# Challenges and Strategies in Machining of Continuous Fiber-Reinforced Metal Matrix Composites: From Conventional to Non-conventional Machining

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**Abstract:** Continuous fiber-reinforced metal matrix composites (CFMMCs) exhibit exceptional specific strength and high-temperature resistance, making them ideal for aerospace applications. However, their anisotropic and heterogeneous structure lead to severe machining challenges, including tool wear, fiber pull-out, and interfacial debonding. This review summarizes the current state of CFMMCs machining, emphasizing the role of energy field-assisted machining and their limitations. Conventional machining (CM) exhibits complex material removal mechanisms involving plastic deformation, brittle fracture, and interface failure. Ultrasonic vibration-assisted machining (UVAM) reduces cutting forces and residual stress through acoustic softening, while laser-assisted machining (LAM) induces fiber ductile transition and matrix softening. Femtosecond laser machining further enables high-precision, low-damage ablation. Despite these advances, research gaps remain regarding anisotropic effects, parameter coordination, and damage-service life relationships. The development of multi-energy field synergy, AI-based closed-loop control, and integrated additive-subtractive platforms is also analyzed. Finally, based on the current development status and the requirements of aerospace manufacturing, future trends in CFMMCs machining are proposed.

**Key words:** continuous fiber-reinforced metal matrix composites (CFMMCs); conventional machining (CM); energy field-assisted machining; AI-based closed-loop control

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## 0 Introduction

Continuous fiber-reinforced metal matrix composites (CFMMCs), typically composed of continuous fibers (e.g., silicon carbide, carbon) and metallic matrices (e.g., titanium alloys, magnesium alloys, and aluminum alloys), represent a class of high-performance materials. Owing to their excellent specific strength, high-temperature resistance, and superior fatigue performance, CFMMCs have become the material of choice for high-end aerospace components[1-4]. In recent years, numerous world-renowned enterprises and research institutions have extensively explored the application of CFMMCs in critical aerospace parts such as rotor/stator blades, blings, thin-walled structures, and rotating components (Fig.1)[5-8]. As a typical representative of advanced metal matrix composites (MMCs), CFMMCs exhibit pronounced anisotropy. By tailoring fiber orientation and ply stacking sequence, their mechanical properties can be optimized for specific loading conditions, enabling higher load-carrying capacity and meeting the stringent demands of complex service environments in aerospace and automotive industries[9-10].

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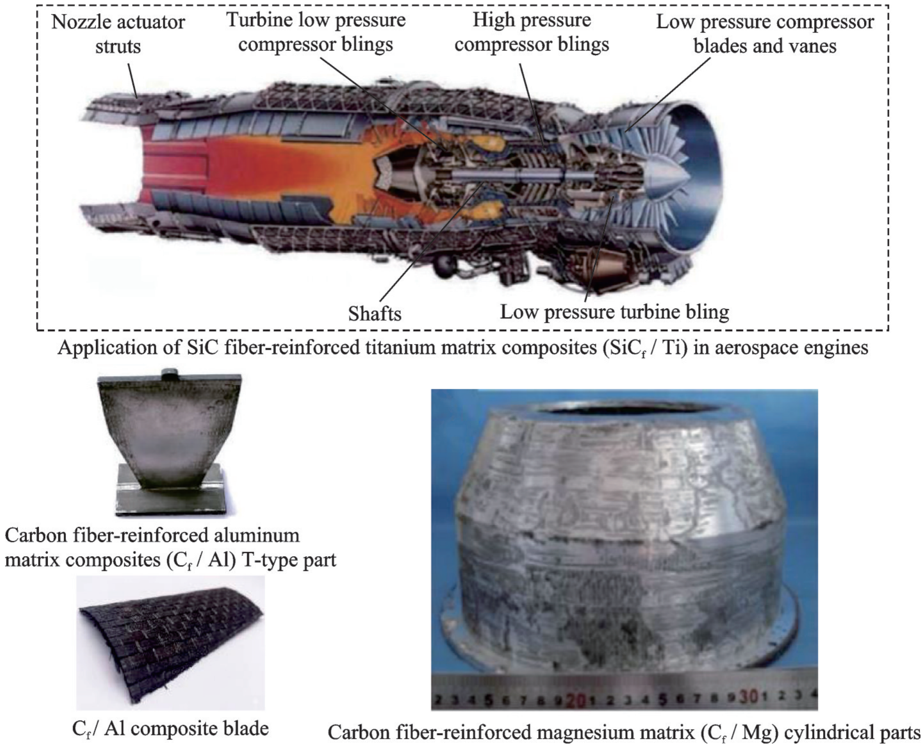



Fig.1 Application of different types of CFMMCs[5-8]

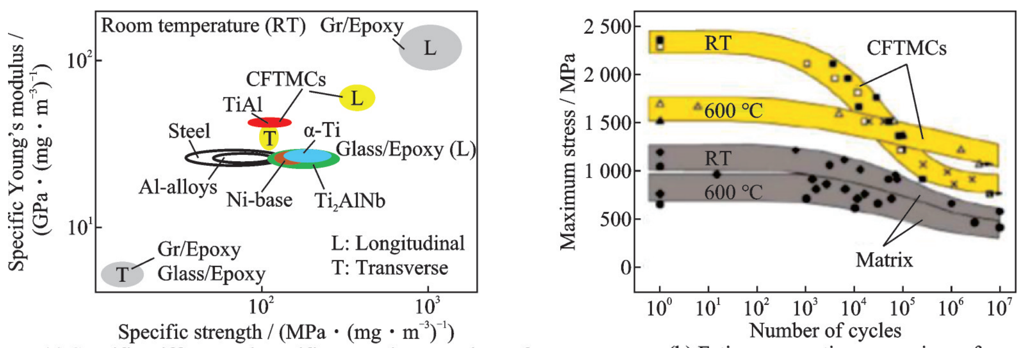
Unlike monolithic metals, CFMMCs are not a simple physical mixture of matrix and reinforcement. Instead, they achieve a substantial enhancement in material properties through the synergistic design of a "ductile matrix combined with hard fibers"[11-14]. Specifically, the ductile metal matrix (e.g., titanium, aluminum, and magnesium alloys) ensures overall plasticity and impact resistance, effectively absorbing and dissipating external energy. Meanwhile, the high-strength, high-modulus reinforcing fibers (e.g., silicon carbide (SiC) and carbon (C) fibers) serve as the primary load-bearing phase, carrying the majority of the applied load and thus significantly improving specific strength and specific stiffness. Furthermore, the incorporation of continuous fibers effectively hinders crack initiation and propagation. Energy dissipation during the crack growth occurs through mechanisms such as fiber bridging and pull-out. In addition, the fibers substantially enhance creep and fatigue resistance at elevated temperatures. It is the synergistic interplay of these mechanisms that endows CFMMCs with comprehensive mechanical advantages unattainable by any single constituent phase[15-17].

Table 1 summarizes the mechanical and physical properties of typical MMCs, including Al matrix, Mg matrix, and Ti matrix MMCs. The key properties (tensile strength, hardness, density, and thermal conductivity) are compared, demonstrating the improvements over unreinforced matrices[18-29].

Taking continuous fiber-reinforced titanium matrix composites (CFTMCs) as an example, their static mechanical properties are particularly remarkable. Their tensile strength reaches 1 500—2 000 MPa, comparable to that of high-strength alloy steels, while their density is only approximately 4.5 g/cm$^3$[30]. As a result, CFTMCs exhibit significantly higher specific stiffness and specific strength than conventional materials such as nickel-based superalloys (Fig.2(a)). Regarding fatigue performance, under ambient conditions, the typical low-cycle fatigue strength of CFTMCs reaches 1 800 MPa at $10^4$ cycles, demonstrating excellent resistance to cyclic loading. At elevated temperatures, both low-cycle and high-cycle fatigue strengths are at least twice those of conventional titanium alloys (Fig.2(b)). Notably, CFTMCs retain more than 80% of their room-temperature strength at 800 ℃[30], revealing exceptional high-temperature mechanical stability. Moreover, CFTMCs fully inherit the inherent cor-

**Table 1 Summary of tensile strength, hardness, density, and thermal conductivity for typical MMCs (Al, Mg, and Ti matrices)[18-29]**

| Matrix type | Material composition | Tensile strength/MPa | Hardness/HV | Density/($g \cdot cm^{-3}$) | Thermal conductivity/($W \cdot m^{-1} \cdot K^{-1}$) | Reference |
|---|---|---|---|---|---|---|
| Al | AA6061 | 310 ± 15 | 105 ± 5 | 2.70 | 167 | [18] |
| Al | AA6061 + 10% SiC | 420 ± 20 | 140 ± 8 | 2.75 | 160 | [19] |
| Al | AA7075 + 5% CNTs | 550 ± 25 | 180 ± 10 | 2.72 | 175 | [20] |
| Al | AA2024 + Hybrid (SiC + CNTs) | 480 ± 18 | 155 ± 7 | 2.73 | 168 | [21] |
| Mg | AZ91 | 250 ± 12 | 80 ± 4 | 1.81 | 78 | [22] |
| Mg | AZ91 + 10% SiC | 350 ± 18 | 120 ± 6 | 1.85 | 75 | [23] |
| Mg | AZ31 + 5% CNTs | 320 ± 15 | 110 ± 5 | 1.83 | 82 | [24] |
| Mg | AZ91 + Hybrid (CF + MWCNT) | 380 ± 20 | 135 ± 7 | 1.84 | 80 | [25] |
| Ti | Ti64 | 950 ± 40 | 350 ± 15 | 4.43 | 7.1 | [26] |
| Ti | Ti64 + 10% TiC | 1 200 ± 50 | 450 ± 20 | 4.50 | 6.8 | [27] |
| Ti | Ti64 + 5% TiB | 1 100 ± 45 | 420 ± 18 | 4.48 | 7.0 | [28] |
| Ti | Ti64 + Hybrid (TiC + TiB) | 1 300 ± 55 | 480 ± 22 | 4.52 | 6.9 | [29] |




(a) Specific stiffness and specific strength comparison of CFTMCs and astronautic structural materials

(b) Fatigue properties comparison of CFTMCs and Ti alloy

Fig.2 Performance comparison of CFTMCs and different materials[30]

rosion resistance of the titanium alloy matrix, exhibiting excellent resistance to aggressive corrosive environments such as seawater and acidic media[31-34], which further expands their potential applications in marine engineering and the chemical industry.

Particle-reinforced metal matrix composites (PMMCs) are frequently integrated into high-performance aerospace and military applications[35-40]. Their popularity stems from a favorable combination of high specific mechanical properties and thermal stability, particularly within titanium, magnesium, and aluminum matrix systems. Compared with PMMCs, CFMMCs achieve further significant enhancements in strength, stiffness, and toughness through fiber bridging and load-bearing effects, exhibiting particularly outstanding performance in fatigue resistance and impact tolerance. The continuous fiber architecture enables efficient load transfer from the ductile matrix to the high-strength reinforcement, thereby improving the composite's ability to withstand cyclic and dynamic loading conditions. The presence of fibers effectively inhibits crack initiation and propagation by promoting mechanisms such as fiber bridging, crack deflection, and fiber pull-out, thereby substantially extending the service life of the material[41-42].

In contrast, although PMMCs improve matrix stiffness and wear resistance through the introduction of hard particles, the inherent differences in interfacial bonding characteristics between particles and the matrix result in weaker resistance to crack propagation. The discontinuous nature of particle reinforcement leads to localized stress concentrations and limited crack-bridging capability, making PMMCs more susceptible to failure under cyclic or impact loads. Consequently, the toughness and fatigue performance of PMMCs are generally inferior to those of CFMMCs[43-44]. Furthermore, the design flexibility afforded by fiber orientation and architecture in CFMMCs allows for tailored anisotropic properties, enabling optimization for specific loading directions, which is not readily achievable in PMMCs.

On the other hand, ceramic matrix composites (CMCs), despite their extremely high temperature resistance and oxidation resistance, which offer significant advantages in extreme thermal environments, suffer from poor fracture toughness due to their intrinsic brittleness. CMCs are prone to catastrophic failure caused by rapid crack propagation, which severely limits their application in structural components subjected to complex loads[45-49]. In contrast, CFMMCs, through the judicious selection of reinforcing fibers such as SiC fibers, not only maintain excellent mechanical properties at elevated temperatures but also possess good fatigue resistance and service stability. Furthermore, CFMMCs exhibit better machinability and repairability, avoiding the processing difficulties and service limitations associated with the brittleness of ceramic matrix materials[50-54].

Fabrication technology is a key factor influencing the development of composite materials. An ideal fabrication technique should preserve fiber and matrix properties, control interfacial reactions, minimize adverse effects, and simultaneously meet the demands of large-scale production[55-60]. The fabrication methods for CFMMCs include the foil-fiber-foil process, mono-tape process, matrix-coated fiber process, and physical vapor deposition, among others[61-64]. Fig.3 illustrates the complete fabrication process flow of SiC fiber-reinforced titanium matrix composites ($SiC_f$/Ti), from individual fiber preparation to multi-fiber arrays and finally to the consolidation of final components[65], where VHP is the vacuum hot pressing and HIP the hot isostatic pressing. First, using tungsten (W) or carbon (C) as the core material, SiC is deposited on the core surface by chemical vapor deposition (CVD) to form SiC fibers. Subsequently, a coating is deposited on the fiber surface using CVD or physical vapor deposition (PVD) to obtain coated or precursor fibers with specific interfacial properties. The prepared fibers are then arranged in an orderly manner to form a fiber preform structure. Through subsequent densification and consolidation processes such as diffusion bonding or hot pressing, the fibers are embedded into the titanium matrix, ultimately forming a multi-fiber-reinforced composite structure. In recent years, with continuous scientific and technological advances, novel fabrication techniques such as compression molding, fiber spinning, and laser additive manufacturing have emerged, offering more efficient, low-cost, and high-performance solutions[66-71]. Different fabrication methods can be selected according to the end-use requirements of the composite to optimize its mechanical properties, thermal stability, and durability, thereby promoting its widespread application in aerospace, automotive, defense, and other fields.

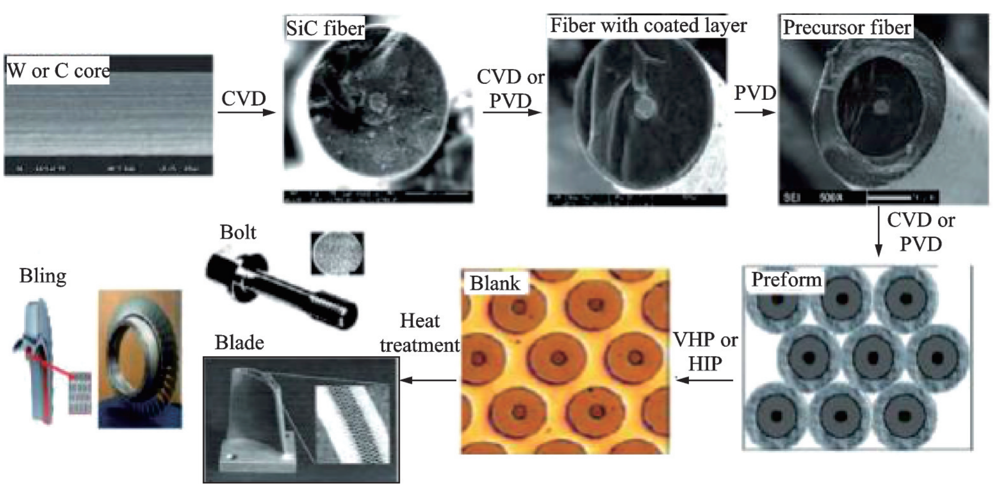



Fig.3 Preparation process of SiC fiber-reinforced titanium matrix composites[65]

CFMMCs are experiencing increasingly widespread application demands in high-end equipment manufacturing fields such as aerospace. Although composites can in most cases be shaped by near-net-shape forming techniques without requiring subsequent machining, secondary processing steps including grinding, milling, drilling, or turning remain inevitably necessary due to stringent assembly accuracy requirements. However, compared with monolithic metals, the cutting and grinding difficulty of CFMMCs is substantially higher, and this difference fundamentally originates from their unique heterogeneous two-phase microstructure.

From a materials science perspective, the machining difficulties of CFMMCs can be attributed to three scales. At the macroscopic scale, the oriented arrangement of fibers leads to pronounced anisotropy in mechanical properties, with differences in machining resistance exceeding 300% depending on direction[72-74]. At the mesoscopic scale, fundamental differences exist in the material removal mechanisms between the fiber and matrix regions[75-77]. At the microscopic scale, the substantial property disparity between hard fibers (e.g., SiC fibers with a hardness of approximately 2 800 HV) and the relatively soft metal matrix (e.g., titanium alloy at about 350 HV, aluminum alloy at about 150 HV, and magnesium alloy at about 80 HV) render the machining process highly susceptible to various forms of damage[78-82].

Specifically, the material removal mechanism of CFMMCs during machining is distinctly different from that of monolithic metals. Unlike pure metals, where material removal is dominated by plastic deformation, the presence of high-hardness reinforcing phases in CFMMCs significantly impedes the plastic flow of the metal matrix, leading to complex multi-mechanism coupled machining behavior. During the tool-workpiece interaction, material removal simultaneously involves plastic deformation of the matrix, brittle fracture of the reinforcing phase, and interfacial debonding, manifesting as fiber pull-out, fragmentation, and microcrack propagation[83-87]. Moreover, the reinforcing phase content in CFMMCs is relatively high. In a single cutting pass, the cutting tool alternately contacts both ductile and brittle phases in similar proportions. This multi-mechanism coupled material removal behavior not only exacerbates tool wear, particularly flank wear and micro-chipping, but also generates defects such as fiber debonding pits and microcracks on the machined surface[88-92]. Common damage modes include fiber pull-out, fiber fracture (especially during transverse machining), and fiber-matrix interfacial debonding, with interface damage depths reaching up to 50 μm[85]. These defects not only reduce machining accuracy but also severely impair the fatigue performance and service life of components. Therefore, developing efficient and low-damage machining technologies for CFMMCs has become a complex and urgent task.

To date, numerous studies have been conducted on the cutting and grinding of composites such as carbon fiber-reinforced polymers (CFRPs)[93-95], CMCs[96-98], and PMMCs[99-101], providing important references for understanding the machining mechanisms of CFMMCs. However, compared with the aforementioned composites, CFMMCs exhibit more significant discrepancies in thermophysical and mechanical properties between the ceramic fibers and the metal matrix. Specifically, ceramic fibers such as SiC fibers possess very low coefficients of thermal expansion and high-temperature stability, whereas metal matrices such as titanium and aluminum alloys exhibit relatively high coefficients of thermal expansion and good plasticity. This substantial property disparity readily leads to thermal expansion stress mismatch and incompatible deformation between the fibers and the matrix during machining, particularly under locally elevated temperatures and complex stress fields, thereby further inducing machining damage such as interfacial debonding, fiber fracture, and microcrack initiation[102-104]. These issues elevate the machining difficulty of CFMMCs to a level far exceeding that of traditional metallic materials and other types of composites.

However, in stark contrast to the increasingly widespread application demands of CFMMCs, systematic reports on the machining of these materials in the open literature remain very limited[105-107]. Although preliminary studies have achieved some progress in conventional cutting, grinding, and energy-field-assisted machining methods such as laser-assisted machining (LAM) [106] and ultrasonic vibration-assisted machining (UVAM) [105], the field is still largely in an exploratory stage. Existing research has mostly focused on feasibility validation and preliminary process parameter optimization for single machining methods, while studies on multi-energy-field synergistic machining, intelligent process monitoring, and the establishment of process systems tailored for engineering applications remain severely insufficient. Consequently, a significant gap remains before a complete and mature machining process system suitable for complex structural components made of CFMMCs can be established. It should be noted that the aforementioned pioneering work has laid an important foundation for subsequent research, particularly in providing valuable experimental data, theoretical models, and technical references for understanding the material removal mechanisms of CFMMCs, the evolution of fiber-matrix interfacial damage, and the influence of machining parameters on surface integrity. Given the increasingly urgent application demands for CFMMCs in high-end equipment manufacturing, further in-depth research on efficient, low-damage, and intelligent machining technologies remains an important challenge that urgently needs to be addressed.

# 1 Turning Process

Although research and development efforts on CFMMCs began as early as the 1960s, progress in their machining technologies remained slow for several decades. It was not until the 1990s that Cronjäger et al.[89] made the first attempt to machine CFMMCs by machining carbon fiber-reinforced aluminum composites ($C_f/Al$) using polycrystalline diamond (PCD) tools. Their exploratory work focused on tool wear, process optimization, and machining quality. However, following this initial effort, systematic studies on the machining of CFMMCs remained scarce for a considerable period.

## 1.1 Conventional turning

A significant breakthrough did not occur until 2023, when Zan et al.[85] at the University of Nottingham conducted orthogonal cutting experiments on $SiC_f$/Ti-6Al-4V composites. In the section on turning, fundamental material removal mechanisms are often investigated through orthogonal cutting experiments to simplify the 3D stress state into a 2D plane strain model. They systematically investigated the influence of temperature on chip morphology, material removal mechanisms, and surface integrity by comparing cryogenic (−180 ℃, CT), room temperature (24 ℃, RT), and high temperature (400 ℃, HT) conditions. The results demonstrated that workpiece temperature profoundly affected the deformation mechanism and deformation depth of the Ti-6Al-4V matrix. As shown in Fig.4, both

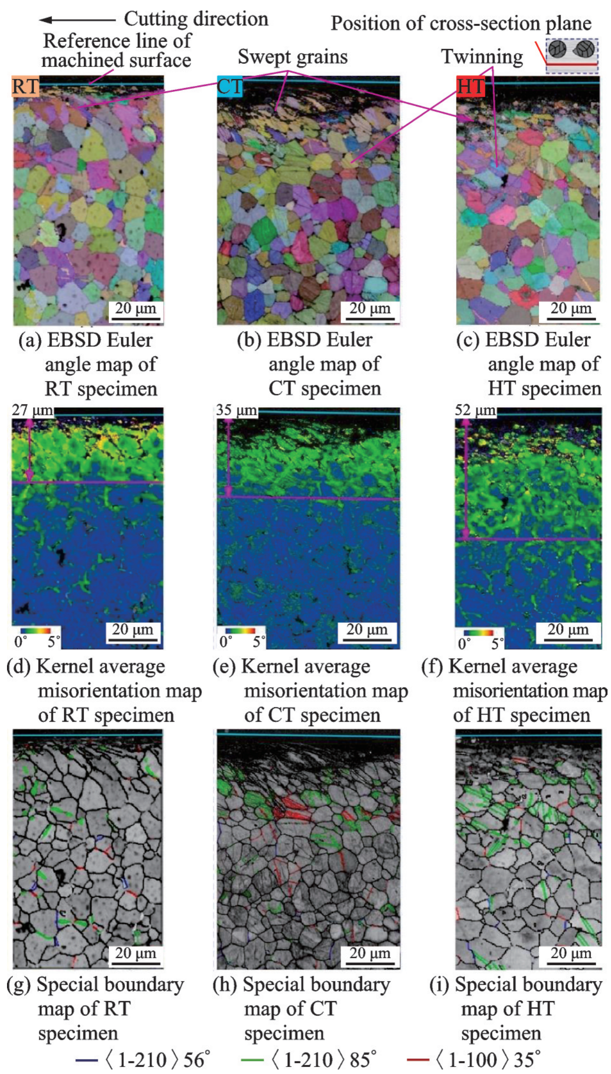



Fig.4 Electron backscatter diffraction (EBSD) characterization of matrix cross-sections after machining at 50 m/min and a cutting depth of 0.1 mm

cryogenic and high temperatures induced greater matrix deformation depths than room temperature, which in turn led to more extensive fiber cracking. This study significantly advanced the understanding of cutting mechanisms in fiber-reinforced titanium matrix composites.

### 1.2 Ultrasonic vibration-assisted turning

Integrating CFMMCs into aerospace components requires precise thinning of the titanium cladding, yet conventional subtractive methods often compromise structural integrity through machining-induced cracks and fiber fractures. The current lack of a comprehensive understanding regarding thinning-related deformation, coupled with a deficiency in low-stress processing alternatives, represents a major barrier to the practical deployment of these high-performance composites.

To overcome these limitations, researchers have turned to energy-field-assisted machining technologies, among which UVAM has emerged as a promising solution. UVAM applies high-frequency (20—50 kHz) small-amplitude oscillations to either the cutting tool or the workpiece, generating periodic tool-workpiece separation. This induces an acoustic softening effect that promotes dislocation motion while effectively reducing cutting forces and machining stresses. These characteristics make UVAM particularly suitable for heterogeneous difficult-to-machine materials such as fiber-reinforced composites[71].

Through a series of orthogonal experiments, a research group from Beihang University[103] characterized the microstructural transitions and macroscopic deformation of CFMMCs under UVAM conditions. Their data indicates that UVAM yields a 20% reduction in machining forces and a 60% decrease in surface residual stress compared to the conventional machining (CM). While acoustic softening was responsible for the decline in surface stress, high-frequency stress waves were found to intensify subsurface stress levels. Notably, the SiC fibers acted as a catalyst for ultrasonic energy, facilitating dislocation annihilation and dynamic recrystallization. This process effectively lowered the dislocation density within the matrix and reorganized the interfacial stress field, resulting in a more stable and uniform fiber-matrix transition, as shown in the mechanistic comparison in Fig.5.

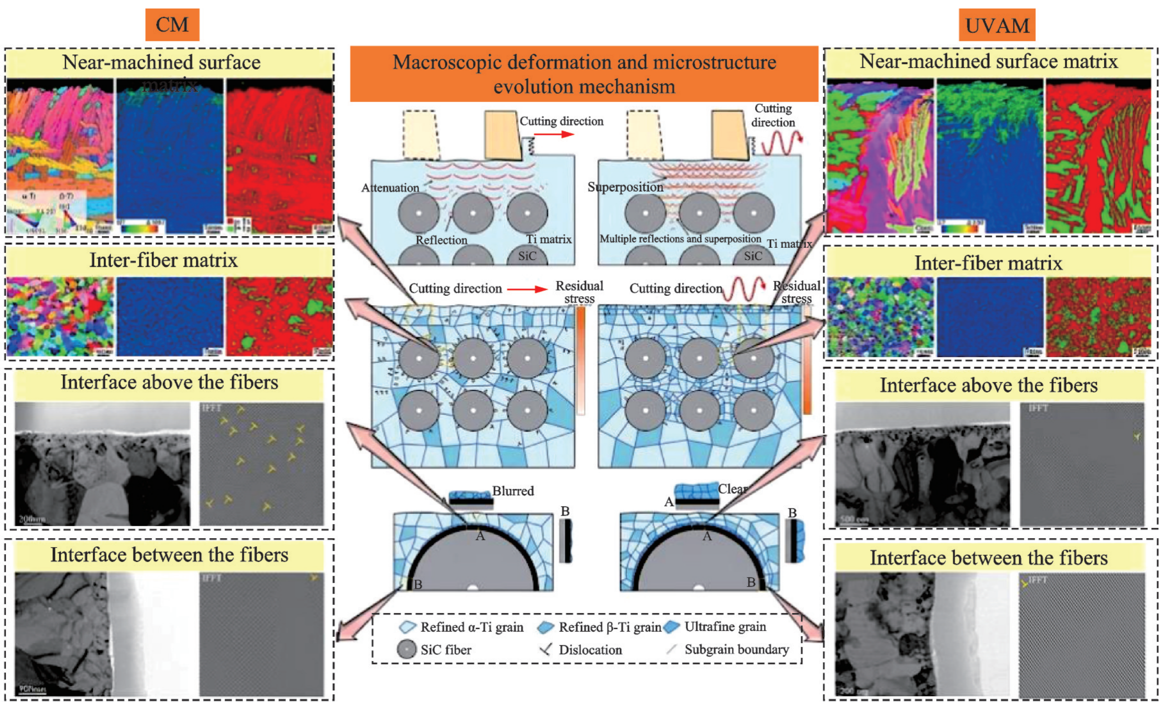



Fig.5 Comparison of macroscopic deformation and microstructure evolution mechanism between CM and UVAM of $SiC_f/Ti$[103]

Despite these advancements, several limitations remain in the current understanding. First, the study did not directly address the material removal mechanism of the composite, particularly the dynamic response of the fiber-matrix interface during machining and its subsequent influence on material properties. Second, systematic optimization of machining parameters was not conducted, which hinders the practical application of UVAM to complex structural components.

### 1.3 Laser-assisted turning

LAM offers an alternative approach by enabling localized thermal softening of the workpiece material through rapid heating. This technique significantly reduces cutting forces and tool wear while suppressing crack propagation in brittle phases. Consequently, LAM is particularly well-suited for difficult-to-machine materials characterized by high hardness, high brittleness, and high strength. Compared with CM, LAM provides distinct advantages in terms of improved machining efficiency, extended tool life, and enhanced surface integrity[90].

Leveraging these benefits, researchers have explored the application of laser-assisted turning (LAT) to high-volume-fraction CFMMCs. Dandekar and Shin[87] investigated the feasibility and advantages of LAT in Al-2%Cu/$Al_2O_3$ composites with a fiber volume fraction of 62%. Although CFMMCs possess high specific strength and excellent corrosion resistance, their machinability is severely compromised by the hard and brittle nature of the fibers and the high interfacial strength, often resulting in severe tool wear and subsurface damage.

To address this challenge, the study employed a three-phase multi-physics finite element model incorporating the fiber, matrix, and interface, combined with systematic experiments. The effects of laser preheating on cutting forces, specific cutting energy, surface roughness, tool wear, and fiber fracture or debonding were comprehensively evaluated. A thermal model was developed to quantitatively relate the material removal temperature $T_{mr}$ to key parameters including laser power, feed rate, and cutting speed, and was subsequently validated through experiments.

Fig.6 presents a comparison of the workpiece and surface morphology between conventional turning (C-Turning) and LAT[87]. The results demonstrated that at $T_{mr}$ = 300 ℃, machining performance was significantly enhanced: Specific cutting energy, surface roughness, and tool wear were all reduced by approximately 65%, while fiber fracture and interfacial debonding depths were markedly diminished. Moreover, the cutting process became more stable, as evidenced by the lowest ratio of thrust force to main cutting force. Both simulations and experiments consistently indicated that increasing the material removal temperature reduces the mechanical load on fibers and suppresses brittle fracture. Additionally, employing a larger rake angle and a lower cutting speed was found to further reduce machining damage.

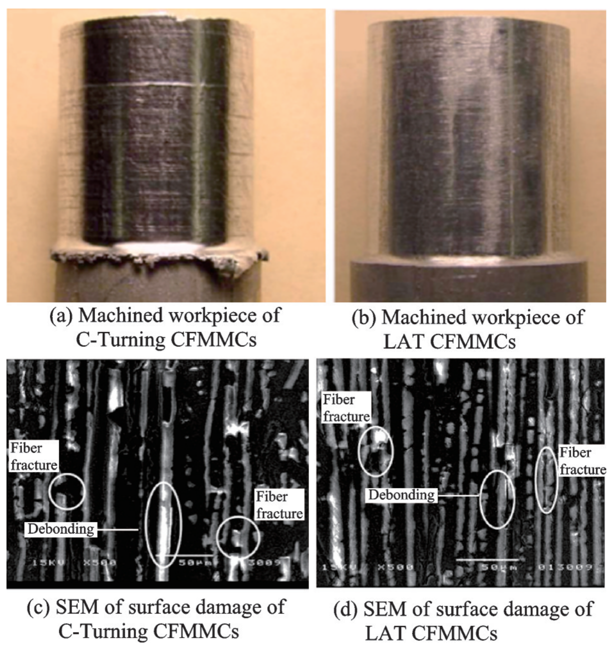



Fig.6 Comparison of surface morphology between C-Turning and LAT of CFMMCs[87]

## 2 Milling Process

### 2.1 Conventional milling

A comprehensive study by Wang et al.[88] on the side milling of $SiC_f$/Ti thin-walled parts indicates that these composites experience significantly higher global dynamic instability than unreinforced titanium alloys. Despite this instability, the structural displacements for vertical and horizontal fiber orientations were lower than the titanium baseline by 33.2% and 56.93%, respectively. This suggests that while the composite structure introduces complex vibrational challenges, the presence of fiber reinforcement significantly enhances the overall stiffness and resistance to deformation compared to monolithic alloy counterparts.

Vibration analysis showed that the vertical fiber layout suffered from minimum stiffness at the tool entry, leading to a peak vibration of 154.3 m/$s^2$. In contrast, the horizontal layout experiences a more critical stiffness drop at the tool exit, with vibrations reaching 160.7 m/$s^2$. Mechanistically, the vertical arrangement favors constrained plastic flow within the matrix and elastic interfacial adjustment, with energy being dissipated primarily through longitudinal stress wave transmission and interfacial friction. The specific side milling configuration and the resulting deformation mechanisms for these $SiC_f$/Ti components are further detailed in Fig.7[88].

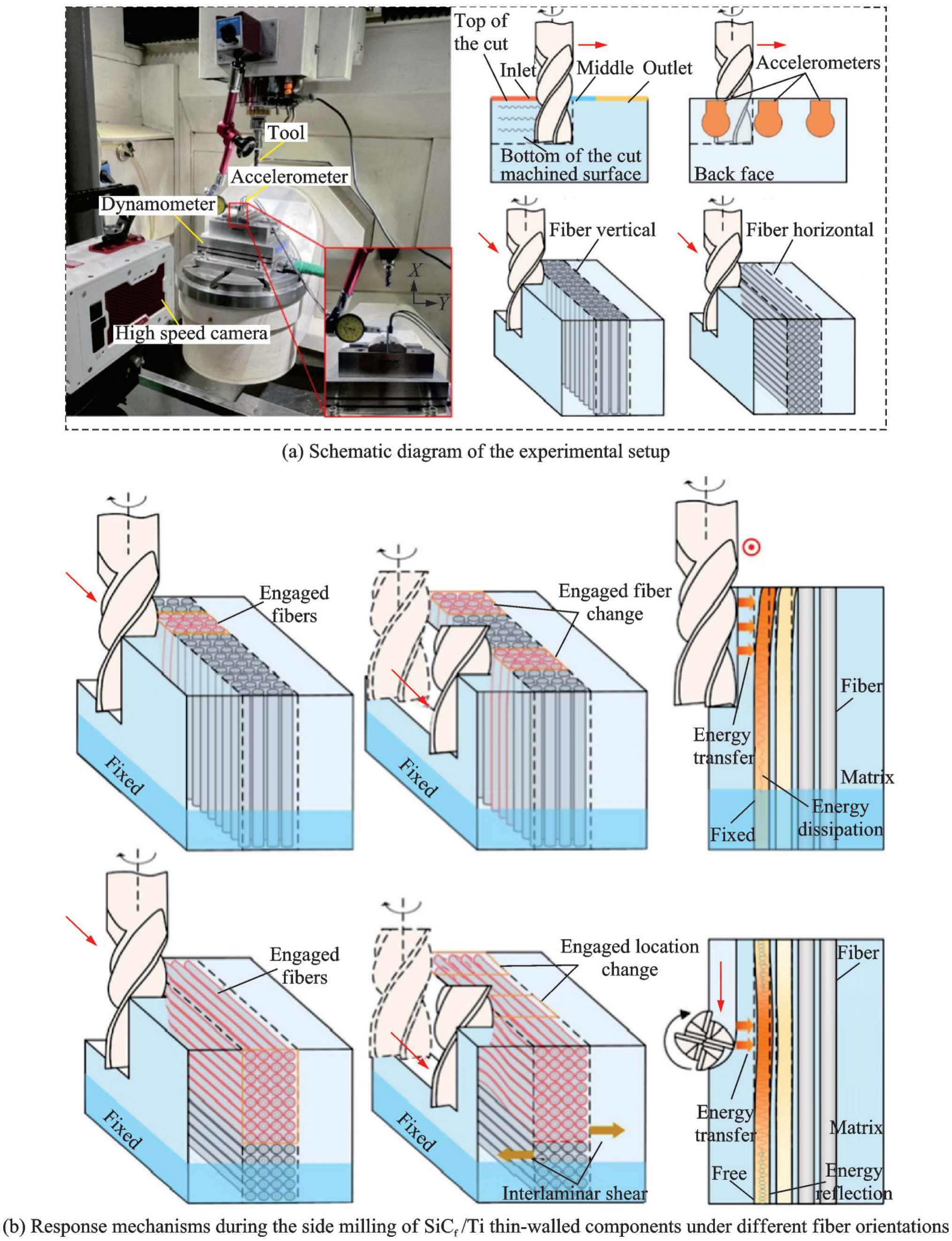



Fig.7 Side milling of $SiC_f$/Ti thin-walled components[88]

It should be noted that this study focused primarily on displacement and vibration responses during machining. However, it did not evaluate the surface integrity of the machined thin-walled components, including surface roughness, residual stress, and subsurface damage, nor did it assess their subsequent effects on fatigue performance and service life.

In a separate study, Zhang et al.[79] investigated HfZrTiTaNbCu-reinforced 2A97 aluminum matrix composites with a low fiber volume fraction of 0.2%. Utilizing finite element simulations, the researchers conducted a systematic evaluation of how fiber orientations (45°, 90°, and 135°), machining parameters, and tool coating thickness influence cutting forces, thermal loads, surface quality, and tool degradation. The findings demonstrated a direct correlation between increased machining parameters and elevated cutting forces and temperature. Fiber alignment proved to be a critical factor; for instance, the cutting force observed at 90° orientation was approximately 53% lower than that at 135°. Additionally, the thermal variance between the 45° and 90° fiber arrangements reached 26 ℃, highlighting the high sensitivity of the thermal-mechanical response to the internal architecture of the composite.

## 2.2 Laser-assisted milling

Laser-assisted milling (LA-Milling) has also been successfully applied to the machining of CFMMCs. Mypati et al.[90] conducted a comparative study between conventional milling (C-Milling) and LA-Milling of $Ti6Al4V/SiC_f$ composites. They proposed a novel "fully inverse LA-Milling" mode, which separately optimized the temperature fields in the titanium matrix and SiC fiber regions. This approach achieves localized softening of the titanium matrix while avoiding thermal damage to the SiC fibers, as schematically illustrated in Fig.8.

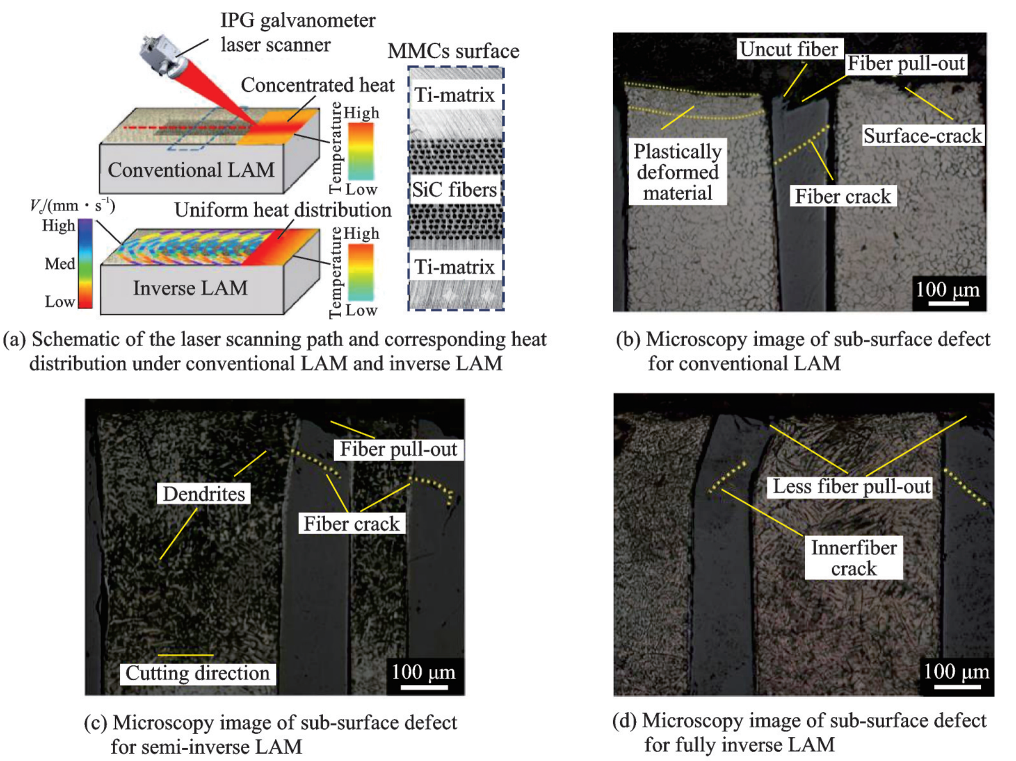



Fig.8 C-Milling and LA-Milling of $SiC_f$/Ti-6Al-4V with machining direction perpendicular to fiber axis[90]

The experimental results demonstrated that fully inverse LA-Milling reduced cutting forces by 62% and extended tool life by 60%. Furthermore, it significantly improved chip morphology and microstructure, while reducing microcracks and grain distortion. However, this study adopted only a feed direction perpendicular to the fiber axis, and thus did not account for the influence of fiber anisotropy on the material removal mechanism. Additionally, the effect of machined surface integrity on the fatigue life of components was not systematically investigated.

## 3 Grinding Process

### 3.1 Conventional grinding

Unlike milling and turning, grinding removes material through the simultaneous micro-cutting action of numerous abrasive grains on the grinding wheel surface, offering distinct processing advantages. Each abrasive grain acts as a microscopic cutting edge, and their collective participation in material removal results in an extremely small depth of cut per grain and uniformly distributed cutting forces. This effectively prevents machining damage commonly associated with local stress concentrations, such as fiber fracture, interfacial debonding, and subsurface microcracks. Furthermore, grinding achieves superior surface quality and dimensional accuracy, making it particularly suitable for difficult-to-machine materials with heterogeneous and anisotropic characteristics, including CFMMCs[86]. Consequently, grinding has become a critical and often final step in the machining of CFMMC components.

The ground surface is the product of interactions between adjacent abrasive grains, which renders understanding the mechanical action of a single grain on the material particularly complex. To address this challenge, single-grain grinding and single-grain scratching methods have emerged as reliable approaches for elucidating the material removal mechanisms under abrasive grain action[91, 102, 105]. These methods have yielded important insights into the microscopic formation of machined surface morphology, thermo-mechanical coupling effects, and grinding tool wear.

Li[104] conducted systematic research on the grinding of $C_f/Al$ composites. Through the coupling of multiple methods and optimization of process parameters, grinding damage in $C_f/Al$ composites was effectively controlled, providing systematic theoretical guidance and process recommendations for achieving high-quality machining. Although this study focused directly on $C_f/Al$, the multi-scale simulation framework established, the coupled analysis method relating fiber orientation to process parameters, and the "brittle-ductile" interfacial removal mechanism revealed through single-grain experiments have provided valuable references for subsequent research on other CFMMC systems.

Feng et al.[92] systematically investigated the material removal mechanisms and damage evolution laws of $SiC_f/TC17$ composites under single cubic boron nitride (CBN) abrasive grain high-speed grinding (grinding speed in 80 m/s), considering different fiber orientation angles ($\theta_f = 0°$, 30°, 60°, and 90°), as shown in Fig.9. The study revealed that under the action of a single abrasive grain, material damage exhibited multi-mode coupling characteristics, including matrix coating, fiber micro-fracture, and macro-fracture. Furthermore, the damage mode is jointly governed by the fiber embedding depth and the maximum undeformed chip thickness. As the embedding depth decreases, the fibers undergo three progressive damage stages: Surface micro-fracture, exposure and deformation of the internal tungsten core, and macro-fracture or pull-out. The study further quantified the influence of process parameters, demonstrating that reducing the maximum undeformed chip thickness significantly lowered the critical embedding depth for damage mode transition. For instance, at $\theta_f = 90°$, decreasing the chip thickness from 0.8 μm to 0.1 μm reduced the critical value by 8—10 μm. This work elucidates the coupled fiber-matrix removal mechanism at the single-grain scale, providing an important theoretical foundation for low-damage precision grinding of CFMMCs.

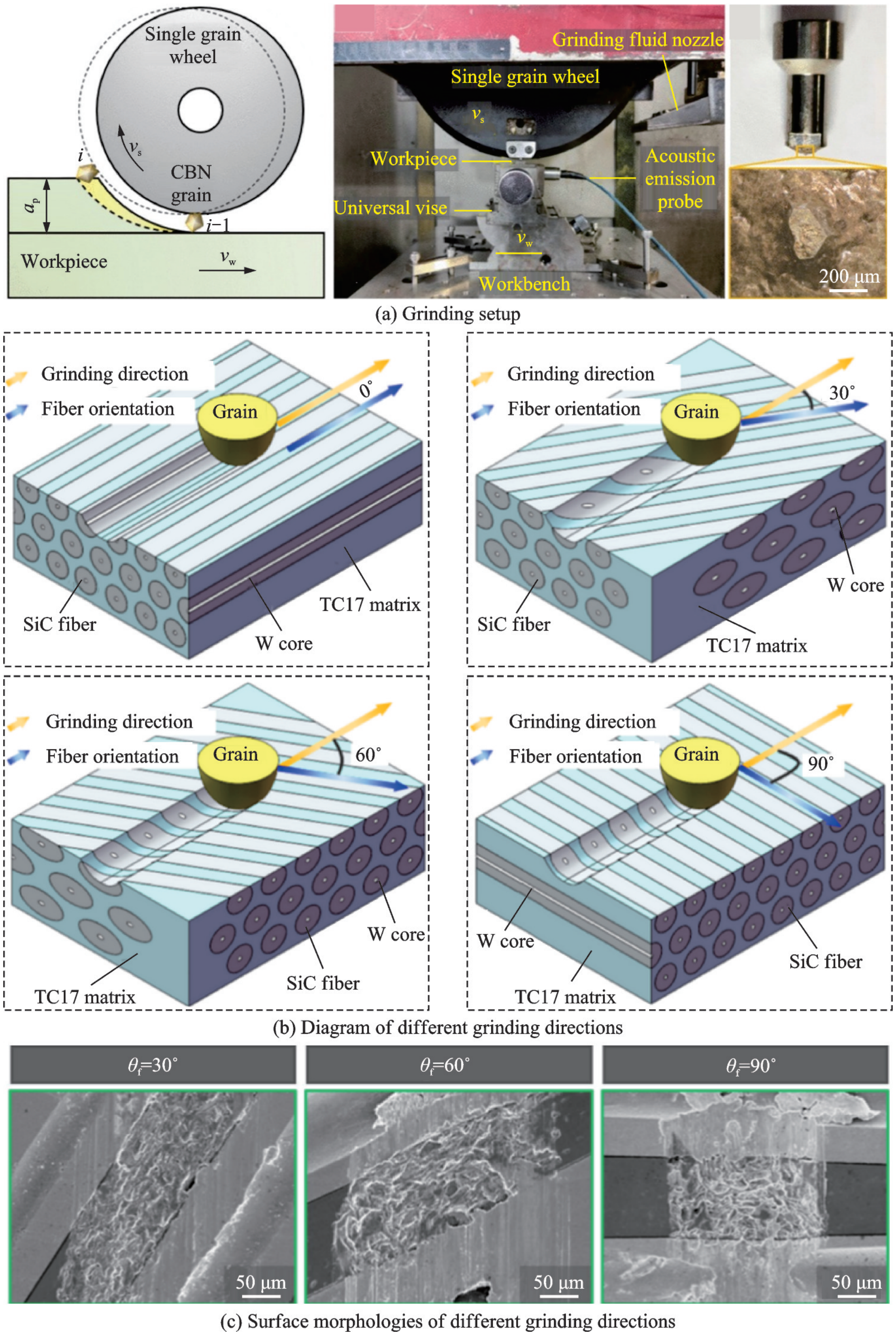



Fig.9 High-speed grinding of $SiC_f$/Ti with single CBN grain along different fiber directions[92]

### 3.2 Ultrasonic vibration-assisted grinding

Current research on ultrasonic vibration-assisted grinding of CFMMCs encompasses aspects such as material removal mechanisms[91], grinding wheel wear[83], and numerical simulations[84]. Ding et al.[105] systematically investigated the application of ultrasonic vibration in the machining of $SiC_f$/TC17 composites. Their experimental data revealed that ultrasonic vibration-assisted grinding (UVAG) reduced grinding forces by 18.6% relative to conventional grinding (CG). The research highlighted that the fiber orientation was a primary determinant of machining resistance; the maximum grinding forces were generated when processing perpendicular to the fibers, whereas parallel grinding yielded the lowest force values.

Regarding surface integrity, UVAG achieved a 19.1% improvement in surface roughness compared to CG. However, the study noted that the severity of machining-induced damage depended heavily on the fiber layout. Longitudinal grinding was found to be the most detrimental condition, characterized by prominent fiber pull-out from the titanium matrix. These findings offer critical insights into the removal mechanisms and provide a basis for developing damage-suppression strategies for the high-precision processing of CFMMCs.

However, several limitations should be noted. The experiments only considered a limited number of fiber orientations, specifically perpendicular and longitudinal directions, without systematically covering other angles such as 30°, 45°, and 60°. Moreover, the study focused primarily on grinding forces and surface morphology, without in-depth investigation of subsurface damage depth or the fatigue performance of machined components. A quantitative relationship between process parameters and service life has yet to be established. Fig.10 illustrates the surface morphology evolution of $SiC_f/Ti$ under UVAG along different fiber directions[105].

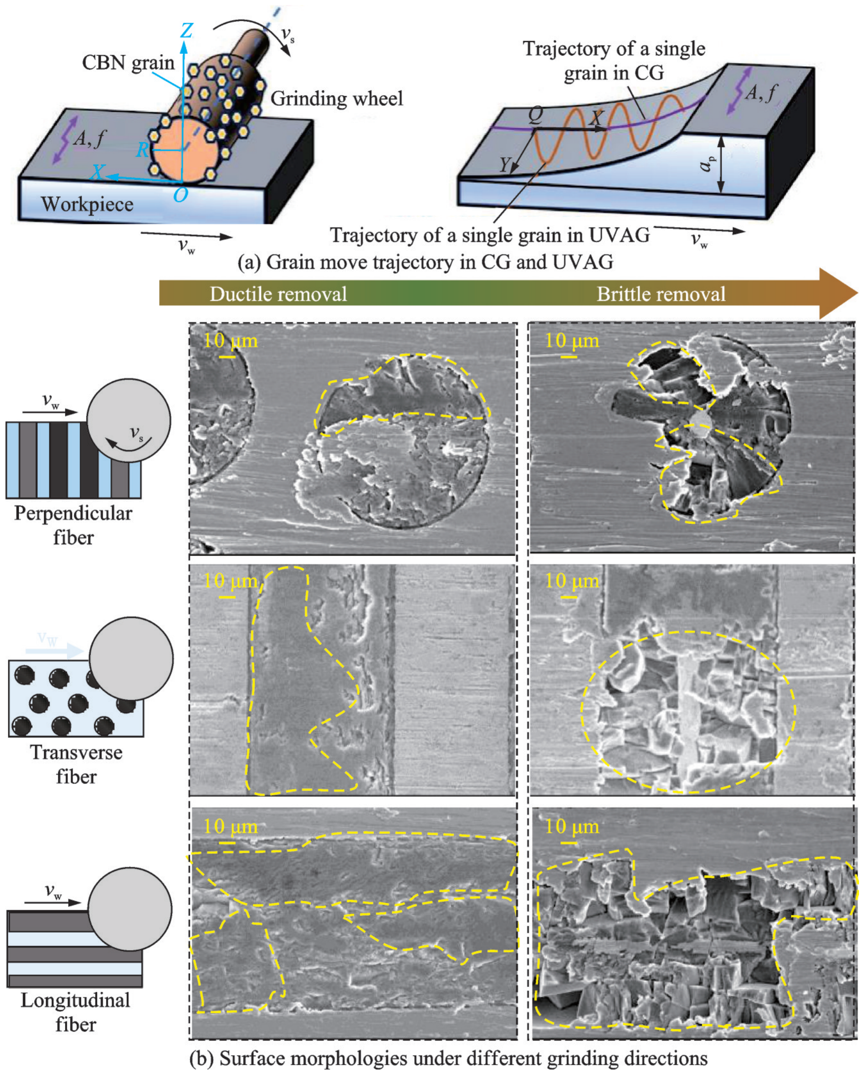



Fig.10 Illustration and comparison between CG and UVAG of $SiC_f/Ti$[105]

### 3.3 Laser-assisted grinding

To address the machining challenges posed by $SiC_f/Ti$, Xu et al.[106] proposed a laser-assisted grinding (LAG) method and systematically investigated its material removal mechanisms and machined surface characteristics. The study revealed the improvement effects of laser assistance on the grinding process from multiple perspectives, including grinding process variation, tool wear state, surface morphology, and subsurface microstructure deformation.

The results showed that LAG offered significant advantages over CG in terms of cutting force, vibration, and tool wear. This improvement is primarily attributed to the laser-induced change in the deformation mechanism of SiC fibers, which transitions from brittle fracture to semi-ductile fracture failure. Regarding surface morphology, LAG produced smoother surfaces because the laser-induced thermal effect softened the titanium matrix, promoting matrix coating that covered the pits generated by fiber fracture. In contrast, CG conditions exhibited pronounced burr formation. At the microstructural level, the introduction of laser assistance in LAG caused SiC fibers to predominantly undergo ductile fracture, characterized by 45° deformation, increased dislocation density, and stacking fault accumulation. In CG, however, fibers primarily exhibited brittle fracture with greater fracture depth and limited plastic deformation, as evidenced by fewer dislocations and stacking faults.

Despite the clear advantages of LAG in improving $SiC_f$/Ti machining quality demonstrated by Ref.[106], certain limitations remain. The study focused primarily on process feasibility validation and did not systematically explore the coupled optimization of different laser parameters such as power and scanning speed with grinding parameters such as cutting depth and feed rate. Fig.11 presents a sche-

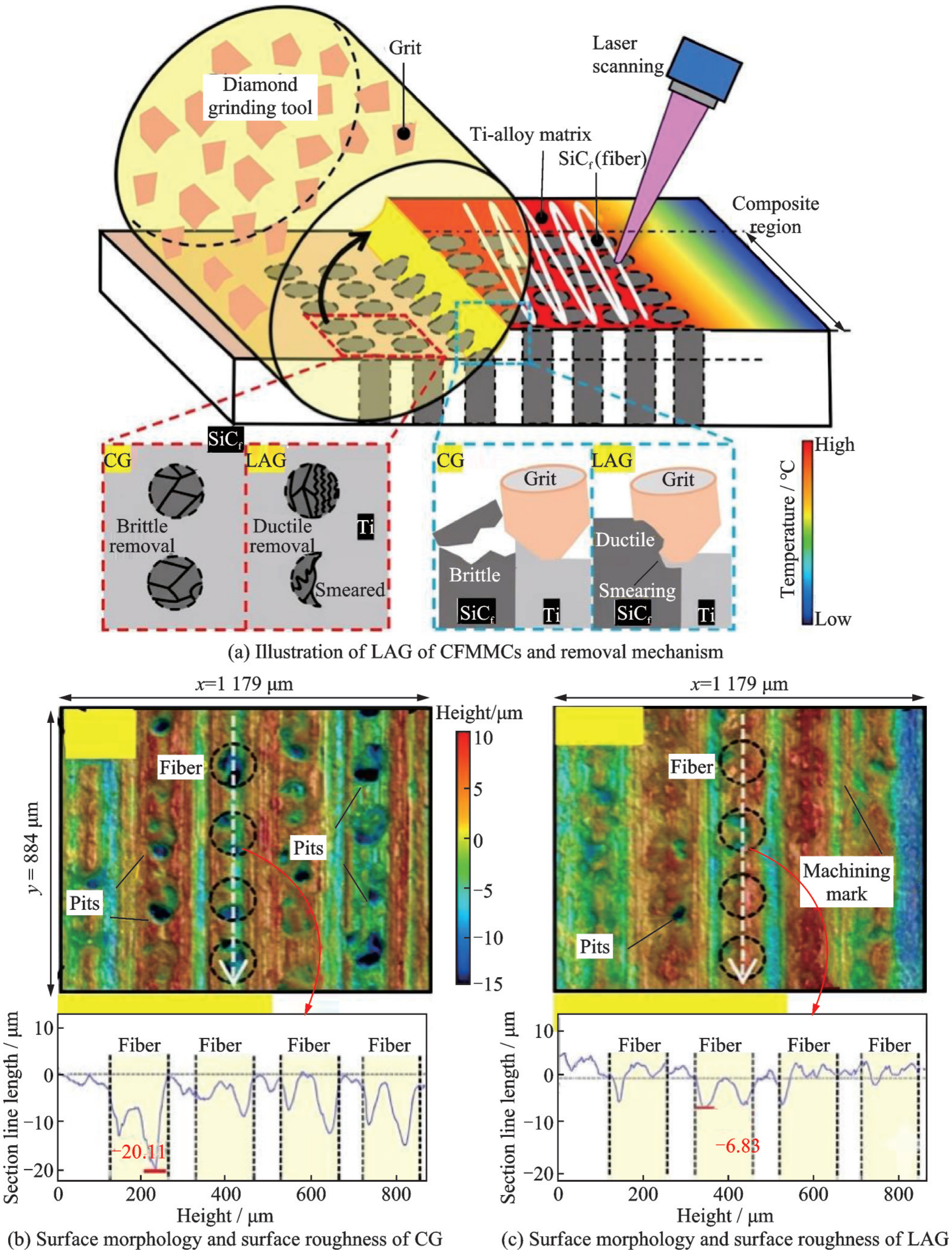



Fig.11 Illustration and comparison between CG and LAG of $SiC_f$/Ti[106]

matic illustration and comparison between CG and LAG of CFMMCs[106].

## 4 Laser Process

While UVAM is effective in mitigating surface degradation, it remains hampered by significant tool wear and a performance dependence on vibration orientation. Alternatively, LAM facilitates the processing of these materials by softening the matrix and shifting fiber fracture behavior from a brittle to a semi-ductile mode. However, the successful implementation of LAM requires precise synchronization between laser settings and machining parameters[106]. In this context, femtosecond laser machining has emerged as a superior alternative for CFMMCs[107], offering high-precision capabilities and minimal thermal damage, which are essential for the efficient processing of these challenging composites.

In the $SiC_f$/Ti processing, Wang et al.[107] identified that the distinct properties of the fiber and matrix led to asynchronous removal and selective ablation. Their results indicate that the removal volume scales directly with laser power and scan frequency. The SiC fibers undergo a "sublimation-expansion-solidification" cycle, resulting in a spore-like surface morphology, while the titanium matrix develops a scale-like texture (Fig.12[95]). Oxidation during this process involves a competition between the accumulation of $SiO_2$ and the removal of $TiO_2$. Although synchronous, low-damage removal was achieved at ten scans with a roughness fluctuation of 0.731 μm, the study lacked a quantitative correlation between processing variables and final quality. Furthermore, the impact of such machining on the mechanical integrity and service life of CFMMCs remains unexplored, marking a critical area for future research.

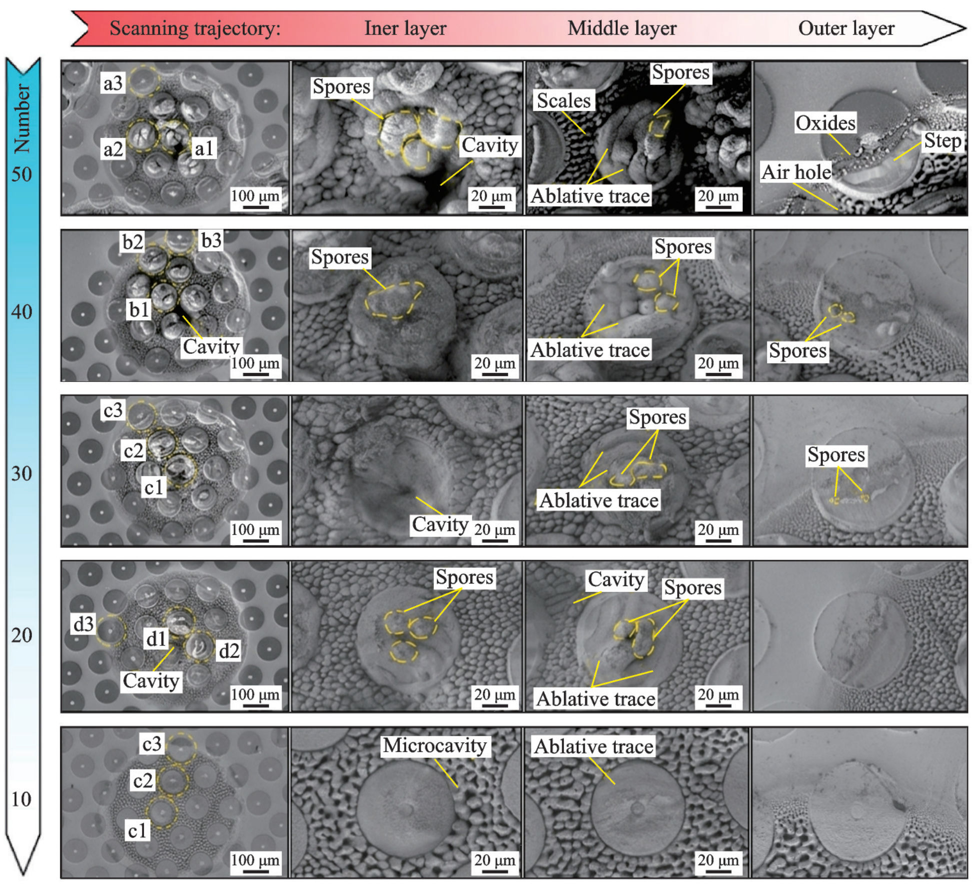



Fig.12 Ablation morphology of $SiC_f$/Ti under femtosecond laser machining[95]

## 5 Future Prospects of CFTMCs Machining

Despite their desirable macroscopic mechanical properties such as high strength and hardness, CFMMCs present substantial challenges in precision machining. These difficulties originate from the material's intrinsic multiscale heterogeneity. Based on the advantages and limitations of the above machining technologies, this section provides an outlook from the perspective of application demands.

At the macroscopic level, the mechanical behavior of the material is highly anisotropic. In particular, fiber orientation plays a dominant role in governing key machinability indicators, such as cutting resistance, plastic flow characteristics, and thermal sensitivity. Consequently, the cutting response of CFMMCs varies significantly with direction, leading to inconsistent and unpredictable machining outcomes.

At the mesoscopic level, the root cause of degraded machinability lies in the stark contrast between the two constituent phases. The fiber phase, typically composed of hard, brittle ceramic materials such as SiC, carbon, or $Al_2O_3$, resists plastic deformation and tends to fail in a brittle manner. In contrast, the metal matrix phase (e.g., Al, Mg, Ti, or Cu) is relatively soft and ductile, exhibiting strong adhesion and smearing tendencies. This brittle-ductile mismatch gives rise to a highly complex and coupled material removal mechanism. Under the action of the cutting tool, the interaction between these two incompatible phases inevitably generates severe machining defects, including fiber pull-out, matrix tearing, interlayer delamination, poor surface finish, burr formation, and accelerated tool wear.

Thus, the machining difficulty of CFMMCs is not attributable to a single factor, but rather emerges from the interplay between mesoscopic machinability disparity and macroscopic anisotropic behavior. Effectively addressing this multiscale challenge requires a holistic strategy that coordinates material responses across different length scales.

Owing to their unique fiber-matrix interface characteristics and the pronounced anisotropy induced by continuous fiber reinforcement, CFMMCs exhibit fundamentally different mechanical responses and material removal mechanisms compared to conventional monolithic metals or PMMCs. Looking ahead, future developments in the machining of CFMMCs (Fig.13) are expected to follow the trajectories outlined below.

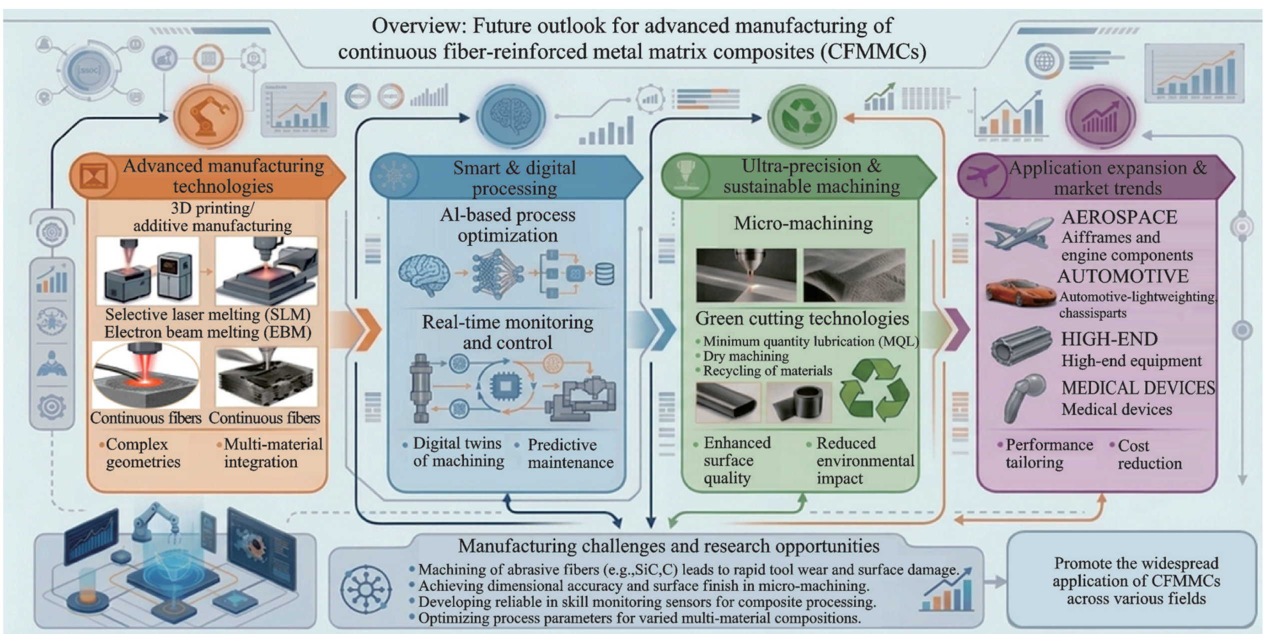



Fig.13 Emerging trends and future pathways in CFMMCs machining

(1) Advanced manufacturing and additive technologies

The focus will shift toward the integration of complex geometries and multi-material structures. By leveraging techniques like selective laser melting (SLM) and electron beam melting (EBM), manufacturers can achieve precise placement of continuous fibers within the metal matrix. This enables the creation of high-performance components that go beyond traditional geometric constraints.

(2) Smart and digital processing

The industry is moving toward AI-based process optimization and real-time monitoring. Through the implementation of digital twins and predictive maintenance, the manufacturing process will become a closed-loop system. Multi-modal sensor data and machine learning algorithms will be used to monitor tool wear and fiber fracture in real-time, ensuring autonomous decision-making and consistency.

(3) Ultra-precision and sustainable machining

Future machining will prioritize both high accuracy and environmental responsibility. Micromachining will provide fine surface finishes, while green cutting technologies, such as minimum quantity lubrication (MQL), dry machining, and material recycling, will minimize environmental impact. These advancements aim to reduce tool wear when handling abrasive fibers while maintaining superior surface quality.

(4) Application expansion and market trends

The ultimate goal is to promote the widespread application of CFMMCs across diverse high-tech sectors. Key markets include aerospace (airframes and engine components), automotive (lightweighting and chassis parts), high-end equipment, and medical devices. Research will drive cost reduction and performance tailoring to meet the specific requirements of these extreme service environments.

(5) Manufacturing challenges and research opportunities

To realize this outlook, research must address critical bottlenecks, such as the rapid tool wear caused by abrasive fibers (e.g., SiC, C) and the difficulty of achieving dimensional accuracy in micro-machining. Developing reliable in-skill monitoring sensors and optimizing process parameters for varied multi-material compositions remain the primary frontiers for future innovation.

In summary, the manufacturing of CFMMCs is evolving into an intelligent, sustainable, and highly integrated ecosystem. By overcoming current machining challenges through digital twins and green technologies, CFMMCs are set to become a cornerstone material for the next generation of aerospace and high-performance engineering applications.

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# 连续纤维增强金属基复合材料加工中的挑战与策略：从传统加工到非传统加工

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**摘要：**连续纤维增强金属基复合材料（Continuous fiber-reinforced metal matrix composites, CFMMCs）具有优异的比强度和耐高温性能，是航空航天领域极具应用潜力的先进结构材料。然而，其各向异性和非均质结构导致加工过程中面临严峻挑战，包括刀具磨损、纤维拔出和界面脱粘等问题。本文综述了CFMMCs加工技术的研究现状，重点分析了能场辅助加工的作用机制及其局限性。传统加工（Conventional machining, CM）过程中材料去除机制复杂，涉及塑性变形、脆性断裂和界面失效等多种形式。超声振动辅助加工（Ultrasonic vibration-assisted machining, UVAM）可通过声软化效应降低切削力和残余应力，而激光辅助加工（Laser-assisted machining, LAM）则能够诱导纤维韧性转变和基体软化。飞秒激光加工进一步实现了高精度、低损伤烧蚀加工。尽管已取得上述进展，但在各向异性效应、工艺参数协同匹配以及加工损伤与服役寿命关联机制等方面仍存在研究不足。本文还分析了多能场协同、基于人工智能的闭环控制以及增减材一体化平台的发展趋势。最后，结合当前发展现状与航空航天制造需求，提出了CFMMCs加工技术的未来发展方向。

**关键词：**连续纤维增强金属基复合材料；传统加工；能场辅助加工；基于人工智能的闭环控制

**研究亮点：**

1. 系统综述了CFMMCs从传统加工到特种加工的研究进展及主要加工难题。
2. 阐明了基体塑性变形、纤维脆性断裂和界面失效耦合作用下的材料去除机制。
3. 对比分析了超声振动、激光和飞秒激光等能场辅助加工方法的作用机制与局限性。
4. 提出了多能场协同、智能闭环控制、损伤-寿命关联和增减材一体化等未来发展方向。