Precision Machining of Hard-to-Cut Materials: Current Status and Future Directions

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***Abstract*—Machining difficult materials like superalloys, ceramics, and composites is fundamental in industries where performance is paramount, such as the auto industry, aerospace, and medicine. These materials with relatively high strength, hardness, and high-temperature capabilities pose difficulties in machining, thus calling for improved precision machining technologies. This survey paper presents a detailed review of the current state of the art of precision machining of these difficult materials, along with advances observed in tools for cutting, machining techniques, and new technologies. They range from carbide, ceramics, super hard tools, and geometry of tools, and this topic also deals with tool coatings. The article also discusses specifics of the traditional and nontraditional machining processes: turning, milling, electrical discharge, and laser machining, as well as the relations between additive and hybrid manufacturing. The importance of new technologies or digital and intelligent manufacturing systems in enhancing the accuracy and productivity of machining is also illustrated. Furthermore, the paper also provides information on how digital and intelligent manufacturing technologies can enhance machining efficiency and accuracy. Moreover, future research will aim to minimize tool wear, enhance surface finish and integrity, and environmentally conscious machining. The paper concludes with a hopeful note on the potential of future research to revolutionize the precision machining industry, offering high performance and reliability in critical applications while maintaining a focus on sustainability.**

***Keywords*—Precision machining; hard-to-cut materials; cutting tools; machining processes; emerging technologies**

I. INTRODUCTION

A. Context

Nowadays, many industrial sectors require construction supplies characterized by superior mechanical and functional features [1]. Construction materials exhibit exceptional hardness, abrasion resistance, temperature-resistant strength, enhanced thermal conductivity, and oxidation and corrosion resistance and are indispensable in a variety of high-demand industries, including aerospace [2], biomedical [3], electronics, and automotive [4]. Despite these unique features, these materials are regarded as hard to cut because of their poor machinability [5].

Recent advancements in cutting tools, including carbide, ceramics, and super-hard tools, have significantly improved the machinability of hard-to-cut materials [6]. Innovative tool geometries and coatings have further enhanced machining performance. Moreover, conventional and non-conventional machining methods such as turning, milling, Electrical Discharge Machining (EDM), and laser machining are gaining attention for their role in addressing these challenges [7]. Integrating hybrid machining techniques, including additive manufacturing, has opened new avenues for achieving greater precision and customization in the machining process [8].

B. Challenges

There are several major problems associated with machining hard-to-cut components, including the high levels of machining forces [9], the high levels of vibrations encountered in machining systems [10], the concentration of heat, the rapid increase in machining temperature [11], rapid tool wear, and catastrophic tool failure [12], as well as frequent instability loss and significant deterioration of surface finishes [13].

Maintaining surface integrity while improving efficiency is a critical challenge that hinders the machining of hard-to-cut materials [14]. Moreover, with increasing demands for sustainable practices, addressing environmental concerns in machining processes remains largely underdeveloped [15]. Sustainable machining, aimed at reducing energy consumption, tool wear, and waste generation, is becoming increasingly essential, but solutions are still in the early stages of implementation [16].

C. Contribution

The primary aim of this paper is to deliver a thorough overview of current advances in precision machining of hard-to-cut steels, focusing on the challenges and innovations in cutting tools, machining processes, and new technologies. By analyzing recent advances in material compositions, coatings, and geometries, as well as both conventional and non-conventional machining techniques, this article aims to provide comprehensive insights into state-of-the-art methods and practices. In addition, an attempt is made to identify future research directions to address existing challenges such as tool wear, surface integrity, and sustainability. Ultimately, the goal is to support continuous improvement in machining efficiency, accuracy, and sustainability in industries that rely on these demanding materials.

The novelty of this study lies in its exploration of integrating digital and intelligent manufacturing technologies to improve machining efficiency and accuracy. By reviewing these advancements and suggesting future research avenues, the paper contributes to ongoing efforts to improve precision machining for high-demand applications across various industries.

II. CHARACTERISTICS OF HARD-TO-CUT MATERIALS

Materials with challenging machining characteristics possess exceptional mechanical and thermal properties, which make them indispensable for high-performance applications but also pose significant challenges during machining [17, 18]. As illustrated in Fig. 1, materials like ceramics, nickel-based superalloys, titanium alloys, and composites exhibit varying degrees of hardness, strength, thermal resistance, and other critical properties that directly impact their machinability. These inherent properties lead to issues like rapid tool wear, high cutting forces, and poor machinability, which compares key challenges across materials. Consequently, machining these materials requires specialized cutting tools and advanced techniques tailored to their specific characteristics [19]. Understanding these unique properties, as detailed in Table I, is essential for developing effective machining strategies that ensure precision, efficiency, and the desired surface quality of manufactured components.

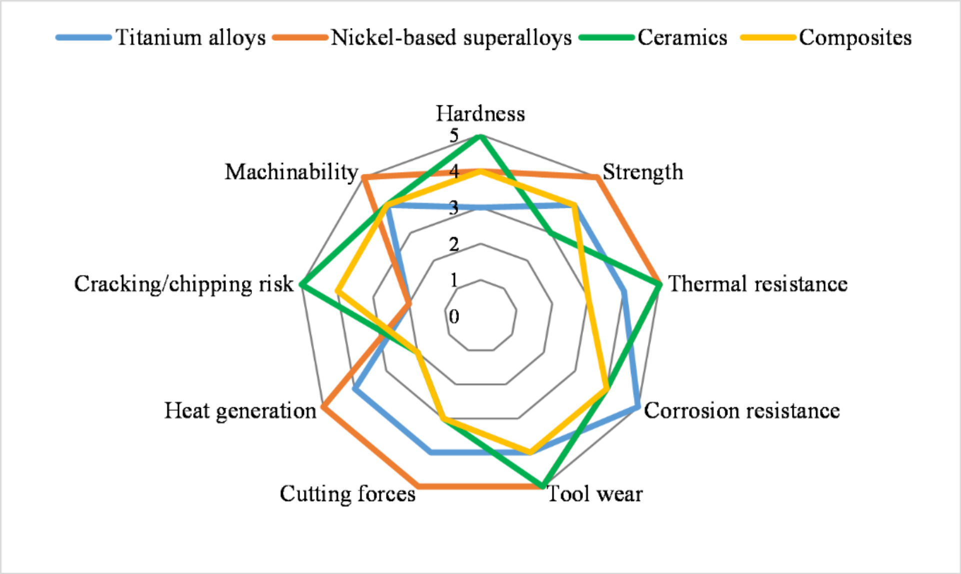

Fig. 1. Key properties and machining challenges of hard-to-cut components.

TABLE I. COMPARATIVE CHARACTERISTICS AND MACHINING CHALLENGES OF HARD-TO-CUT MATERIALS

Materials	Properties				Challenges					Relevant industries			
	High hardness	High strength	Thermal resistance	Corrosion resistance	Rapid tool wear	High cutting forces	Heat generation	Risk of cracking/chipping	Poor machinability	Aerospace	Automotive	Biomedical	Power Generation
Titanium alloys	Medium	High	High	Very high	High	High	High	Low	High	✓	✓	✓	
Nickel-based superalloys	High	Very high	Very high	High	High	Very high	Very high	Low	Very high	✓	✓		✓
Ceramics	Very high	Medium	Very high	High	Very high	Medium	Low	Very high	High	✓	✓	✓	
Composites	High	High	Medium	High	High	Medium	Low	High	High	✓	✓	✓	

A. *Titanium Alloys*

Titanium alloys, known for their outstanding biocompatibility, corrosion resistance, and strength-to-weight percentage, have become essential in aerospace, biomedical, and chemical processing [20]. Despite these advantages, machining titanium alloys presents significant challenges with cutting tools, given their strong chemical reactivity and limited thermal conductivity. These properties result in heat concentration in cutting areas, causing rapid tool wear and possible workpiece damage.

In addition, the high strength of titanium alloys increases cutting forces, further exacerbating tool wear and shortening tool life [21]. To mitigate these problems, various strategies are used, such as using advanced tool materials such as cemented carbide and ceramics, high-pressure cooling systems, and optimizing cutting parameters. Innovations in tool coatings such as Titanium Aluminum Nitride (TiAlN) have also shown promise in improving tool performance and longevity. Understanding the machinability characteristics of titanium alloys is critical to developing efficient and precise machining procedures that satisfy the rigorous demands of high-performance applications [22].

B. *Nickel-based Superalloys*

Nickel-based superalloys like Hastelloy and Inconel are important materials for high-temperature and high-voltage uses, especially in the aerospace and power generation fields [23]. These alloys are valued for their superior mechanical characteristics under high temperatures, including their strength, stability, and resistance to corrosion. However, due to several factors, such materials are notoriously hard to machine. Nickel-based superalloys' thermal strength and work-hardening properties result in significant cutting forces and rapid tool wear.

Moreover, their poor thermal conductivity results in heat accumulating in cutting zones, increasing tool wear and potentially compromising the workpiece's surface integrity. Advanced machining techniques, such as super-hard cutting tools (e.g., cubic boron nitride), optimized cutting parameters, and high-pressure coolant systems, are essential to addressing these challenges. Coatings such as TiAlN and AlCrN on carbide tools can improve tool life and performance [24]. Understanding machinability issues and implementing effective machining strategies are critical to successfully manufacturing nickel-based superalloy components, ensuring reliability and performance in demanding applications.

C. *Ceramics*

Ceramics, such as cutting tools, medical devices, and aerospace components, are commonly employed in products with high hardness, wear resistance, and thermal stability. Their exceptional properties are ideal for high-stress, high-temperature environments [25]. However, ceramics are also extremely brittle and have low fracture toughness, which makes them difficult to process. The brittleness of ceramic causes cracking and chipping to occur during processing, which can significantly affect the final product's surface quality and dimensional accuracy.

Conventional machining methods often produce inadequate material removal and excessive tool wear coefficients. Advanced techniques like Laser-Assisted Machining (LAM), EDM, and Ultrasonic Machining (USM) are increasingly adopted to address these challenges. These methods help reduce cutting forces, increase material removal rates, and improve surface finish. Additionally, innovations in diamond-coated tools and fine-grain ceramic tool materials have shown promise in improving the machinability of ceramics. Understanding ceramics' unique properties and machining challenges is critical to developing effective machining strategies that ensure ceramic components' high precision and reliability.

D. *Composites*

Composites like Glass Fiber-Reinforced Polymers (GRP) and Carbon Fiber-Reinforced Polymers (CFRP) offer many advantages in the automotive, aerospace, and sports equipment fields for their excellent strength-to-weight balance, corrosion resistance, and adaptable properties [26]. Despite these advantages, machining composite materials presents significant challenges due to their heterogeneous and anisotropic nature. The different material properties within the composite structure lead to different wear on the cutting tools and cause problems, including matrix cracking, fiber pull-out, and delamination.

Conventional machining techniques often struggle to maintain the integrity of the fibers and the matrix, resulting in less accurate dimensional measurements and inferior surface finishes [27]. To mitigate these problems, advanced machining strategies like Abrasive Water Jet Machining (AWJM), laser machining, and ultrasonic-assisted machining are used. These methods provide greater control over the machining process, reducing damage and improving surface quality. In addition, developing special cutting tools with optimized geometries and coatings has improved the machinability of composite materials. Understanding the specific machining challenges and developing tailored strategies are critical to effectively and precisely manufacturing composite components, ensuring their performance and longevity in demanding applications.

III. ADVANCES IN CUTTING TOOLS

Cutting tools have made significant progress, driven by the need to boost the machinability of hard-to-cut components. Modern cutting tools are designed to withstand extreme conditions when machining superalloys, ceramics, and composites. As detailed in Table II, tool materials, geometries, and coatings innovations have greatly improved tool efficiency, extended tool lifespan, and machining efficiency. The application of super-hard materials, including Cubic Boron Nitride (CBN) and Polycrystalline Diamond (PCD), as well as advanced coatings like Diamond-Like Carbon (DLC) and TiAlN, has resulted in better wear resistance and heat dissipation. Additionally, optimized tool geometries, including micro-textured surfaces and variable helix designs, have contributed to reduced cutting forces and improved chip evacuation. These advances are critical to overcoming hard-to-cut material challenges and enabling high-precision, high-efficiency machining processes.

A. *Tool Materials*

Carbide tools, ceramic tools, PCD, and CBN are among the most advanced materials used in cutting tools, thanks to their exceptional hardness, thermal stability, and wear resistance. As detailed in Fig. 2, these materials exhibit distinct features that make them useful for different machining applications. Understanding their comparative performance is essential for selecting the appropriate tool for specific machining tasks.

1) Carbide tools: Carbide tools are commonly used when cutting hard-to-cut materials for their extreme hardness, toughness, and wear resistance. Composed primarily of tungsten carbide particles bonded to a metallic cobalt matrix, these tools are designed to keep their cutting-edge and functional integrity even in extreme situations. Carbide tools are particularly effective in high-speed machining operations where they can withstand the heat generated without losing their hardness.

TABLE II. ADVANCES IN CUTTING TOOLS

Aspect	Description	Examples	Benefits
Carbide tools	Commonly used for their hardness, toughness, and wear resistance.	Coatings: TiAlN, TiCN, DLC. Improvements: Ultra-fine carbides, special bonding phases.	High-speed machining capabilities, reduced friction, improved thermal stability, and extended tool life.
Ceramic tools	Known for superior hardness, high-temperature stability, and resistance to wear and chemical erosion.	Materials: Si3N4, Al2O3, SiC. Innovations: Whisker-reinforced ceramics, fine-grained ceramics.	Maintains hardness at high temperatures, is suitable for high-speed machining, reduces the likelihood of thermal damage, and is excellent for interrupted cutting.
PCD tools	Polycrystalline diamond tools are ideal for non-ferrous metals, composites, and abrasive materials.	High hardness and thermal conductivity are excellent for surface finish and unsuitable for ferrous materials.	Longer tool life, higher cutting speeds, improved productivity, minimal delamination, and fiber pull-out in composites.
CBN tools	Cubic boron nitride tools, designed for ferrous materials, have high thermal stability and wear resistance.	Effective for hardened steels, cast iron, and superalloys.	Higher cutting speeds, reduced cycle times, improved efficiency, excellent precision, and tool longevity in high-stress conditions.
Optimized rake angles	Improves chip formation, reduces cutting forces, and minimizes tool wear.	Positive rake angles for better shearing action.	Smoother cuts, better surface finishes, improved tool life, and reduced machining forces.
Variable helix angles	Reduces vibration and chatter during machining.	Varying helix angle along the cutting edge.	A more stable cutting process, better material removal rates, tool life, and surface quality are needed.
Micro-textured surfaces	Reduces friction and improves lubrication.	Microscopic patterns or textures on cutting surfaces.	Lower heat generation, higher machining efficiency, less tool wear, and better surface finishes.
Specialized edge preparations	Enhances durability and performance of cutting tools.	Techniques: Honing, chamfering.	Increased tool strength, resistance to chipping, reduced crack initiation, and improved reliability and performance for brittle materials.
Customized geometries	Tailored to specific applications for optimal performance.	Features: Complex groove designs, variable pitch, advanced chip breakers.	Enhanced performance, reduced tool wear, improved machining efficiency, and better suitability for specific material and process requirements.

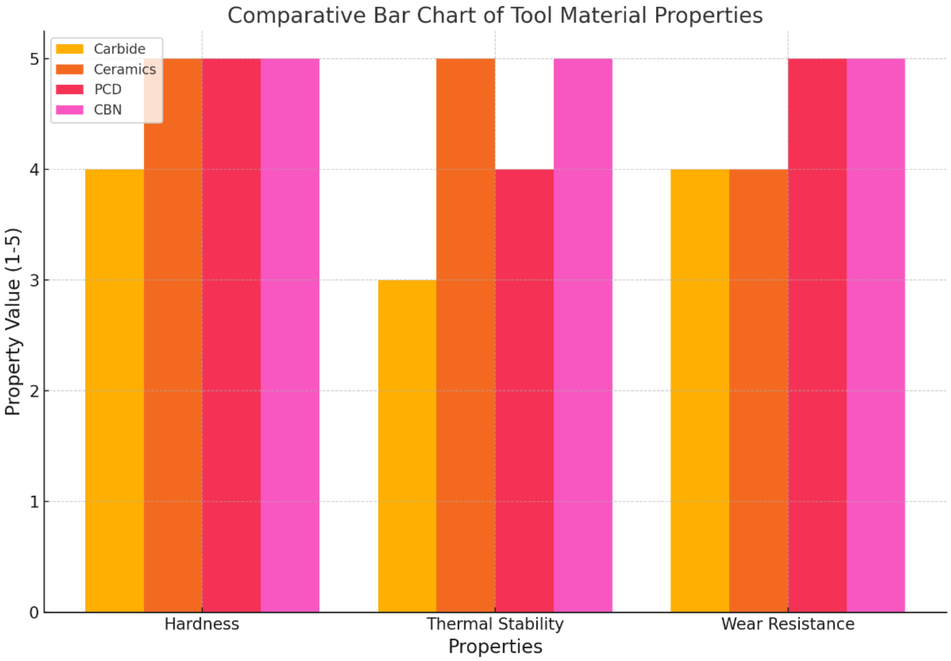

Fig. 2. Key properties of cutting tool materials.

The performance of carbide tools can be significantly enhanced by applying various coatings, improving wear resistance, thermal stability, and reducing friction. As illustrated in Fig. 3, different coatings like TiAlN, Titanium Carbonitride (TiCN), DLC, and AlCrN offer varying performance levels across these key metrics. Recognizing these variations is essential for choosing the most effective coating suited to the machining requirements.

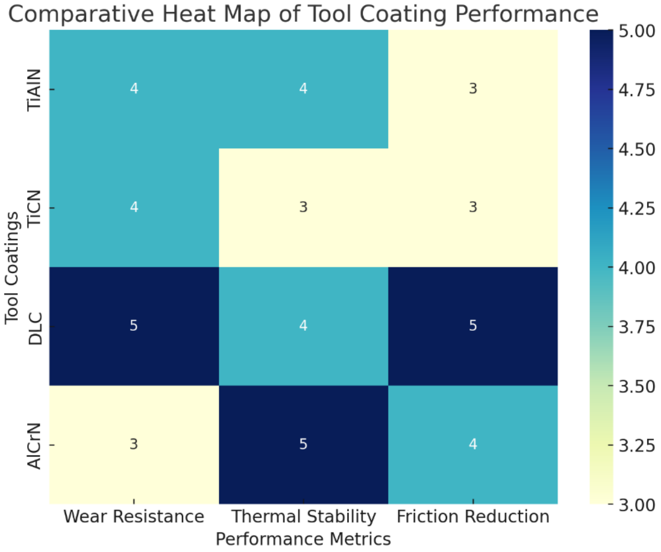

Fig. 3. Comparative heat map of tool coating performance.

Additionally, innovations in the microstructure and composition of cemented carbide tools have improved toughness and thermal cracking resistance. This includes the use of ultra-fine carbides that provide a balance between hardness and toughness and the incorporation of particular bonding phases to improve the overall performance of the tool.

2) Ceramic tools: Ceramic tools are highly effective at machining hard-to-cut items owing to their superior hardness, high-temperature stability, and wear and chemical erosion resistance. These tools are typically made of materials such as Silicon Carbide (SiC), Aluminum Oxide (Al2O3), and Silicon Nitride (Si3N4), which provide excellent mechanical properties even at elevated temperatures. This makes ceramic tools particularly suitable for high-speed machining applications where traditional tools may fail.

Ceramic tools can maintain hardness at temperatures that would soften other tool materials. This thermal stability enables higher cutting speeds and feeds, improving productivity while minimizing the thermal degradation of the workpiece. For example, silicon nitride-based ceramics are renowned for their toughness and resistance to thermal shock, enabling interrupted cutting operations.

Ceramic tools also benefit from advances in materials science, such as the development of whisker-reinforced ceramics. These materials contain silicon carbide whiskers in an aluminum oxide matrix, significantly improving fracture toughness and resistance to thermal shock. This makes them more robust under demanding machining conditions and extends their applicability to a wider range of hard-to-cut components.

However, ceramic tools' brittleness remains a challenge, as they are more prone to chipping and breaking under mechanical stress. To mitigate this, manufacturers have developed advanced tool geometries and surface treatments to improve the durability and performance of ceramic tools. For example, fine-grained ceramics and specially developed edge preparations help reduce the susceptibility to chipping.

3) Polycrystalline diamond and cubic boron nitride tools: PCD and CBN tools represent the pinnacle of cutting materials, distinguished by their exceptional hardness and wear resistance. These super-hard materials are specifically designed for the most demanding machining tasks with difficult-to-cut materials. PCD tools consist of fine diamond particles sintered in a metallic matrix under intense pressure and temperature. These tools have excellent thermal and hardness conductivity, providing excellent performance on non-ferrous metals, composites, and abrasive materials. The superior wear resistance of PCD tools enables longer tool life and higher cutting speeds, which translates into improved productivity and cost efficiency.

PCD tools are particularly effective in applications that require high surface quality, such as machining CFRP and aluminum alloys. Their ability to maintain sharp cutting edges ensures minimal delamination and fiber pull-out in composites while providing excellent surface finishes on metals. However, PCD tools are unsuitable for machining ferrous materials because chemical interactions at high temperatures lead to rapid tool wear. CBN tools are second only to diamonds in terms of hardness and are specifically designed for machining ferrous materials. CBN is synthesized by bonding cubic boron nitride grains with a ceramic or metallic binder. This creates a tool that can withstand extreme temperatures and maintain its cutting edge even under high-stress conditions.

CBN tools are particularly effective when machining hardened steels, cast iron, and superalloys. Their high thermal durability and abrasion resistance make them suitable for high-speed machining and finishing operations where precision and tool longevity are critical. CBN tools can operate at significantly higher cutting speeds than traditional carbide tools, reducing cycle times and improving overall efficiency. The development of advanced CBN grades and coatings has further enhanced their performance. These innovations have improved toughness and resistance to edge chipping, making CBN tools more versatile for a broader range of applications. In addition, new manufacturing techniques have enabled the production of CBN tools with complex geometries and expanded their applicability in precision machining.

B. *Tool Geometries*

Geometry affects the performance of cutting tools, particularly when dealing with hard-to-cut components. Advances in tool geometries have significantly improved cutting tool efficiency, precision, and life. Critical innovations in tool geometries include optimized rake angles, variable helix angles, and micro-textured surfaces designed to address specific machining challenges associated with difficult-to-machine materials. The rake angle of a cutting tool influences chip formation, cutting forces, and heat generation. Optimized rake angles diminish cutting forces and minimize tool wear. Positive rake angles can improve the shearing action on difficult-to-cut metals, resulting in smoother cuts and better surface finishes. However, when choosing the rake angle, the sharpness must be balanced with the tool's strength to avoid premature failure.

Variable helix angles are designed to reduce vibration and chatter during machining, which is common when machining hard materials. By varying the helix angle along the cutting edge, these tools can disrupt the harmonic frequencies that cause chatter, resulting in a more stable cutting process. This improves surface quality, prolongs tool life, and results in higher material removal. Micro-textured tool surfaces are another significant advance in tool geometry. These tools have microscopic patterns or textures on their cutting surfaces to reduce friction and improve lubrication. The microtextures can serve as a reservoir for cutting fluids or can be used to break contact between the tool and the workpiece, thereby reducing heat generation and wear. This technology is particularly beneficial for machining difficult-to-machine materials where high temperatures and friction are a significant problem.

Edge preparation techniques such as honing and chamfering improve the durability and performance of cutting tools. For example, ground edges can improve tool strength and resistance to chipping, while beveled edges help reduce the formation of cracks in brittle tool materials such as ceramics and CBN. These unique edge treatments are tailored to the specific requirements of machining difficult-to-machine materials and ensure excellent reliability and performance. In addition to general advances, there is a growing trend toward customizing tool geometries for particular applications. This involves developing tools with unique features, such as complex groove design, variable pitch, and advanced chip breakers tailored to the particular requirements of the machining material and the machining process. Custom geometries can significantly increase performance, reduce tool wear, and improve machining efficiency.

IV. MACHINING PROCESSES

Machining processes for hard-to-cut materials are constantly evolving to meet the unique challenges of these materials. Table III details that traditional machining methods, such as turning and milling, have been optimized with advanced techniques and technologies to increase their effectiveness. Non-conventional machining processes, including EDM, Laser Beam Machining (LBM), and USM, offer alternative approaches to achieving high precision and surface quality in these difficult-to-machine materials. Integration of these methods and innovations in machining strategies and process controls is essential to improving productivity, reducing tool wear, and ensuring the integrity of end components. This section covers conventional and non-conventional machining processes and highlights their applications, advantages, and advances.

The effectiveness of different machining processes in handling hard-to-cut materials varies significantly based on factors such as precision, surface finish, material removal rate, and tool wear. As shown in Fig. 4, conventional processes like turning and milling and non-conventional methods like EDM, LBM, and USM exhibit different strengths across these key metrics. Understanding these differences is crucial for selecting the appropriate machining process based on the specific material and application requirements.

TABLE III. MACHINING PROCESSES FOR HARD-TO-CUT MATERIALS

Process	Description	Advantages	Limitations	Key Applications
Turning	Rotates the workpiece against a stationary cutting tool to remove material.	High precision, well-established, suitable for a variety of materials	Rapid tool wear, high cutting forces, heat generation	Aerospace, automotive, and biomedical components
Milling	Uses a rotating cutting tool to remove material from a stationary workpiece, creating complex geometries.	Versatile, high precision, capable of intricate details	High cutting forces, tool wear, heat generation	Aerospace, automotive, mold making, complex part manufacturing
EDM	Uses electrical discharges to erode the material, which is ideal for complex shapes and hard materials.	Precise, capable of intricate shapes, no mechanical stress	Slow process, limited to conductive materials, electrode wear	Turbine blades, injection molds, precision surgical instruments
LBM	Uses a focused laser beam to remove material, suitable for precise and complex shapes.	High precision, non-contact process, minimal heat-affected zone	High initial investment, material-specific challenges, potential thermal effects	Aerospace components, medical devices, microelectronic components, automotive parts
USM	Uses high-frequency ultrasonic vibrations with abrasives to remove material, which is effective for hard and brittle materials.	Non-thermal process, minimal mechanical stress, high precision	Slow material removal rate, tool wear, complex setup	Hard ceramic components, composite materials, precision surgical instruments, microelectronic components

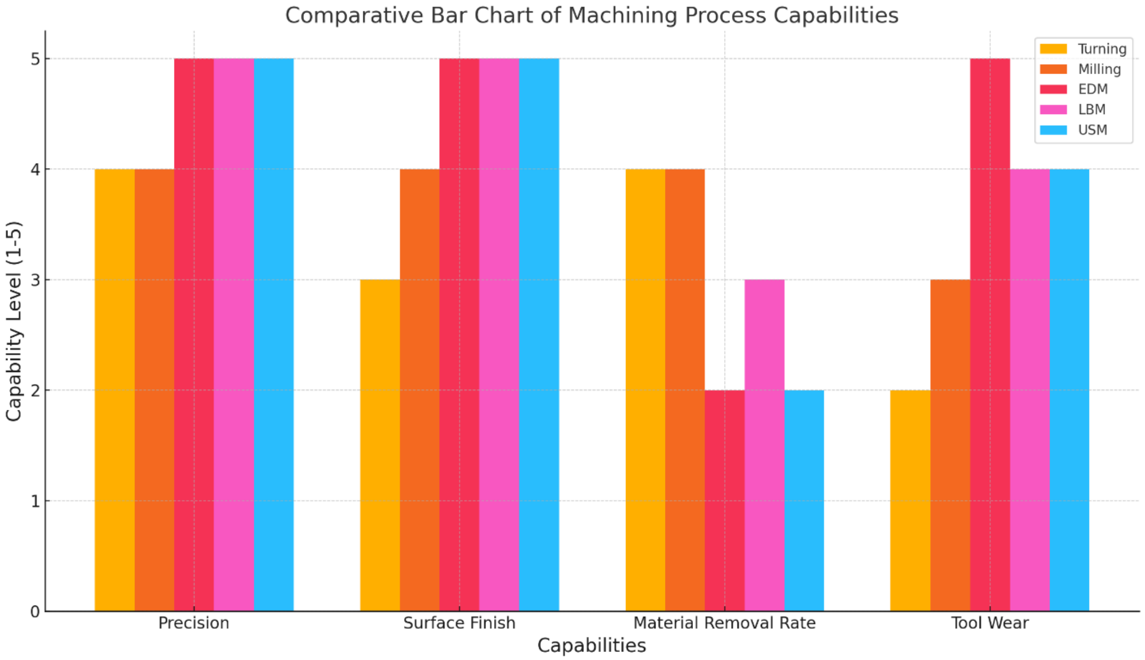

Fig. 4. Machining process capabilities.

A. *Conventional Machining*

1) Turning: Turning is a fundamental machining process often used to produce hard-to-cut materials. The workpiece is rotated against a stationary cutting tool, gradually removing material to achieve the desired shape and dimensions. While turning is a well-established process, machining difficult-to-machine materials such as titanium alloys, nickel-based superalloys, ceramics, and composites presents unique challenges that require specialized approaches and advanced technologies.

Turning hard-to-cut materials often leads to problems such as rapid tool wear, high cutting forces, and elevated temperatures in the cutting zone. These challenges can impact the surface finish, dimensional accuracy, and overall efficiency of the machining process. For example, the low thermal conductivity of titanium alloys causes heat to concentrate at the cutting edge, accelerating tool wear and potentially damaging the workpiece. Similarly, the work-hardening property of nickel-based superalloys increases cutting resistance, making it challenging to maintain tool sharpness and precision.

To overcome these challenges, using advanced tool materials and coatings is essential. Carbide tools with special coatings such as TiAlN and AlCrN offer improved wear resistance and thermal stability. Ceramic tools, known for their hardness and heat resistance, are also used for turning high-temperature materials. PCD and CBN tools are increasingly used due to their exceptional hardness and ability to maintain sharp edges, particularly in finishing operations.

Choosing the proper cutting parameters is crucial for successfully turning hard-to-cut materials. This includes optimizing cutting speed, feed rate, and depth of cut to balance tool life and machining efficiency. Lower cutting speeds are often used to reduce heat generation, while appropriate feed rates help control cutting forces and achieve a desired surface finish. High-pressure coolant systems effectively dissipate heat and lubricate the cutting zone, extending tool life and improving machining performance.

Innovative turning techniques such as multi-axis turning and high-speed turning have been developed to improve the performance and flexibility of the process. Multi-axis turning allows more complex geometries to be machined with greater precision and fewer setups. High-speed turning, made possible by advances in machine tool technology, helps reduce machining time and improve surface quality by operating at higher spindle speeds and feed rates. The integration of tool condition monitoring systems is becoming increasingly important. These systems use sensors and data analytics to monitor tool wear and predict failures, enabling timely tool changes and minimizing downtime. This real-time monitoring helps maintain consistent quality and improves overall process reliability.

2) Milling: Milling is a versatile machining process for shaping and contouring hard-to-cut materials. In milling, a rotating cutting tool removes material from a stationary workpiece, allowing the creation of complex geometries, slots, and intricate details. Despite its versatility, milling hard-to-cut materials such as titanium alloys, nickel-based superalloys, ceramics, and composites presents significant challenges due to their inherent properties.

Milling these materials requires high cutting forces, rapid tool wear, and significant heat generation. The brittleness of ceramics and composites further complicates the process and increases the risk of chipping and delamination. Materials such as titanium and nickel-based superalloys have low thermal conductivity, resulting in heat concentration at the cutting edge, increasing tool wear, and compromising surface integrity.

To overcome these challenges, advanced tool materials such as carbide, ceramic, PCD and CBN are used. Carbide tools with special coatings such as TiAlN and DLC increase wear resistance and reduce friction, improving tool life and performance. Ceramic tools are ideal for high-speed milling operations due to their high hardness and thermal stability. PCD and CBN tools offer excellent edge retention and are particularly suitable for finishing operations in hard and abrasive materials.

The selection of suitable milling parameters is crucial for the efficient machining of hard-to-cut materials. This includes optimizing spindle speed, feed rate, and cut depth to balance tool life and machining efficiency. High-speed milling techniques coupled with advanced toolpath strategies help reduce cycle times and improve surface quality. Adaptive control systems and real-time monitoring further improve process stability and tool performance.

Innovative techniques such as trochoidal and high-feed milling were developed to meet the specific challenges of hard-to-cut materials. Trochoidal milling is a circular tool path that shortens the time the tool engages with the material, minimizing heat generation and tool wear. In high-feed milling, however, shallow cutting depths are used with high feed rates, which distributes the cutting forces more evenly and extends tool life.

Adequate coolant and lubrication strategies are essential when milling hard-to-cut materials to regulate heat and reduce friction. High-pressure coolant systems, cryogenic cooling, and Minimum Quantity Lubrication (MQL) techniques improve heat dissipation, tool life, and better surface finishes. These cooling methods are particularly beneficial for maintaining the tool's and the workpiece's structural integrity.

Implementing tool condition monitoring systems in milling operations enables real-time tool wear and performance assessment. These systems can use sensors and data analysis to predict failures and optimize tool change intervals, minimizing downtime and ensuring consistent machining quality. This proactive approach increases overall process reliability and efficiency.

B. Non-Conventional Machining

1) Electrical discharge machining: EDM is an unconventional process that has become an important method for machining hard-to-cut materials. EDM uses electrical discharges or sparks to remove material from the workpiece. This enables precise machining of complex geometries and hard materials that are difficult to machine using traditional methods. This process is particularly effective for hardened steels, superalloys, and conductive ceramics.

EDM works on the principle of spark erosion. The workpiece and electrode are immersed in a dielectric fluid, usually deionized water or oil. When a voltage is applied, a spark discharge occurs in the small gap between the electrode and the workpiece, generating intense heat (up to 12,000 °C) that melts and vaporizes a small portion of the workpiece material. The dielectric fluid cools and washes away the eroded particles, providing a clean machining environment.

There are two main types of EDM: wire EDM and die-sinking EDM. Wire EDM uses a thin, electrically conductive wire as an electrode to cut through the workpiece, making it ideal for producing intricate shapes and fine details. Die-sinking EDM, on the other hand, uses a pre-formed electrode to create cavities and complex contours in the workpiece, and it is commonly used in mold and die-making.

EDM offers several advantages when machining hard-to-cut materials. It can produce complicated shapes and high-precision components with excellent surface finish, regardless of the material's hardness. The absence of mechanical forces during machining eliminates problems related to tool wear and deformation common in traditional machining processes. EDM is also suitable for processing heat-treated materials without causing thermal deformation or internal stresses.

Despite its advantages, EDM has certain limitations. The process is relatively slow compared to traditional machining methods and is less suitable for mass production. In addition, EDM is limited to electrically conductive materials, which limits its scope. Electrode wear can also be a problem and requires frequent replacement and careful selection of electrode materials.

Recent advances in EDM technology focus on improving process efficiency, precision, and surface quality. Innovations such as high-speed EDM, multi-axis EDM, and adaptive control systems have improved the capabilities of EDM. High-speed EDM machines utilize advanced power and control systems to increase material removal rates and reduce machining time. Multi-axis EDM enables more complex geometries and greater accuracy by allowing simultaneous movements along multiple axes. Adaptive control systems optimize machining parameters in real time, improving process stability and tool life.

EDM is widely used in the aerospace, automotive, medical, and tool and mold industries. It is particularly valuable for producing components with complicated geometries, fine features, and high surface quality requirements. Typical applications include turbine blades, injection molds, and precision surgical instruments, whereas traditional machining methods are inadequate in accuracy and material integrity.

2) Laser beam machining: LBM is a high-precision, non-conventional machining process that uses a focused laser beam to remove material from the workpiece. This process is particularly effective for machining hard-to-cut materials such as ceramics, superalloys, and composites, which are challenging to machine using traditional methods. LBM offers significant advantages in precision, flexibility, and the ability to machine complex shapes without direct contact with the workpiece.

With LBM, a high-energy laser beam is directed onto the surface of the workpiece. The intense energy of the laser beam heats, melts, and vaporizes the material in the target area. The material removal process is highly localized, minimizing the Heat-Affected Zone (HAZ) and reducing the risk of thermal deformation. Different lasers, such as CO2, Nd, and fiber, are used depending on the material and specific application requirements. Laser beam processing offers several notable advantages:

- Precision and accuracy: LBM can produce extremely fine features and intricate geometries with high precision and repeatability.
- Non-contact process: The lack of physical contact between the tool and the workpiece eliminates mechanical stresses and tool wear, enhancing the machining of brittle and hard materials.
- Minimal heat-affected zone: The localized nature of the laser beam minimizes thermal damage to surrounding material, maintaining the integrity and properties of the workpiece.
- Versatility: LBM can machine a wide range of materials, including metals, ceramics, polymers, and composites, making it suitable for various industrial applications.
- Despite its advantages, LBM also has some limitations:
- High initial investment: The cost of laser machining equipment can be significant, making it a considerable investment for manufacturers.
- Material-specific challenges: Different materials absorb laser energy differently, which can affect the efficiency and quality of the machining process. Optimizing parameters for each material is crucial.
- Thermal effects: Although minimal, there is still a risk of thermal effects such as micro-cracking or changes in material properties, particularly in sensitive materials.

Advances in laser technology have significantly improved the capabilities of LBM. High-power and ultra-short pulse lasers like femtosecond have improved material removal rates and machining precision. These lasers produce extremely short bursts of energy, minimizing heat diffusion and reducing the heat-affected zone. Beam delivery systems and control software advances have enabled more complex and precise machining operations. Due to its precision and versatility, LBM is widely used in various industries. Key applications include:

- Aerospace: Machining of turbine blades, intricate cooling channels, and other high-performance components made from superalloys and composites.
- Medical Devices: Manufacturing of precision surgical instruments, implants, and medical device components that require high accuracy and surface quality.
- Electronics: Fabrication of microelectronic components, Printed Circuit Boards (PCBs), and Micro-Electromechanical Systems (MEMS).
- Automotive: Production of precise components and tooling for high-performance engines and lightweight structures.

3) Ultrasonic machining: USM is an unconventional process that uses high-frequency ultrasonic vibrations to remove material from a workpiece. This technique is particularly effective for machining hard and brittle materials such as ceramics, glass, and advanced composites. USM offers significant advantages in precision, surface quality, and the ability to machine complicated shapes without substantial thermal or mechanical stress.

USM uses a tool vibrating at an ultrasonic frequency (typically 20 to 40 kHz) to strike abrasives onto the workpiece. The tool does not directly contact the workpiece but transfers energy through the abrasive particles suspended in the slurry. These particles act as cutting materials and erode the material from the workpiece through a combination of mechanical action and micro-chipping. The ultrasonic vibrations increase the effectiveness of the abrasive particles and lead to efficient material removal with minimal effort. USM offers several key advantages:

- Non-thermal process: USM does not generate significant heat during machining, eliminating thermal damage and preserving the workpiece's material properties.
- Minimal mechanical stress: The low amplitude vibrations used in USM induce minimal mechanical stress, reducing the risk of cracks and defects, especially in brittle materials.
- High precision and surface finish: USM can achieve high precision and excellent surface finishes, making it suitable for intricate and delicate components.
- Versatility: USM can machine various materials, including hard metals, ceramics, glass, and composites, offering broad applicability across different industries.

Despite its advantages, USM also faces some limitations:

- Slow material removal rate: Compared to other machining methods, USM has a relatively slow material removal rate, which can limit its application in high-volume production.
- Tool wear: The process's abrasive nature can lead to significant tool wear, necessitating frequent tool maintenance and replacement.

- Complex setup: The setup and maintenance of ultrasonic machining equipment require skilled operators and precise control systems.

Recent advances in ultrasonic machining have focused on improving process efficiency and expanding its applications. Innovations like multi-frequency ultrasound systems and hybrid machining processes have improved material removal rates and tool life. Hybrid processes that combine ultrasonic machining with other techniques, such as EDM or laser machining, leverage the strengths of both methods to achieve excellent results. Additionally, advancements in tool materials and abrasive slurries have improved performance and reduced wear. Due to its precision and ability to machine hard materials, ultrasonic machining is widely used in various industries. Key applications include:

- Aerospace: Machining of hard ceramic components, composite materials, and intricate features in high-performance parts.
- Medical devices: Manufacturing precision surgical instruments, dental tools, and medical implants that require high accuracy and smooth surfaces.
- Electronics: Fabrication of microelectronic components, optical devices, and advanced materials used in electronic packaging.
- Tool and die making: Production of complex molds, dies, and wear-resistant components from hard and brittle materials.

V. CONCLUSION

Precision machining of hard-to-cut materials remains a critical challenge and opportunity in modern manufacturing, driven by the need for high-performance components in the aerospace, automotive, biomedical, and electronics industries. This survey provided a comprehensive overview of the current state of precision machining techniques, focusing on conventional and non-conventional methods and highlighting advances in cutting tools, machining processes, and new technologies. Advances in cutting tool materials such as carbide, ceramic, PCD, and CBN have significantly improved the machinability of hard-to-cut materials by extending tool life, reducing wear, and enabling higher machining speeds. Innovative tool geometries and coatings also contribute to the efficiency and precision of the machining processes. Traditional machining methods, including turning and milling, have evolved with optimized cutting parameters, advanced cooling strategies, and real-time monitoring systems to meet the unique challenges of these materials. Meanwhile, unconventional machining techniques such as EDM, LBM, and USM offer alternative solutions for achieving high precision and complex geometries without causing thermal or mechanical damage.

Integrating digital technologies, including IoT, AI, and big data analytics, transforms precision machining and enables smarter, more efficient, and more adaptable manufacturing processes. These technologies improve process monitoring, predict tool wear, and optimize machining parameters in real time, improving productivity and quality. Future research and development should address the remaining challenges in precision machining, such as reducing tool wear, improving surface integrity, and developing more sustainable machining processes. Innovations in hybrid manufacturing processes and the continued development of digital and intelligent manufacturing technologies will play a critical role in overcoming these challenges and pushing the boundaries of what is possible when machining difficult-to-machine materials.

REFERENCES

[1] J. Ahmad and Z. Zhou, "Mechanical properties of natural as well as synthetic fiber reinforced concrete: a review," Construction and Building Materials, vol. 333, p. 127353, 2022.

[2] S. B. Nagaraju, H. Priya, Y. G. T. Girijappa, and M. Puttegowda, "Lightweight and sustainable materials for aerospace applications," in Lightweight and Sustainable Composite Materials: Elsevier, 2023, pp. 157-178.

[3] H. T. Mohan, K. Jayanarayanan, and K. Mini, "A sustainable approach for the utilization of PPE biomedical waste in the construction sector," Engineering Science and Technology, an International Journal, vol. 32, p. 101060, 2022.

[4] M. Vishnupriyan, R. Annadurai, K. C. Onyelowe, and N. Ganasen, "Review on electronic waste used as construction materials-a scientometric analysis," Cogent Engineering, vol. 10, no. 2, p. 2283307, 2023.

[5] O. Adekomaya and T. Majozi, "Sustainable reclamation of synthetic materials as automotive parts replacement: effects of environmental response on natural fiber vulnerabilities," Environmental Science and Pollution Research, vol. 31, no. 12, pp. 18396-18411, 2024.

[6] R. Bag, A. Panda, A. K. Sahoo, and R. Kumar, "Sustainable high-speed hard machining of AISI 4340 steel under dry environment," Arabian Journal for Science and Engineering, vol. 48, no. 3, pp. 3073-3096, 2023.

[7] D. L. Soni and V. S. N. Neigapula, "Tool surface texturing in machining performance: state of art and recent developments," International Journal on Interactive Design and Manufacturing (IJIDeM), pp. 1-29, 2024.

[8] C. Zhang, D. Zou, M. Mazur, J. P. Mo, G. Li, and S. Ding, "The state of the art in machining additively manufactured titanium alloy Ti-6Al-4V," Materials, vol. 16, no. 7, p. 2583, 2023.

[9] E. García-Martínez, A. Molina-Yagüe, V. Miguel, and A. Martínez-Martínez, "Harmonic-based-on analysis to discriminate different mechanical actions involved in the machining of hard-to-cut materials," The International Journal of Advanced Manufacturing Technology, pp. 1-15, 2024.

[10] G. Gao, Y. Wang, Z. Fu, C. Zhao, D. Xiang, and B. Zhao, "Review of multi-dimensional ultrasonic vibration machining for aeronautical hard-to-cut materials," The International Journal of Advanced Manufacturing Technology, vol. 124, no. 3, pp. 681-707, 2023.

[11] I. Sharmin, M. A. Gafur, and N. R. Dhar, "Preparation and evaluation of a stable CNT-water based nano cutting fluid for machining hard-to-cut material," SN Applied Sciences, vol. 2, pp. 1-18, 2020.

[12] R. Kang, H. Ma, Z. Wang, Z. Dong, and Y. Bao, "Effect of tool wear on machining quality in milling Cf/SiC composites with PCD tool," Journal of Manufacturing Processes, vol. 105, pp. 370-385, 2023.

[13] R. Binali, H. Demirpolat, M. Kuntoğlu, and H. Sağlam, "Machinability investigations based on tool wear, surface roughness, cutting temperature, chip morphology and material removal rate during dry and MQL-assisted milling of Nimax mold steel," Lubricants, vol. 11, no. 3, p. 101, 2023.

[14] R. A. Laghari, M. Jamil, A. A. Laghari, A. M. Khan, S. S. Akhtar, and S. Mekid, "A critical review on tool wear mechanism and surface integrity aspects of SiCp/Al MMCs during turning: prospects and challenges," The

International Journal of Advanced Manufacturing Technology, vol. 126, no. 7, pp. 2825-2862, 2023.

[15] M. E. Korkmaz, M. Gupta, N. S. Ross, and V. Sivalingam, "Implementation of green cooling/lubrication strategies in metal cutting industries: A state of the art towards sustainable future and challenges," Sustainable Materials and Technologies, vol. 36, p. e00641, 2023.

[16] S. K. Lodhi, I. Hussain, and A. Y. Gill, "Artificial Intelligence: Pioneering the Future of Sustainable Cutting Tools in Smart Manufacturing," BIN: Bulletin of Informatics, vol. 2, no. 1, pp. 147-162, 2024.

[17] H. Attia et al., "Physics based models for characterization of machining performance–A critical review," CIRP Journal of Manufacturing Science and Technology, vol. 51, pp. 161-189, 2024.

[18] S. Seyedi, B. Pourghebleh, and N. Jafari Navimipour, "A new coplanar design of a 4 - bit ripple carry adder based on quantum - dot cellular automata technology," IET Circuits, Devices & Systems, vol. 16, no. 1, pp. 64-70, 2022.

[19] M. U. Farooq, M. A. Ali, S. Anwar, and H. A. Bhatti, "Process parameters optimization and performance analysis of micro-complex geometry machining on Ti6Al4V," International Journal on Interactive Design and Manufacturing (IJIDeM), pp. 1-21, 2024.

[20] M. Hourmand, A. A. Sarhan, M. Sayuti, and M. Hamdi, "A comprehensive review on machining of titanium alloys," Arabian Journal for Science and Engineering, vol. 46, pp. 7087-7123, 2021.

[21] D. Y. Pimenov et al., "A comprehensive review of machinability of difficult-to-machine alloys with advanced lubricating and cooling techniques," Tribology International, p. 109677, 2024.

[22] S. T. Haider, M. A. Shah, D.-G. Lee, and S. Hur, "A review of the recent applications of aluminum nitride-based piezoelectric devices," Ieee Access, vol. 11, pp. 58779-58795, 2023.

[23] N. Rathi, P. Kumar, and A. Gupta, "Non-conventional machining of nickel based superalloys: A review," Materials Today: Proceedings, 2023.

[24] Q. He et al., "Enhancing Tool Performance in High-Speed End Milling of Ti-6Al-4V Alloy: The Role of AlCrN PVD Coatings and Resistance to Chipping Wear," Journal of Manufacturing and Materials Processing, vol. 8, no. 2, p. 68, 2024.

[25] M. Sarıkaya et al., "A state-of-the-art review on tool wear and surface integrity characteristics in machining of superalloys," CIRP Journal of Manufacturing Science and Technology, vol. 35, pp. 624-658, 2021.

[26] H. Youssef, H. El-Hofy, A. Abdelaziz, and M. El-Hofy, "Accuracy and surface quality of abrasive waterjet machined CFRP composites," Journal of Composite Materials, vol. 55, no. 12, pp. 1693-1703, 2021.

[27] S. S. Akhtar, "A critical review on self-lubricating ceramic-composite cutting tools," Ceramics International, vol. 47, no. 15, pp. 20745-20767, 2021.