, similar to flood cooling, HPC systems involve high fluid consumption and associated environmental concerns, which has led to ongoing research into more sustainable alternatives.

The effectiveness of cooling and lubrication strategies is also closely linked to tool wear mechanisms. For instance, MQL primarily mitigates adhesive wear by reducing friction, whereas cryogenic cooling is more effective in suppressing diffusion wear by lowering temperature. Hybrid approaches can address multiple wear mechanisms simultaneously, offering a more comprehensive solution. This multi-mechanism perspective has become increasingly important in recent studies, which emphasize the need to tailor cooling strategies based on specific machining conditions and desired performance outcomes.

In addition to improving tool life, cooling strategies have a significant impact on surface integrity. Lower cutting temperatures generally result in reduced thermal damage, improved surface roughness, and favorable residual stress profiles. Cryogenic machining, in particular, has been associated with the generation of compressive residual stresses, which enhance fatigue performance. On the other hand, inadequate cooling can lead to tensile residual stresses and surface defects, which are detrimental to component performance.

Despite the progress achieved in recent years, several challenges remain in optimizing cooling and lubrication strategies for titanium machining. One key issue is the lack of a unified framework for selecting the most appropriate cooling method under varying machining conditions. The performance of different techniques depends on multiple factors, including cutting speed, feed rate, tool material, and workpiece microstructure. Furthermore, the interaction between cooling strategies and advanced machining techniques, such as ultrasonic vibration-assisted turning, is not yet fully understood. These complexities highlight the need for integrated experimental and modeling approaches to develop more robust and adaptable cooling solutions.

Overall, recent research (2020–2025) demonstrates that cooling and lubrication strategies are critical enablers for improving the machinability of titanium alloys. While MQL and cryogenic cooling have shown significant potential, hybrid approaches appear to offer the most promising pathway for achieving optimal performance. Future developments are expected to focus on intelligent and adaptive cooling systems that can dynamically respond to changing machining conditions, thereby enhancing efficiency, sustainability, and process reliability.

## **V. SURFACE INTEGRITY IN TURNING OF TITANIUM ALLOYS**

Surface integrity is a critical performance indicator in the machining of titanium alloys, particularly in high-value applications such as aerospace and biomedical components, where fatigue life, corrosion resistance, and structural reliability are strongly dependent on surface and subsurface conditions. Unlike conventional materials, titanium alloys exhibit complex surface integrity characteristics due to their unique thermo-mechanical behavior during machining. Recent studies have emphasized that surface integrity in titanium machining is governed by a combination of surface roughness, residual stresses, microhardness, and subsurface microstructural alterations, all of which are highly sensitive to cutting conditions and tool–workpiece interactions (Wu et al., 2025; Umbrello et al., 2021).

Surface roughness is one of the most widely investigated parameters, as it directly influences friction, wear, and fatigue performance. In turning operations, surface roughness is primarily affected by feed rate, tool geometry, and process stability. However, in titanium machining, additional factors such as tool wear and built-up edge formation play a dominant role. The instability of the tool–chip interface, caused by adhesion and segmented chip formation, leads to irregular material flow and surface defects. Recent investigations have

demonstrated that advanced machining techniques, such as ultrasonic vibration-assisted turning, can significantly reduce surface roughness by stabilizing the cutting process and improving chip formation mechanisms (Li et al., 2022; Wang et al., 2025).

Residual stress is another fundamental aspect of surface integrity, with a direct impact on fatigue behavior. Machining-induced residual stresses result from the combined effects of mechanical deformation and thermal gradients in the cutting zone. In general, compressive residual stresses are beneficial, as they inhibit crack initiation and propagation, thereby enhancing fatigue life, whereas tensile residual stresses can accelerate crack growth and reduce component durability (Elsheikh et al., 2022). The nature and magnitude of residual stresses are strongly influenced by machining parameters and cooling strategies. High cutting temperatures are often associated with tensile residual stresses near the surface, while controlled cooling conditions, such as cryogenic machining, promote compressive stress formation (Shokrani et al., 2020; Wang et al., 2023).

Microhardness and subsurface deformation further contribute to the overall surface integrity of titanium components. During machining, severe plastic deformation occurs beneath the machined surface, resulting in a work-hardened layer. The thickness and characteristics of this layer depend on cutting conditions, tool wear, and thermal effects. In titanium alloys, moderate work hardening can improve wear resistance, but excessive deformation may lead to embrittlement and reduced fatigue performance. Recent studies have shown that advanced surface modification processes, such as ultrasonic surface rolling, can significantly enhance surface hardness and induce deeper compressive stress layers, thereby improving fatigue life (Zhu et al., 2023).

Microstructural alterations are also commonly observed in titanium machining due to the combined effects of high temperature and severe deformation. These alterations may include grain refinement, phase transformation, and the formation of so-called “white layers,” which are characterized by high hardness and brittleness. The formation of such layers is strongly dependent on cutting temperature and tool wear conditions. It has been reported that excessive thermal loading can lead to the development of thermally affected layers, which negatively impact mechanical performance and reliability (Wu et al., 2025). In contrast, controlled machining environments, particularly those employing cryogenic cooling, can suppress undesirable microstructural changes and maintain subsurface integrity (Shokrani et al., 2020).

The relationship between surface integrity and fatigue performance has been a major focus of recent research. Titanium components are frequently subjected to cyclic loading, making fatigue resistance a critical design consideration. Surface roughness, residual stress, and microstructural defects collectively influence crack initiation and propagation. Compressive residual stresses and smooth surface finishes have been shown to significantly extend fatigue life, whereas tensile stresses and surface irregularities act as stress concentrators that accelerate failure (Lai et al., 2023; Wang et al., 2023). Moreover, recent studies suggest that the combined effect of multiple surface integrity parameters should be considered rather than evaluating them independently, as their interactions can produce synergistic or antagonistic effects on fatigue behavior (Lai et al., 2023).

Another important aspect is the influence of machining-induced residual stresses on dimensional accuracy and structural stability. In thin-walled titanium components, residual stress redistribution can lead to distortion and deformation after machining. This issue is particularly critical in aerospace applications, where tight dimensional tolerances are required. Recent investigations have highlighted the need for precise control of residual stress distribution to minimize distortion and ensure component reliability (Xue et al., 2025).

Despite significant progress in understanding surface integrity, several challenges remain. Conflicting results have been reported regarding the influence of cutting parameters and cooling strategies on residual stress and microstructural evolution. These discrepancies are often attributed to differences in experimental setups, tool materials, and measurement techniques. Furthermore, the machining of additively manufactured titanium alloys introduces additional complexity due to anisotropy and microstructural heterogeneity, which can significantly affect surface integrity outcomes (Singh et al., 2024).

Overall, recent research (2020–2025) indicates that surface integrity in titanium turning is governed by a complex interaction of thermal, mechanical, and metallurgical factors. Achieving optimal surface integrity requires an integrated approach that combines appropriate tool materials, optimized cutting parameters, and advanced cooling strategies. Future research is expected to focus on predictive modeling and real-time monitoring of surface integrity, enabling intelligent machining systems capable of controlling surface quality and enhancing component performance.

## **VI. MODELING AND OPTIMIZATION IN TURNING OF TITANIUM ALLOYS**

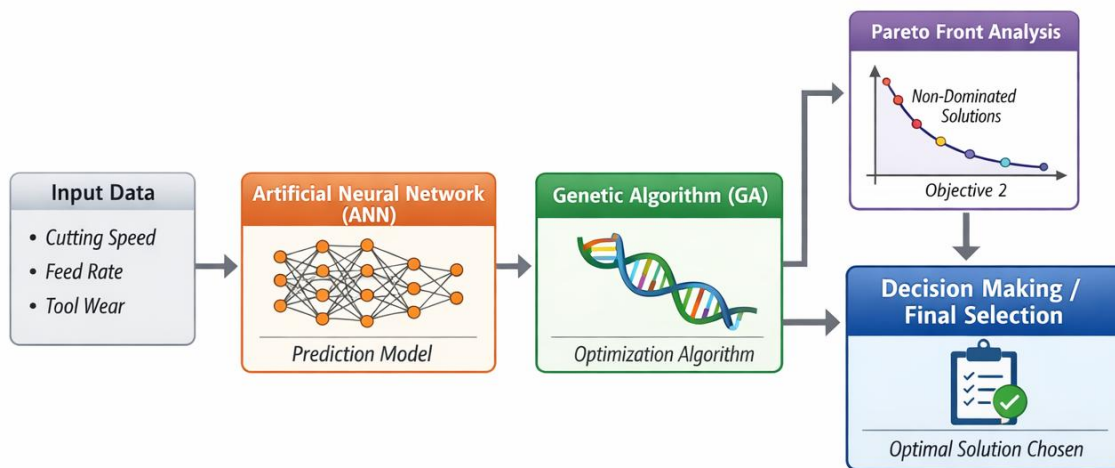
The increasing complexity of machining titanium alloys, driven by the interplay of thermal, mechanical, and tribological phenomena, has necessitated the development of advanced modeling and optimization approaches. In recent years (2020–2025), both physics-based and data-driven methods have been widely employed to predict machining responses and optimize process parameters. These approaches aim to simultaneously improve productivity, tool life, and surface integrity, which are often conflicting objectives in titanium turning.

Mechanistic and physics-based models have traditionally been used to describe cutting forces, temperature distribution, and tool wear. Finite element modeling (FEM), in particular, has been extensively applied to simulate chip formation, stress distribution, and thermal fields during machining. Such models provide valuable insights into the underlying mechanisms governing machinability, including shear localization and heat concentration (Umbrello et al., 2021). However, the accuracy of FEM models strongly depends on material constitutive laws and boundary conditions, which are often difficult to determine for titanium alloys, especially under high strain-rate and high-temperature conditions.

To overcome these limitations, data-driven approaches have gained significant attention. Artificial intelligence (AI) techniques, particularly artificial neural networks (ANN), have been widely used to model the nonlinear relationships between machining parameters and output responses such as surface roughness, cutting force, and tool wear. ANN models are capable of capturing complex interactions among variables and have demonstrated high prediction accuracy in titanium machining applications (Kumar et al., 2022). Nevertheless, their performance depends heavily on the quality and quantity of experimental data, and they often lack interpretability.

In parallel, optimization techniques such as genetic algorithms (GA) and non-dominated sorting genetic algorithms (NSGA-II) have been increasingly applied for multi-objective optimization. These methods enable the simultaneous optimization of multiple conflicting objectives, such as minimizing surface roughness and tool wear while maximizing material removal rate. Recent studies have shown that NSGA-II is particularly effective in generating Pareto-optimal solutions, allowing decision-makers to select optimal machining conditions based on specific requirements (Zhang et al., 2023).

A key trend in recent research is the integration of AI models with optimization algorithms to form hybrid intelligent systems. For example, ANN-GA or ANN-NSGA-II frameworks have been successfully employed to predict machining performance and optimize cutting parameters in a unified approach. These hybrid models leverage the predictive capability of AI and the global search efficiency of evolutionary algorithms, resulting in improved optimization performance compared to standalone methods (Kumar et al., 2022). The general workflow of ANN-GA based multi-objective optimization, including prediction, Pareto front generation, and final decision-making, is illustrated in Fig. 4.



*Figure 4. ANN-GA based optimization framework for titanium turning, including prediction, multi-objective optimization, Pareto front generation, and final decision-making process. Adapted and modified from Kumar et al. [6] and Deb et al. [50].*

Another emerging concept is the application of digital twin technology in machining processes. Digital twins create a virtual representation of the physical machining system, enabling real-time monitoring, prediction, and control of machining performance. By integrating sensor data with predictive models, digital twin systems can dynamically adjust cutting parameters to maintain optimal machining conditions. Although still in its early stages, this approach has significant potential for improving process reliability and enabling intelligent manufacturing in titanium machining.

Despite these advancements, several challenges remain. One major limitation is the lack of generalized models that can accurately predict machining responses across a wide range of cutting conditions and material states. In particular, the machining of additively manufactured titanium alloys introduces additional complexities, such as anisotropy and microstructural heterogeneity, which are difficult to incorporate into existing models

(Singh et al., 2024). Furthermore, the integration of modeling and optimization with real-time process control remains an open research area.

Overall, recent developments indicate that modeling and optimization are essential tools for addressing the challenges of titanium machining. Future research is expected to focus on the integration of physics-based and data-driven approaches, as well as the development of intelligent systems capable of adaptive and real-time optimization.

## **VII. Discussion and Future Perspectives**

The machining of titanium alloys has been extensively studied over the past decades, with significant advancements achieved in tool materials, cooling strategies, and assisted machining techniques. However, despite these developments, titanium alloys remain challenging to machine due to the inherent coupling of thermal, mechanical, and chemical effects. A critical analysis of recent literature (2020–2025) reveals several key insights, contradictions, and research gaps that must be addressed to further improve machining performance.

One of the most important observations is the trade-off between cutting temperature and tool wear. High cutting speeds can reduce cutting forces through thermal softening but simultaneously increase cutting temperature, leading to accelerated tool wear. Similarly, while cryogenic cooling effectively reduces temperature and diffusion wear, it may increase tool brittleness and susceptibility to chipping under certain conditions (Shokrani et al., 2020). These conflicting effects highlight the need for balanced and application-specific machining strategies.

A comparison of different cooling and lubrication techniques reveals that no single method can simultaneously optimize all performance metrics. MQL is effective in reducing friction and improving surface finish but has limited cooling capacity. Cryogenic cooling provides excellent temperature control but may introduce thermal shock issues. Hybrid approaches, which combine the advantages of multiple techniques, have shown the most promising results in recent studies (Dhar et al., 2023; Zhang et al., 2023). However, the mechanisms underlying these hybrid processes are not yet fully understood, and their optimization remains a significant challenge.

Similarly, advanced machining techniques such as ultrasonic vibration-assisted turning (UVAT) and laser-assisted machining have demonstrated clear benefits in reducing cutting forces and improving surface quality. Nevertheless, their effectiveness is highly dependent on process parameters and operating conditions. For example, while UVAT reduces tool–chip contact time and improves chip breakability, its influence on tool wear and surface integrity can vary depending on vibration amplitude and frequency (Li et al., 2022). This variability underscores the need for systematic studies that consider the interactions between machining techniques and process parameters.

Another important issue is the increasing relevance of additively manufactured titanium alloys. While AM technologies enable the production of complex geometries, they introduce new challenges in machining due to anisotropic microstructures, residual stresses, and porosity. Recent studies have reported inconsistent machinability results for AM titanium alloys, indicating that existing machining models and strategies may not be directly applicable to these materials (Singh et al., 2024). This highlights a critical research gap in understanding the relationship between microstructure and machinability in AM components.

From a modeling perspective, although AI-based approaches have shown significant potential, their application is still limited by the availability of high-quality experimental data and the lack of interpretability. Moreover, most existing studies focus on optimizing individual machining responses rather than considering the combined effects of multiple factors, such as tool wear, surface integrity, and energy consumption. This limitation suggests the need for more comprehensive and integrated optimization frameworks.

Based on the above analysis, several future research directions can be identified. First, there is a need for the development of unified models that can capture the complex interactions among thermal, mechanical, and chemical phenomena in titanium machining. Second, hybrid machining techniques should be further explored to fully exploit their potential advantages, particularly through the integration of cooling, lubrication, and assisted machining methods. Third, the machining of additively manufactured titanium alloys requires dedicated research to establish robust process–structure–property relationships. Finally, the integration of digital twin technology and real-time monitoring systems represents a promising pathway toward intelligent and adaptive machining processes.

In conclusion, while significant progress has been made in understanding and improving the machinability of titanium alloys, achieving a balance between productivity, tool life, and surface integrity remains a major challenge. Addressing this challenge will require a multidisciplinary approach that combines advanced materials, innovative machining techniques, and intelligent optimization strategies

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