

REVIEW

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Machined surface formation and integrity control technology of SiC_p/Al composites: a review

Biao Zhao¹, Jianhao Peng¹ and Wenfeng Ding^{1*}

Abstract

SiC particle reinforced Al matrix composites (SiC_p/Al MMCs) have been widely used in aerospace and other fields due to their excellent mechanical properties, and their machined surface integrity is crucial for the use of new generation high-tech equipment. In order to enhance the understanding and regulation of machined surface integrity in Al matrix composites, this article provides a comprehensive review of the research advancements regarding influential factors, damage characteristics, creation techniques for machined surfaces, as well as technologies for controlling machined surface integrity both domestically and internationally. The present study discusses the key issues and solutions in the processing of aluminum matrix composite materials, along with examining the extent and mechanism of various energy field assistance influence on the surface integrity of mechanically processed aluminum matrix composites. Ultimately, this article proposes future research prospects for achieving high surface integrity machining of aluminum matrix composites.

Keywords SiC_p/Al composites, Surface integrity, Energy field assisted machining, Machining damage

1 Introduction

Al matrix composites are composite materials prepared by using a second phase as the reinforcing material and Al (or Al alloy) as the matrix material [1]. The material exhibits exceptional comprehensive properties, including low density, high specific strength and modulus, minimal expansion, excellent thermal conductivity, and outstanding reliability. It has demonstrated promising prospects for extensive applications in aerospace, transportation, nuclear energy, and electronic packaging fields (Fig. 1). The advancement in Al-based composite materials has facilitated the production of lightweight, flexible, and high-performance aircraft and satellites in the

contemporary aerospace industry. For example, Pratt & Whitney Group's SiC_p/Al MMCs was used as an engine fan outlet guide vane on the Boeing 777. Reports show that Al-based composites exhibit 7 times greater erosion resistance than resin-based composites in terms of impact resistance, resulting in a cost reduction of over 30%. Additionally, Al MMCs have gained widespread use and are currently one of the most popular research topics in the manufacturing industry.

The incorporation of reinforcing phases, however, compromises the plasticity, toughness, and machinability of Al MMCs, rendering them challenging to machine. This is primarily evidenced by the accelerated tool wear rate during machining operations, subpar surface finish post-machining, and occurrence of multiple defects [2]. The integrity of the machined surface of Al MMCs is crucial as a key material in the aerospace field [3]. The quality of the machined surface directly impacts product performance, and once accuracy or quality falls short, repairing it becomes nearly impossible. The processing

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Fig. 1 Application of Al matrix composite materials in various fields

of damage can result in surface and interior deterioration of the material, leading to a reduction in its mechanical properties and constraining the optimal design of composite material structures [4]. The presence of processing damage, which serves as the root cause for crack initiation, significantly diminishes the fatigue life of components under cyclic loading conditions. Consequently, this leads to catastrophic failures and incalculable losses during operation. The extensive application of Al MMCs in various fields is severely impeded by the existence of processing damage. The suppression of processing damage and the achievement of high-quality processing in Al MMCs are of significant importance for their application. Consequently, extensive theoretical and experimental research on this topic has been conducted by scholars both domestically and internationally.

This article provides a comprehensive review of the research progress on influencing factors, damage characteristics, surface formation, and surface integrity control technologies of Al-based composite materials during processing, both domestically and internationally.

Furthermore, it discusses the key challenges faced in the processing of Al-based composite materials along with their corresponding solutions. Finally, the research prospects for high surface integrity machining of aluminum matrix composites (Al MMCs) were proposed. Figure 2 illustrates the developmental process of surface creation and control technology to ensure superior surface integrity in Al-based composite materials.

2 Typical damage characteristics and influencing factors

The SiC_p/Al MMCs represent the most prominent category of Al-based composite materials, wherein aluminum or its alloy serves as the matrix and is reinforced with hard and brittle SiC particles. The presence of SiC reinforcement complicates the internal structure of SiC_p/Al composites, rendering cutting operations challenging [11]. The primary manifestations include the intricate contact and friction conditions between the reinforced particles within the matrix and the cutting tool during the machining process, resulting in escalated tool wear

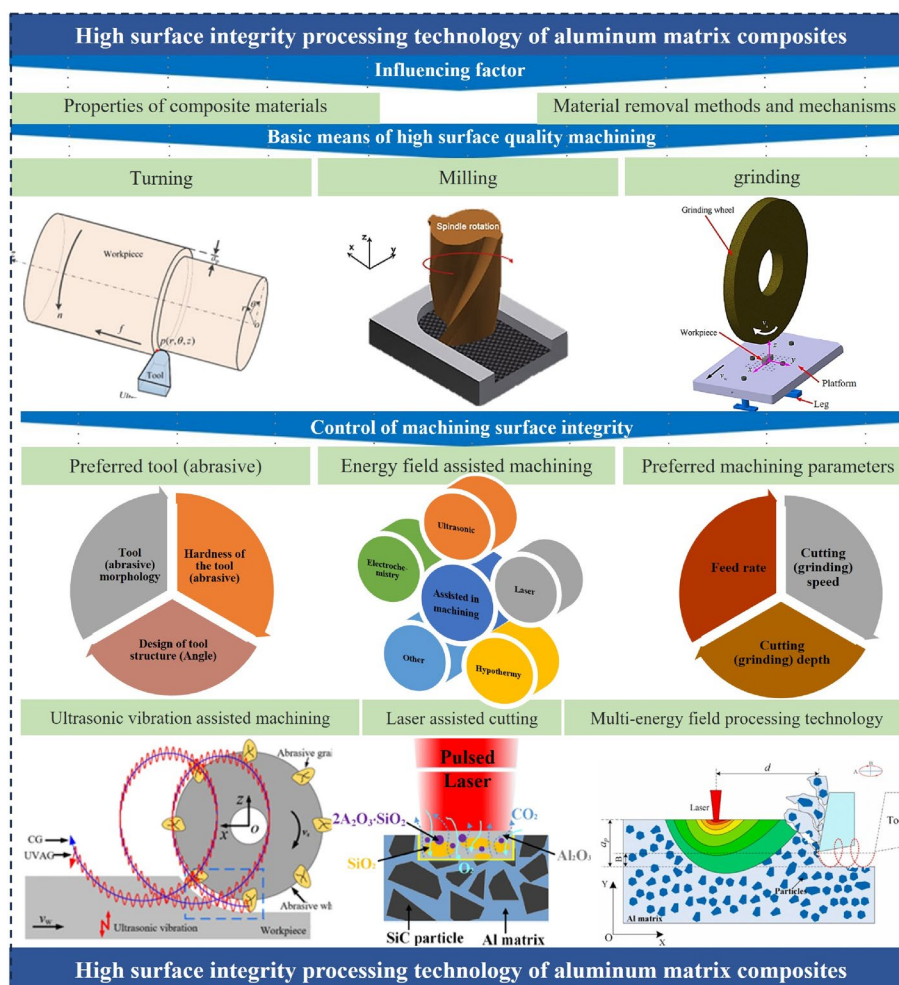


Fig. 2 Surface formation and surface integrity control of Al matrix composite materials [5–10]

and significantly reduced tool lifespan [12]. Furthermore, there exist notable disparities between the reinforced particles and the matrix material in various aspects, thereby leading to a significant impact on the machined surface due to particle motion and deformation behavior [13]. During the cutting process, a significant number of surface and subsurface damages, such as micro voids and microcracks, are generated. Additionally, the accumulation of dislocations caused by inconsistent deformation near the reinforced particles also alters the material removal mechanism, leading to a substantial reduction in both service life and performance of the material.

The combination of finite element analysis (FEA) and experimental investigations is employed by researchers to examine the deformation and failure of materials throughout the modeling process. By comparing the obtained results with experimental data, consistent damage phenomena are produced, thereby revealing the underlying mechanism of damage development.

Additionally, it should be noted that the morphology of machining damage is influenced by both the relative position of reinforcing particles and the cutting edge of the tool. Pramanik et al. [14] simplified the cutting process of particle reinforced composite materials into three scenarios. The interaction between cutting tools and particles alters the fracture and debonding behavior of particles, potentially leading to localized surface hardening during machining. Liu et al. [15] improved the model and summarized the effect of SiC particle removal mode on surface damage morphology. When the cutting edge is positioned above the reinforced particles, it will traverse over them, resulting in micro fragmentation on their surface. Conversely, when the cutting edge is situated within the center of the reinforced particles, fracture will occur at their midpoint. When the cutting edge is positioned below the reinforced particles, it may cause the reinforced particles to be extracted from the matrix, resulting in surface pits. Interfacial debonding could also occur

in all three scenarios. Some studies [16, 17] have also reached similar conclusions, and it has been found that the size of SiC particles significantly affects the quality of the processed surface.

The processing damage of SiC_p/Al composite materials can be categorized into surface damage, subsurface damage, and edge damage based on their respective locations. Among them, typical surface damage features include:

fragmentation of SiC particles, formation of holes due to extraction of SiC particles, grooves formed by scratching the machined surface with SiC particles, cracks formed around SiC particles due to interface debonding, tearing of Al matrix and its coating on the workpiece surface (Fig. 3a-c) [18]. The typical characteristics of subsurface damage primarily encompass particle fracture resulting from direct contact and stress transfer, particle

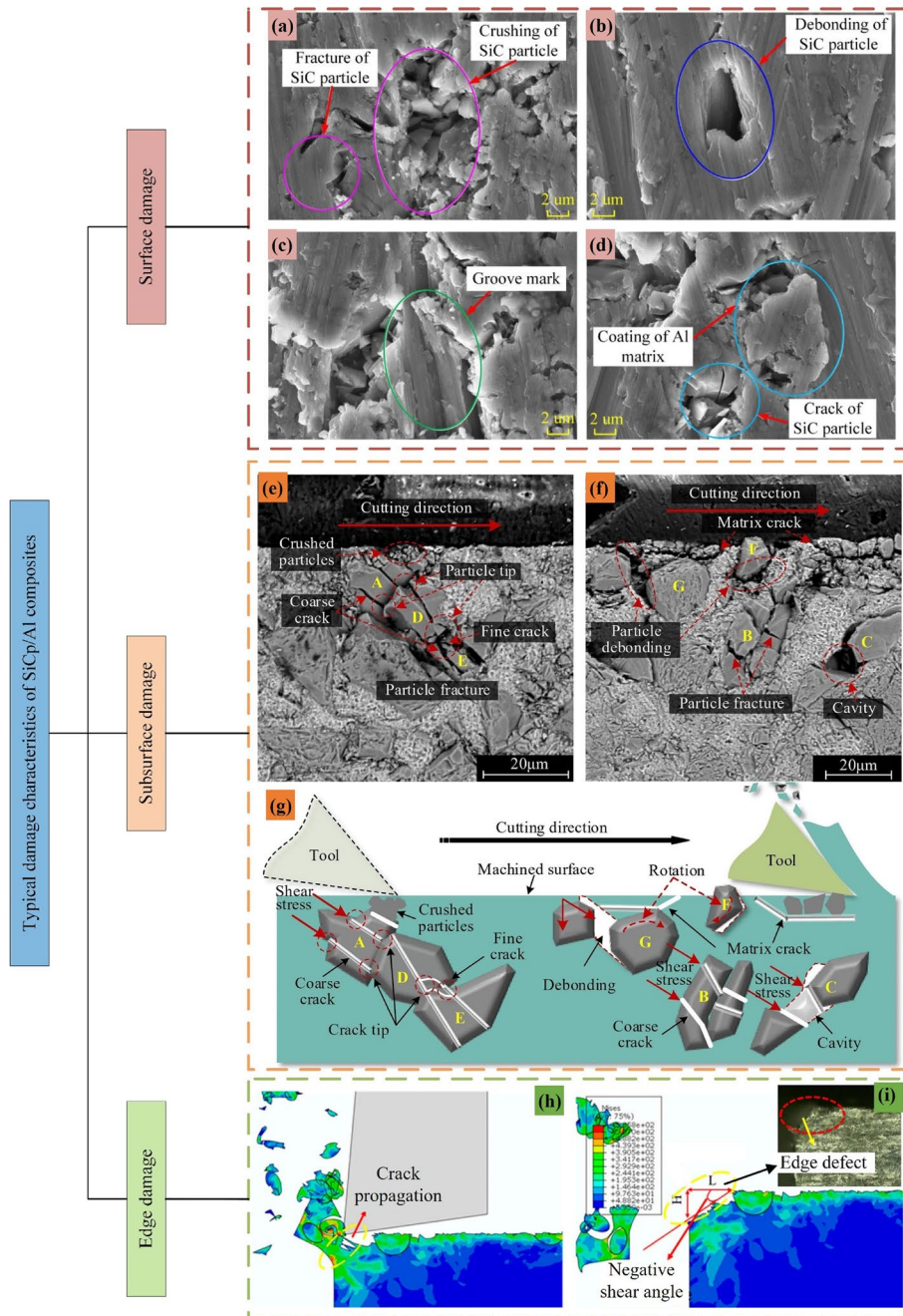


Fig. 3 Processing damage of SiC_p/Al composite material [18–20]

detachment caused by direct contact and matrix displacement, as well as matrix cracking induced by crack propagation (Fig. 3d-f) [19]. The primary manifestation of edge damage is observed as severe edge collapse at the periphery of the workpiece [20], particularly in areas where the flat machining tool cuts into the workpiece (Fig. 3h-i). The primary causes of edge collapse damage include particle fracture, interfacial debonding, and matrix ductile fracture resulting from crack propagation along the negative shear plane. Moreover, an increase in the volume fraction of SiC particles enhances the susceptibility to edge collapse damage during the machining process. Hu et al. [21] explained the formation mechanism of drilling entrance damage in SiC_p/Al composite materials, suggesting that edge damage caused by crack opening and brittle fracture occurs when the maximum principal stress in the outer edge area of the drill bit exceeds the material's tensile strength limit.

The concept of surface integrity typically encompasses parameters such as surface roughness, surface defects, subsurface damage, and residual stress. Attaining optimal machining for high surface integrity is imperative in the application of Al MMCs. Extensive research has been conducted to investigate the influential factors on surface integrity during machining [22, 23].

From the perspective of the workpiece's inherent properties, the characteristics of the reinforcement play a pivotal role in determining the surface quality of the workpiece post-processing. Wu et al. [24] established a 2D model of SiC_p/Al2024, demonstrating that the size, shape, and volume fraction of SiC particles directly affect the machinability of the material. Teng et al. [25] created a 2D milling FEA model of SiC_p/Al composite material reinforced by micro/nanoscale particles (Fig. 4). The tool particle interaction and machined surface morphology of two different scales of Al MMCs were compared. Research findings indicate that nanoscale reinforced particles exhibit enhanced integrity and reduced susceptibility to fracture during the cutting process. The chip morphology exhibits continuity and the surface quality is enhanced, whereas micron-sized particles are susceptible to fracturing and debonding due to stress concentration, leading to chip segmentation and an increase in surface defects. Chen et al. [26] investigated the effect of reinforcement size and distribution on the cutting mechanism using simulated approaches. The machining performance of composite materials can be enhanced by achieving an optimal state with consistent dimensions and uniform dispersion, which also helps to mitigate fluctuations in cutting force and elevate machining quality.

However, simulation of randomly distributed states can better simulate actual working conditions. Bao et al. [27] used the Johnson–Cook constitutive model to

simulate the removal process of 45% and 65% SiC particles, and combined with experiments to study the phenomenon and pattern of burr formation during SiC_p/Al cutting. They infer that a high proportion of SiC volume has an adverse effect on improving surface integrity, as it increases overall brittleness and tensile stress during processing, leading to increased risks of Al burrs protruding, interface debonding, and particle crushing. The key elements controlling the surface morphology of composite materials are the properties and orientation distribution of the reinforcement, as well as the cutting tool. The work hardening of composite materials is directly related to variations in reinforcing size [28].

Choosing different processing methods or adjusting and optimizing processing techniques is the main means for researchers to improve the surface integrity of machining. Lu et al. [29] investigated the surface integrity of SiC_p/Al MMCs using diamond cutting tools and a small depth multiple cutting turning process. Research suggests that the method of multiple cuts with small cutting depths greatly eliminates machining residual stress, with the maximum residual stress being only about 37% of that of a single cut. Secondly, this technology also reduces the hole size of the cutting surface. Hung et al. [30] pointed out that there is a critical cutting depth for brittle plastic transition in MMCs. Zhou et al. [31] obtained through experiments that the cutting speed range for converting surface defects into plastic deformation in 25% SiC_p/Al composite materials is between 100 mm/min and 200 mm/min. Saini et al. [32] used variance analysis and regression equations to determine the optimal cutting amount.

Essentially, the machined surface integrity of Al MMCs is closely related to the removal method and mechanism of reinforcement [33]. Wu et al. [34] established a 3D turning simulation model to study the effect of particle fracture mode on the machined surface. Particle fragmentation, total particle extraction, and particle compression entering the matrix are all observed in SiC reinforced particles. The cutting surface quality improves when the particle failure mode is mostly particle cutting. Therefore, particle properties (volume fraction, shape, size), processing methods, and particle removal methods are the main factors that affect the integrity of the processed surface. The following will be elaborated in detail in the specific processing technology.

3 Surface creation and surface integrity control

Currently, the material removal technologies for Al based composite materials include cutting (mainly turning and milling), grinding, and special machining processes (including high-pressure jet cutting, electric spark cutting, and laser cutting). However, pure special machining

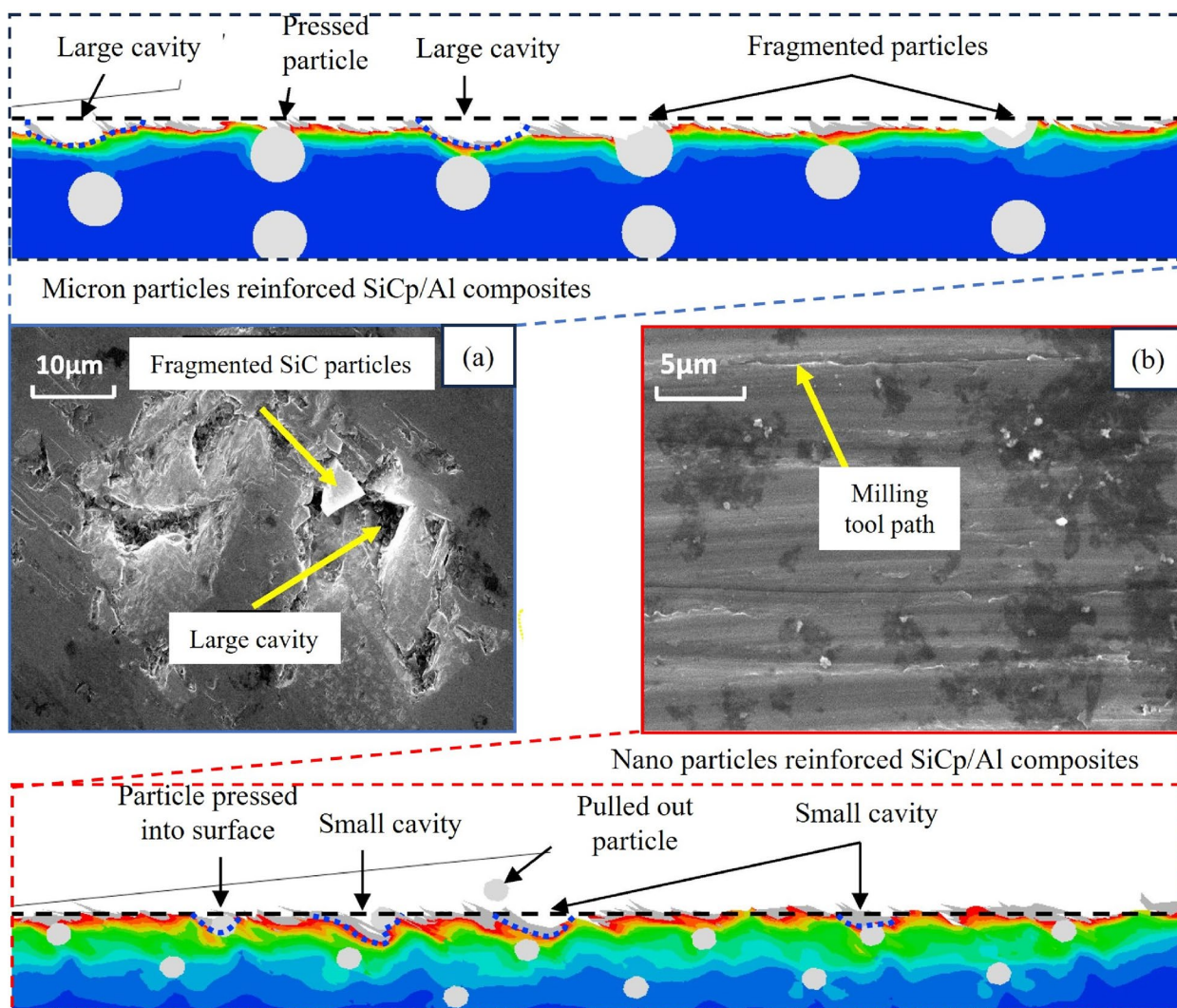


Fig. 4 Milling simulation and surface morphology of two types of enhanced particle sizes [25]

is only used for material segmentation or removal, resulting in low surface quality and difficult to meet the high-precision and high-quality surface requirements in aerospace and other fields [35, 36], Therefore, it will not be discussed separately in this article. This section mainly introduces the latest progress in cutting, grinding and energy field assisted machining technologies in the field of Al MMCs.

3.1 Cutting process

Cutting is the main method for high-quality and efficient removal of Al MMCs, mainly divided into turning and milling. Turning is the most basic and common cutting method, occupying a very important position in production. It is used to process workpieces with rotating surfaces, including Al MMCs. Milling is mostly used in the

form of end face milling to process the flat surface of Al matrix composite workpieces.

Numerous studies have delved into the existence and formation mechanisms of machining defects during the cutting process. When Srivastava [37] turned A359/B₄C/Al₂O₃ composite materials, it was pointed out that during the cutting process, holes are easily formed around silicon carbide particles and aggregate along the shear plane to form microcracks. The formation of these holes and cracks increases with the increase of feed speed. Particles are prone to fracture during the cutting process due to the high stress applied, which is also the main cause of crack initiation and will affect the fatigue life of the workpiece [38]. Zhou et al. [39] established FEA cutting models for two types of SiC_p/Al MMCs, as shown in Fig. 5, taking into account the influence of the shape of SiC_p (circular and irregular) on simulation accuracy. Analysis

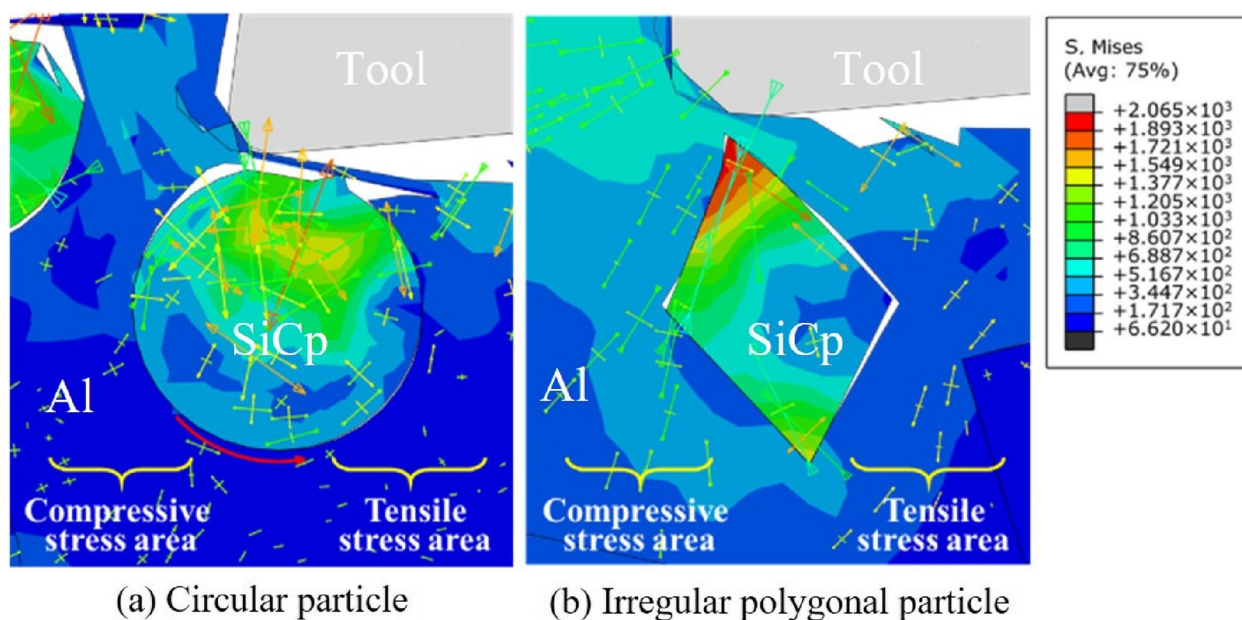


Fig. 5 Finite element cutting models with different enhanced particle shapes [39]

suggests that irregular polygons can more accurately reflect stress distribution and more specifically depict the generation and propagation of microcracks, which is conducive to a more comprehensive prediction of the degree of subsurface damage. Wu et al. [40] developed a FEA model for turning with polygonal SiC particles in order to investigate the material removal mechanism. It was found that SiC particles are prone to fragmentation during the machining process, and are mostly brittle eroded, forming defects such as voids on the machining surface. Xiang et al. [41] pointed out that the chip morphology will be affected by high shear strain in the first deformation zone during high-speed dry turning of 15% volume fraction Al6061/SiC_p composite material, and increasing cutting speed will cause the chips to evolve from serrated to intermittently broken chips.

Due to the extremely high hardness of SiC particles, this may result in rapid tool wear throughout the machining. Therefore, tool material selection, tool structure, and morphology all play a crucial role in optimizing the machining surface integrity of Al MMCs. High speed steel (HSS) has lower hardness and wear resistance, far from meeting the requirements for cutting SiC_p/Al composite materials. Hard alloy tools (WC) only perform well when the volume fraction of SiC particles is low. The core of research on low damage machining tools for SiC_p/Al composite materials is to improve tool wear resistance and sharpness. PCD tools have extremely high hardness and can maintain high wear resistance. They exhibit superior cutting ability when machining hard particle

composite Al matrix materials, and have been found to achieve ductile removal of hard SiC particles. Bian et al. [42] conducted precision milling experiments on SiC_p/Al composite materials with a volume content of 65% SiC particles and an average diameter of 60–80 μm using a single crystal diamond milling cutter with a diameter of 3 mm. The results revealed that an extremely low surface roughness value of R_a of 0.078 μm was obtained under processing parameters such as spindle speed of 10 000 r/min, feed rate of 1 μm per tooth, and cutting depth of 2 μm. Ding et al. [43] examined the cutting performance of PCBN and PCD tools in the turning process of SiC_p/Al MMCs. It was found that there is a positive relationship between the surface quality of machining and tool wear. The higher surface finish of PCD tools is attributed to the low adhesion of diamond materials and the higher wear resistance of PCD tools [44]. Overall, for processing SiC_p/Al MMCs, the higher the hardness of the tool material, the lower the surface roughness.

In addition to the tool material, the structure and surface morphology of the tool have also been proven to affect the quality of the machined surface. A study [45] showed that during turning, the larger the tool rake angle, the lower the surface roughness. The tool rake angle also has an impact on edge damage. As the rake angle increases, the size of edge damage in right angle cutting first decreases and then increases [46]. Liu et al. [47] showed that turning SiC_p/2024Al changed the removal mode of hard particles (pulling and cutting—pressing and cutting) with an increase in negative rake

angle. The surface roughness was the smallest when the tool rake angle was -30° . Lu et al. [48] established a two-dimensional cutting simulation model considering the characteristics of the particle matrix interface, and studied the influence of PCD geometric parameters (mainly the tool rake angle) on the machinability of SiC_p/Al composite materials. The change in tool rake angle can significantly affect the stress state and particle removal form in the machining area, ultimately affecting cutting force and surface integrity. Positive rake angle tools can easily pull particles out of the substrate, causing large surface cavities, while negative rake angle tools can easily cause particles to press into the machined surface and form small cavities. The experimental and simulation results are shown in Fig. 6. The optimal rake angle was -5° , which was conducive to particle fracture and the formation of a smooth machined surface with small cavities. Wang

et al. [49] investigated how textured PCD tools affected cutting performance, as shown in Fig. 7. Infrared nano-second laser processing was used to machine rounded micro grooves on the tool and used for processing SiC_p/Al composite materials. The textured tool reduces cutting force and tool wear, reduces R_a value by 20%, and reduces the interaction between the tool and chips, improving the anti-adhesion effect of the tool surface.

The surface integrity of SiC_p/Al composite materials is highly dependent on particle content and particle size in the material. Researchers investigated the effect of particles on machining surface integrity using various cutting process parameters, giving a theoretical foundation for optimizing the cutting process of Al MMCs.

Zhou et al. [50] established a high-volume fraction (56 vol%) SiC_p/Al MMCs heterogeneous composite FEA model. The particles are randomly distributed polygons,

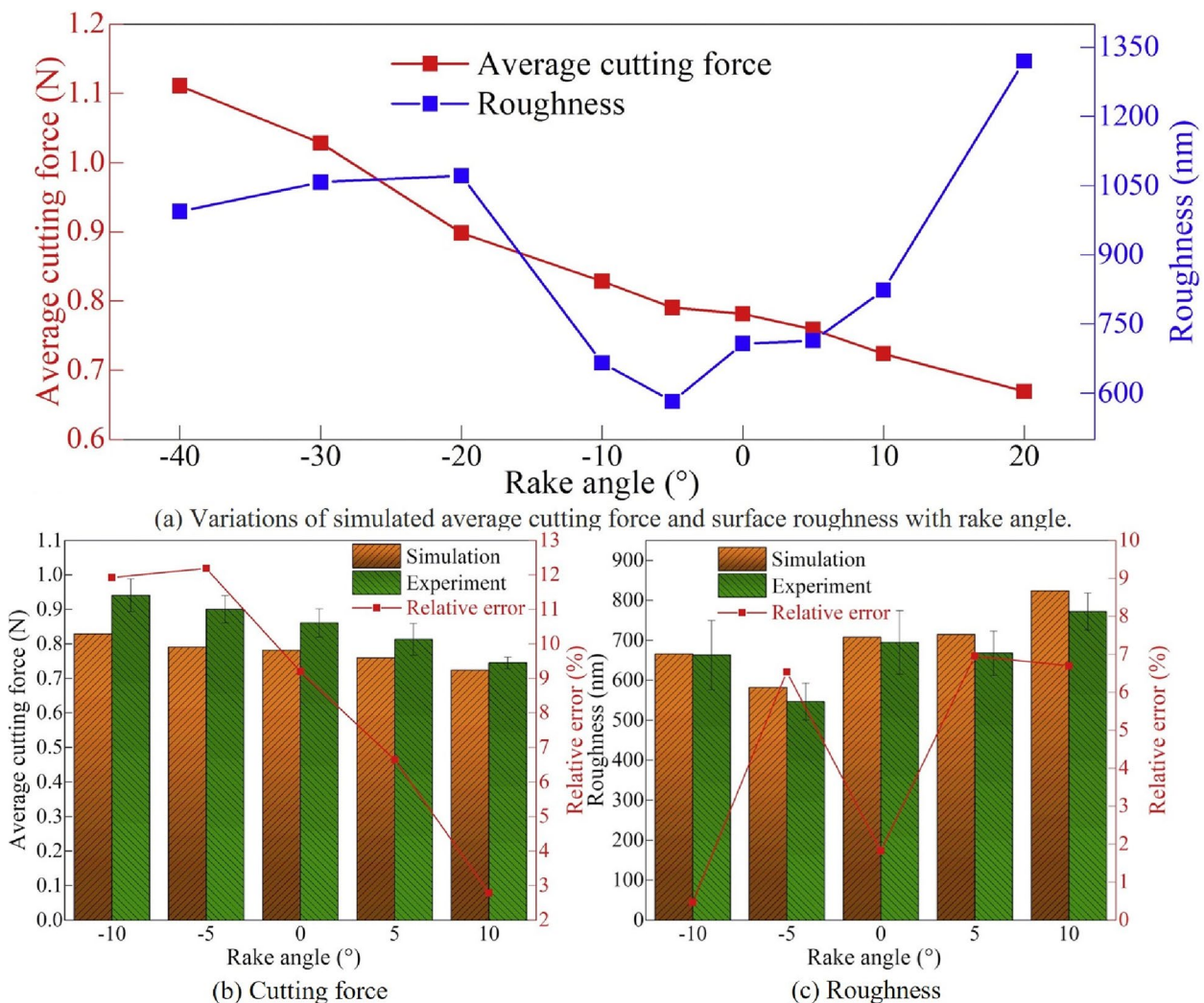


Fig. 6 Relationship between the effect of tool rake angle on average cutting force and roughness [48]

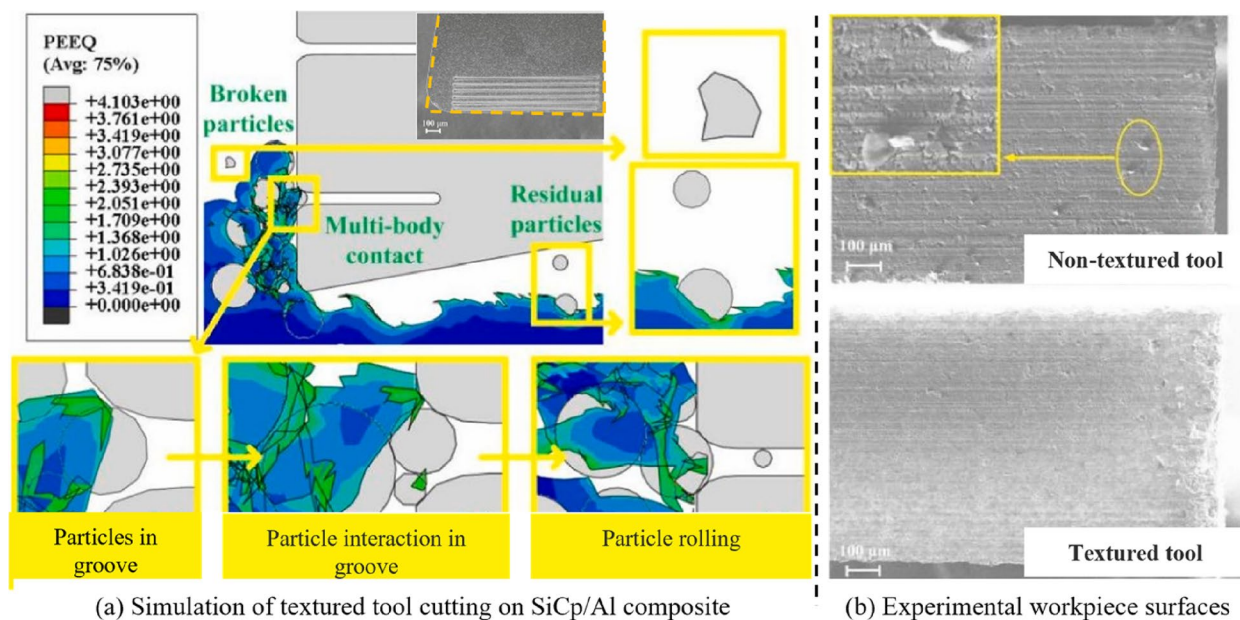


Fig. 7 Cutting simulation and machining surface morphology of texture tools [49]

and the failure behavior of SiC particles is described using the brittle fracture criterion. In addition to studying the effects of different processing parameters on the machinability (surface quality and sub surface residual stress) of composite materials, the formation mechanism of edge defects in cutting SiC_p/Al composite materials with cutting tools was also emphasized. Research has shown that the surface quality and edge defects of machining mainly depend on the form of particle fracture, including fragmentation, partial fragmentation, cutting, fracture, and extraction. Increasing cutting speed and reducing cutting depth is beneficial for reducing the size of edge defects. Pramanik et al. [51] used diamond blades to turn 20% SiC_p/Al MMCs and found that the roughness of the machined surface is most affected by the feed rate. After processing, there is residual compressive stress on the surface, which is caused by the squeezing effect of the tool on SiC particles. Moreover, increasing the feed rate can reduce the longitudinal compressive residual stress. Baburaj et al. [52] experimentally recorded the surface roughness values of 5% SiC_p/Al MMCs turning with hard alloy blades, and optimized the turning parameters of SiC_p/Al (cutting speed, feed rate, cutting depth, and tool tip radius) using genetic algorithm, establishing a surface roughness model. The model shows that the feed rate and cutting depth have the greatest impact on surface roughness, while the tool tip radius has the smallest impact. Wu et al. [40] discussed the effect of cutting depth on the surface integrity and cutting force of Al MMCs with a

20% particle volume ratio through experiments and FEA models, and analyzed the formation mechanism of sub-surface damage. Liu et al. [15] investigated the effect of cutting speed on the removal mode of SiC particles, and the results showed that at higher cutting speeds, due to the work hardening of the matrix, the fracture strength was increased, and more stress was applied to SiC particles, making the stress on SiC particles faster and easier to reach their fracture limit. The fracture of SiC particles occurred before debonding, making it easier for SiC particles to be cut off rather than pulled out, thereby reducing larger machining damage such as pits. Wu et al. [53] have drawn different conclusions through simulation that when the cutting speed is low, the fracture of SiC particles will occur before the interface debonding. These conflicting results may be caused by different interface failure criteria.

The milling process parameters also play an important role in the quality of the processed surface [54]. Jayakumar et al. [55] conducted milling experiments on SiC/Al356 composite materials using ball end milling cutters and found that the surface roughness R_a decreased with increasing cutting speed, feed rate, and cutting depth, fluctuating between 0.564 and 2.804 μm . Zhang et al. [56] analyzed through orthogonal experiments that increasing milling speed can affect the accumulation of chips on the cutting edge, resulting in unstable cutting conditions and an increase in surface roughness. Zhang [57] used PCD micro milling cutters to process 20% volume fraction SiC_p/Al2009 composite materials. The influence of feed

rate, milling speed, and milling depth on surface quality gradually decreases. Xiong et al. [58] obtained a similar conclusion when milling 6% TiB₂/Al composite materials, and the feed rate has a major impact on surface roughness. In addition, he also studied the variation pattern of residual stress, which is positively correlated with the feed rate range and negatively correlated with the milling speed. Overall, the conclusion is that smaller cutting depths, lower cutting speeds, and smaller feed rates lead to better surface finish.

3.2 Grinding process

Grinding processing is the process of numerous abrasive particles being scraped, plowed, and formed into chips to remove material from the workpiece substrate material [59]. Grinding is often used as the final manufacturing process for SiC_p/Al composite materials, exerting a direct influence on the ultimate surface quality. Conventional grinding of SiC_p/Al can produce good machined surface quality with minimal damage [13, 60]. The processing method, however, is also associated with the limitations of minimal material removal per pass and rapid abrasive wear [61].

The characteristics of the cutting tool during the cutting process significantly impact the workpiece's machinability. Similarly, the type of grinding wheel and the arrangement of abrasive particles have an impact on the workpiece's grindability. Xu et al. [62] proposed using SiC grinding wheels for grinding SiC_p/Al composite materials, where a large number of SiC particles were broken and attached to the grinding surface. Considering the high economic efficiency of SiC grinding wheels, they are considered to have the potential for rough grinding of SiC_p/Al MMCs. Du [63] reported that when using

diamond grinding wheels to finely grind 10% SiC_p/Al MMCs, the removal methods of SiC particles exhibit diversity, with fewer brittle fractures and more shear removal (plastic removal), resulting in higher surface quality during grinding. Under the same processing conditions, the surface quality of SiC_p/Al composite materials processed with SiC grinding wheel, CBN grinding wheel, and diamond grinding wheel gradually increases, while surface damage such as debonding, particle breakage, and surface cracks of the reinforcement in the workpiece gradually decreases [64]. Researchers have found great potential for textured grinding wheels to improve the quality of ground surface processing [65, 66]. Li et al. [67] used laser pulse ablation technology (PLA) to texturize diamond particles and dry grind 70% SiC_p/Al composite material using this diamond grinding wheel. The abrasive texturing treatment formed multiple micro cutting edges, as shown in Fig. 8. Multiple micro cutting edges reduce the thickness of each material removal, reducing the probability of brittle removal. On the other hand, they also increase the chip capacity of the grinding wheel, resulting in lower grinding temperature and higher surface integrity. After grinding, delamination and holes are commonly formed on the machined surface of SiC_p/Al workpieces, which is due to the coating of the Al substrate on the ground surface and the pulling out of hard particles. The volume content and processing parameters of the enhanced particles are expected to exert a significant influence on the surface quality of the processing.

The grinding process parameters, serving as the primary means for adjusting the quality of the grinding surface in traditional grinding processes, have been extensively investigated. When SiC_p/Al composite

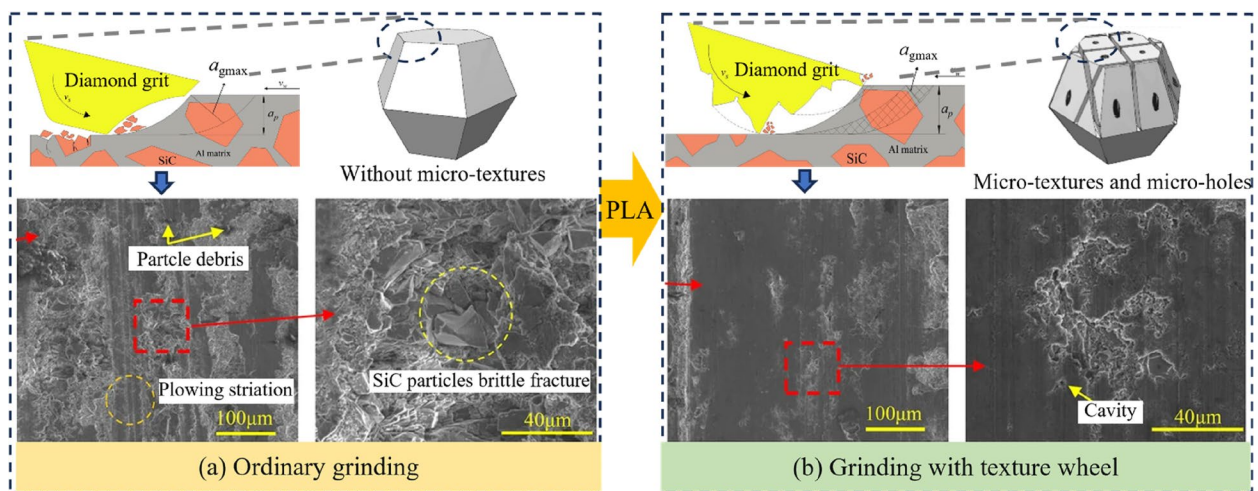


Fig. 8 Grinding mechanism and machined surface of abrasive textured grinding wheel [67]

materials are ground, the removal method is a combination of toughness and brittle breakage. Grinding settings can be changed to change the proportion of toughness and brittle fracture. As the feed speed and grinding depth rise, severe buildup and adhesion phenomena occur on the grinding surface [68]. Du et al. [69] established a simulation model for single diamond grinding, which studied the effects of cutting depth and cutting speed on particle removal and surface formation processes. When the cutting depth was small, there was less collision and friction between abrasive particles and SiC particles. When the cutting speed was high, the Al coating cover up some defects, and the scratch surface of the workpiece was the smoothest. Zhu et al. [70] developed a surface roughness prediction model for 70% SiC_p/Al MMCs. Based on this, the lowest surface roughness can be quickly obtained by optimizing the grinding wheel speed, workpiece feed speed, and grinding depth. Gao et al. [71] established a prediction model for grinding surface roughness of 60% SiC_p/Al composite materials. The model evaluated the impact of three grinding parameters on surface roughness, and the spindle speed had the highest impact. As the speed increased, the surface roughness dropped and subsequently rose. The degree of effect of grinding depth is second, and as the grinding depth increases, the surface roughness first increases and then reduces. Surface roughness is positively connected with feed rate, which has the least influence on it. The minimum value of surface roughness R_a was obtained as 0.51 μm under the same process optimization. Guo et al. [3] used ceramic bonded CBN grinding wheels to process SiC_p/Al workpieces and studied the effect of grinding speed on surface and subsurface damage. The research content covers the evolution of surface damage morphology, the control mechanism of Al crystallization on the sub surface, the effect mechanism of oxygen rich zone distribution on sub surface cracks, and the material removal mechanism. The increase in grinding speed reduces defects such as surface scratches and dents, reduces the plastic deformation of subsurface Al crystals (Fig. 9), reduces the thickness of the first and second deformation zones (Fig. 10), and improves the surface integrity of SiC_p/Al MMCs through high-speed (307.0 m/s) grinding.

However, compared to cutting, there is relatively little research on the grinding process of SiC_p/Al MMCs, and it mainly focuses on the grinding performance of grinding wheels. The wear and blockage of grinding wheels are the difficulties in the grinding process of SiC_p/Al MMCs. This is because during the grinding process, the grinding debris itself can absorb relatively less heat and carry it away. Most of the heat is transferred to the workpiece through the grinding wheel, causing a sudden increase in the temperature of the processing area. Due to the lower

melting point of the aluminum matrix in comparison to silicon carbide, it is more susceptible to undergoing a phase transformation into a molten state. Consequently, the molten aluminum matrix envelops and adheres to the silicon carbide particles, resulting in their bonding with the grinding wheel and subsequently leading to blockage [72].

3.3 Energy field composite processing technology

The increasing demand for surface integrity in machining has rendered traditional mechanical removal alone insufficient. Currently, the development trend in high surface integrity machining technology for SiC_p/Al composite materials involves integrating traditional cutting processing with other non-traditional energy fields to maximize their respective advantages. There are now numerous non-traditional processing methods available for SiC_p/Al MMCs, including as laser aided machining (LAM) and ultrasonic vibration-assisted machining (UVAM), which have been shown to increase surface quality and minimize cutting force [73]. To reduce hardness, enhance ductility, and minimize component damage, LAM integrates localized high-temperature heating with conventional processing techniques. It primarily encompasses laser-assisted turning and milling.

3.3.1 Ultrasonic vibration-assisted machining technology

The UVAM method incorporates ultrasonic vibration into traditional cutting and grinding techniques, enabling the tool or workpiece to experience both high-frequency and regular vibrations while in motion, as shown in Fig. 11. The characteristic of intermittent cutting is observed, which significantly impacts the reduction of cutting force and cutting temperature. Furthermore, it has been experimentally demonstrated to possess advantages in enhancing machining surface quality and diminishing cutting force [74]. It finds extensive application in the processing of hard and brittle materials, high-temperature alloys, as well as composite materials.

UVAM is also applied to machining Al MMCs, and there are advantages in surface integrity during machining [75]. Kim et al. [76] conducted routine turning and ultrasonic vibration-assisted turning (UVAT) experiments on SiC_p/Al composites with particle content of 17% and 15%, and found that the surface roughness of UVAT decreased by 33% and 52.5%, respectively. Wang et al. [18] used ultrasonic vibration-assisted milling to process 20% SiC_p/Al MMCs. Research has shown that UVAM can effectively reduce surface defects. Zhou et al. [72] used rotational ultrasonic surface grinding to grind (45%) SiC_p/Al MMCs. Compared with conventional grinding, the average surface roughness can be reduced by 11.53%. The UVAM process was very crucial

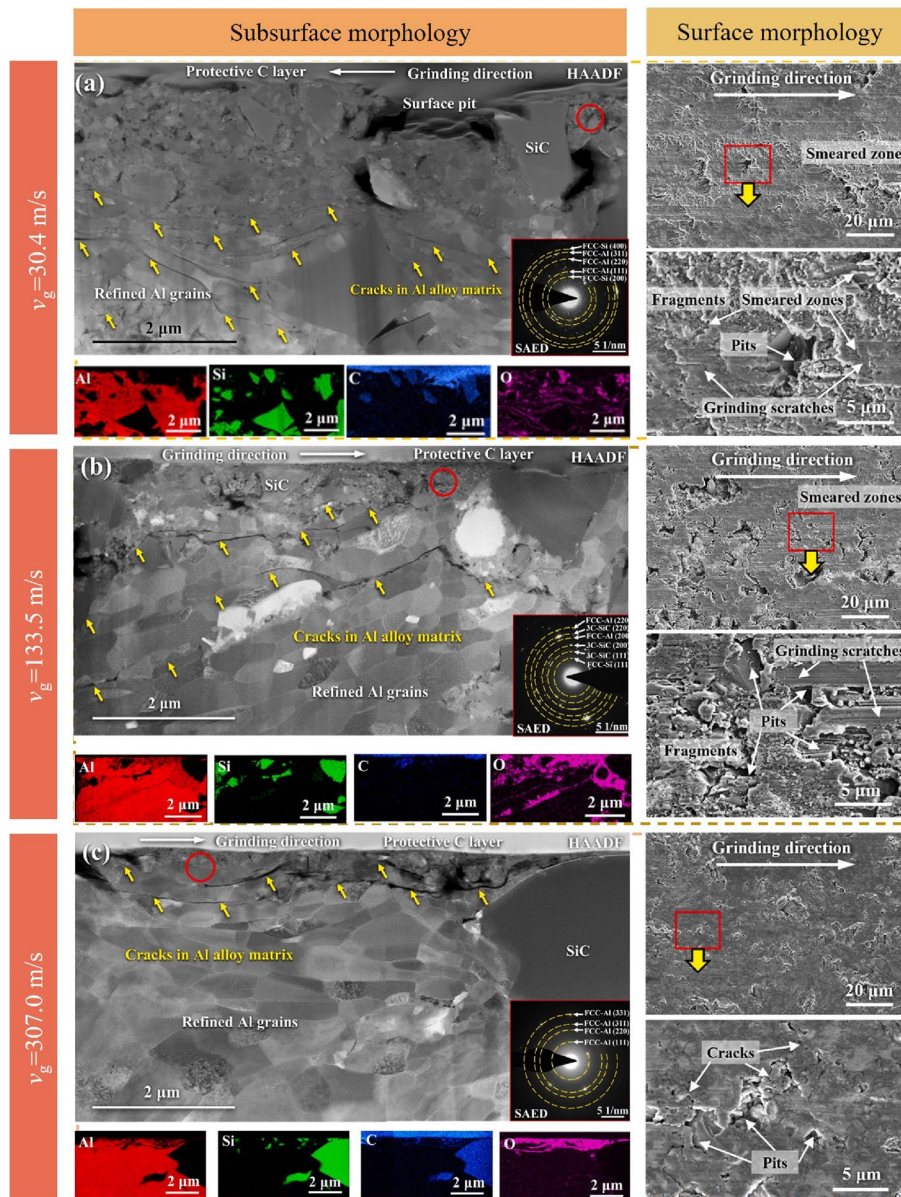


Fig. 9 Effect of grinding speed on subsurface morphology and surface morphology [3]

in determining the quality of the machined surface. Ying et al. [77] studied the ultrasonic vibration-assisted grinding (UVAG) process of SiC_p/Al, and obtained the proportion of the influence of ultrasonic amplitude and grinding parameters on surface roughness through single factor experiments. The conclusion was: ultrasonic amplitude > feed speed > grinding wheel linear speed > grinding depth. The minimum value of R_a was obtained as 0.151 μm when the amplitude was fixed at 2 μm . The machined surface roughness is significantly influenced by the different texture morphologies generated due to variations in vibration characteristics. Liu et al. [78]

suggested using higher cutting speeds and vibration frequencies in ultrasonic vibration-assisted milling, which can reduce surface roughness by more than 40%.

A significant number of researchers have conducted an in-depth analysis on the factors contributing to enhanced surface quality in UVAM through a comprehensive examination of ultrasonic motion characteristics and material removal mechanisms. Zhou et al. [79] studied the mechanism of ultrasonic vibration and material removal during the turning process of SiC_p/Al composite materials through scratch experiments. He believed that ultrasonic vibration can reduce surface roughness

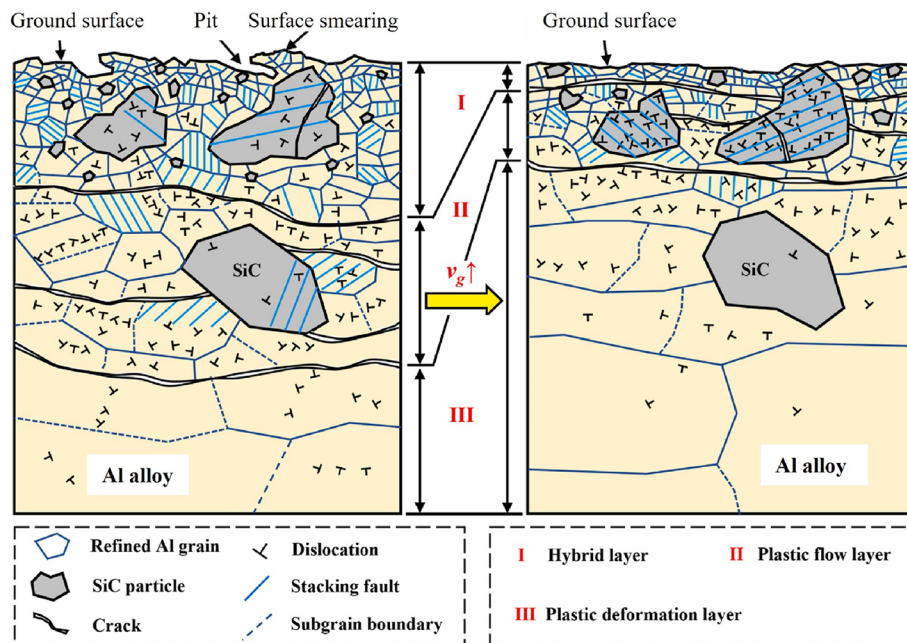


Fig. 10 Effect of grinding speed increase on machining deformation zone [3]

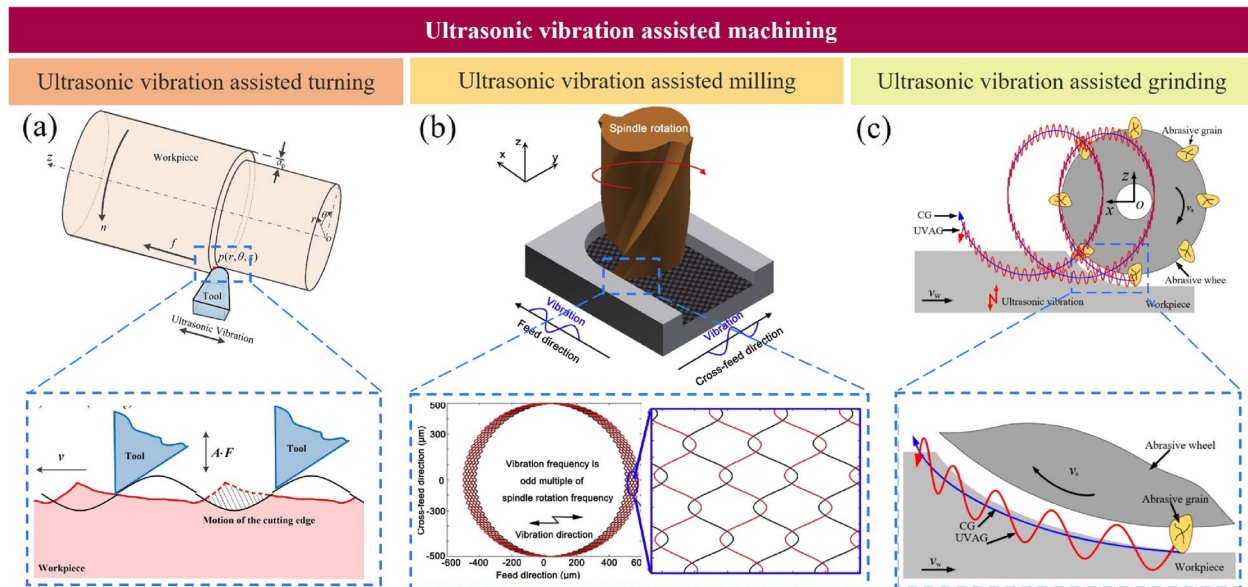
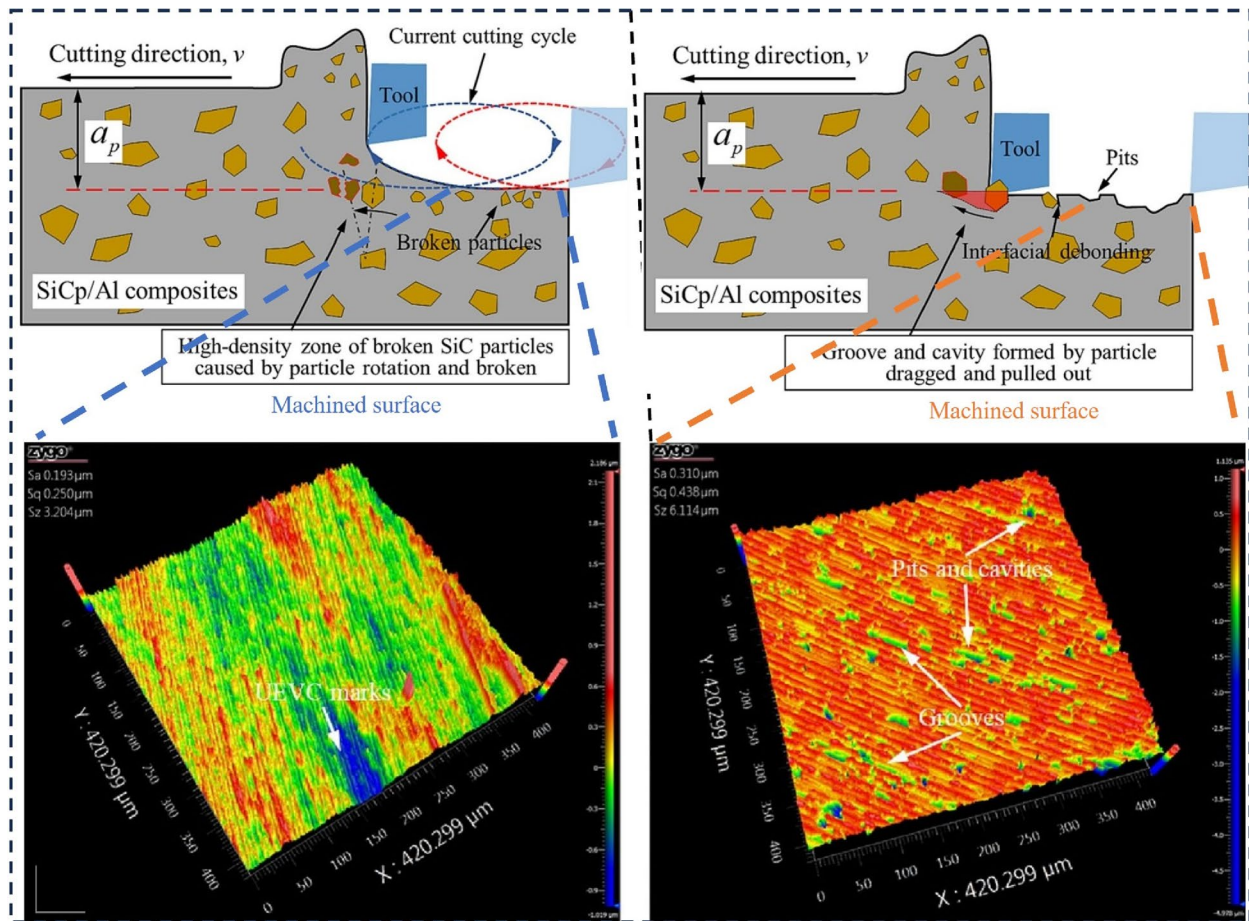


Fig. 11 Three types of ultrasonic vibration-assisted machining models and their motion trajectories [5, 6, 8]

by about 20%. The machining schematic and surface are shown in Fig. 12a and b. High frequency vibration provides greater cutting kinetic energy, making it easier for SiC particles to be broken and filled into defects such as pits, reducing surface scratches caused by broken particles during movement. From Fig. 12c, it can be concluded that the roughness values (R_a and R_z) increased with the

increase of cutting speed. Compared with CT (traditional turning), the roughness values of UVAT surface were significantly reduced, reaching about 20%. In traditional cutting processes, with the advancement of the cutting edge, the passive aggregation of particles is enhanced, ultimately leading to cluster detachment. This is also the reason why surface roughness increases with the increase



(a) Ultrasonic vibration-assisted turning

(b) Conventional turning

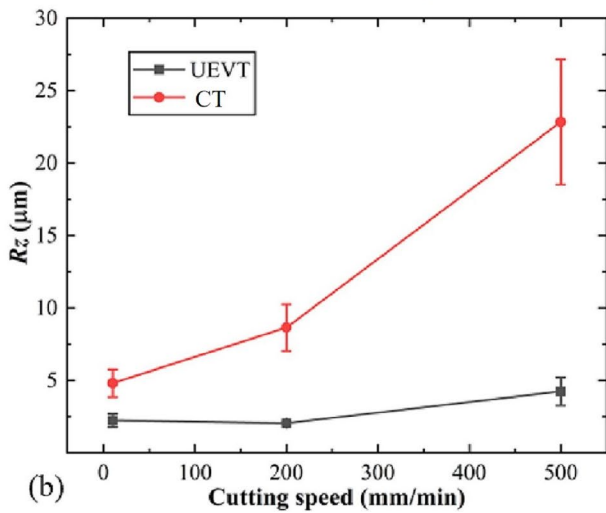
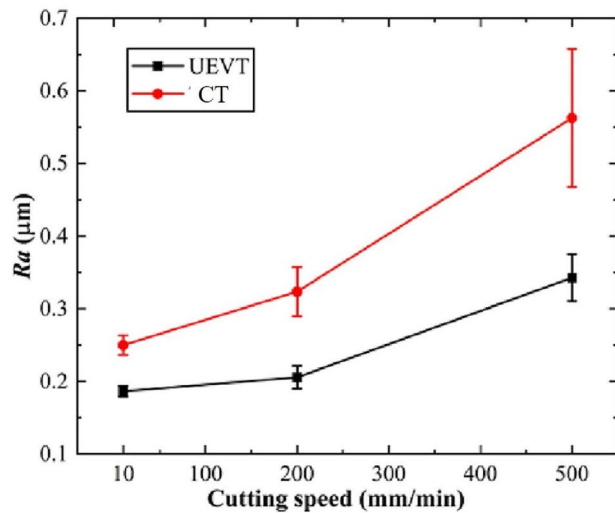


Fig. 12 Schematic diagram of comparison between ultrasonic vibration-assisted turning and traditional turning [79]

of cutting speed. Scholars have reached a similar conclusion through experiments [80]. In traditional turning, the fracture strength of SiC particles was 1427 MPa. In

contrast, UVAM reduced the fracture strength of SiC by 89 MPa. Du et al. [81] discussed the effect of dynamic impact of ultrasonic elliptical vibration on the material

removal mechanism. Ultrasonic elliptical vibration improved the machinability of composite materials. From the perspective of removal process of hard particles, the difficulty of particle fracture was reduced, mainly due to the acoustic softening effect of ultrasound. Li et al. [82] conducted a similar rotational ultrasonic vibration single scratch experiment for high volume fraction composite materials. The sound softening effect and high strain rate impact force brought by ultrasound make hard SiC particles easier to crack and be pressed into the Al matrix, thus filling the defects while also suppressing crack propagation. In terms of subsurface damage, it has also been reduced, as explained by the "skin effect" and stress relaxation effect. Zheng et al. [83] conducted experimental research on ultrasonic vibration-assisted single particle cutting of SiC_p/Al composite materials. The results demonstrated that ultrasonic vibration effectively fractures SiC particles into smaller fragments, thereby enhancing the material removal rate. Simultaneously, the cutting force and friction coefficient between the workpiece material and abrasive particles were observed to be lower compared to conventional machining techniques.

The utilization of ultrasonic vibration cutting overcomes challenges encountered in traditional cutting and

grinding processes, including excessive cutting force, significant tool wear, and subpar surface quality. Table 1 shows the comparison of output parameters between the ultrasonic vibration assisted machining process of SiC_p/Al and traditional mechanical machining. By harnessing the acoustic softening effect of ultrasonic vibrations, the challenges associated with removing difficult-to-machine materials have been significantly mitigated, thereby showcasing remarkable capabilities in enhancing surface quality and minimizing subsurface damage. Moreover, ultrasonic assistance has proven to be highly effective in ameliorating grinding wheel clogging issues and prolonging their operational lifespan.

3.3.2 Laser assisted machining technology (LAM)

LAM is a precision manufacturing technique that involves utilizing a laser beam to heat the workpiece, inducing microstructural changes or localized material modification near the tool, followed by cutting to remove excess material. During the LAM process, external heat sources are utilized to thermally activate local workpiece materials prior to processing, resulting in material softening or modification. Consequently, facile removal using tools is facilitated. Moreover, a substantial

Table 1 Ultrasonic vibration-assisted machining processes and output parameters

Reference	Material	Hybrid process	Process parameters	Output parameters
Wang et al. [18]	SiC _p /Al6160 (20%, 8 μm)	Ultrasonic vibration-assisted milling	Frequency: 25 kHz Amplitude: 2–10 μm Cutting speed: 2000 r/min Feed: 10 mm/min Depth of cut: 0.08 mm	Cutting force: ↓17.03% Surface roughness: ↑23.9%
Zhou et al. [72]	SiC _p /Al (45%, 3 μm)	Rotary Ultrasonic Machining	Frequency: 38.5 kHz Amplitude: 10 μm Cutting speed: 188 m/min Feed: 200 mm/min Depth of cut: 0.04–0.20 mm	Cutting force: ↓13.86% Surface roughness: ↓11.53%
Kim et al. [76]	micro-SiC _p /Al 2124 (17%; 25%)	Ultrasonically assisted turning	Frequency: 22.3 kHz Amplitude: 28 μm Cutting speed: 10–60 m/min Feed: 0.1–0.14 mm Depth of cut: 0.1–0.16 mm	Cutting force: ↓60.5% and 29.5% Surface roughness: ↑33% and 52.5%
Ying et al. [77]	55% SiC _p /Al	Ultrasonic Vibration-Assisted Grinding	Frequency: 38.5 kHz Amplitude: 7 μm Grinding speed: 6.28 m/s Feed: 500 mm/min Depth of cut: 0.02 mm	Cutting force: ↓13.86% Surface roughness: ↓11.53%
Zhou et al. [79]	SiC _p /Al2024 (25%, 10 μm)	Ultrasonic elliptical vibration-assisted turning	Frequency: 43.194 kHz Amplitude: 3.9/3.59 μm Cutting speed: 200 mm/min Feed: 0.2 mm/rev Depth of cut: 0.025 mm	Surface roughness: ↓20%
Bertolini et al. [84]	SiC _p /Al (31.5%, 25 μm)	Ultrasonic vibration-assisted turning	Frequency: 30 kHz Amplitude: 5 μm Cutting speed: 60/120 m/min Feed: 0.02/0.06/0.1 mm/rev Depth of cut: 0.05 mm	Tool wear: ↓51% Surface roughness: ↓21%

reduction in cutting force ensues, thereby yielding superior surface quality. The majority of current research on LAM of SiC_p/Al MMCs focuses on turning and milling processes.

Laser assisted processing rapidly softens difficult to machine materials and improves their machinability. Abedinzadeh et al. [85] studied laser assisted turning (LAT) of SiC-Al₂O₃/Al composite materials, and Fig. 13 shows the machining schematic. The results demonstrate that laser preheating can lower cutting force by 26%, and surface roughness decreased with the decrease of cutting force. Surface roughness was reduced by 51% when cutting conditions were adjusted (laser power, cutting depth, and cutting speed). Zhai et al. [86] analyzed the microstructure, residual stress, and roughness of the machined surface following the LAM experiment, and found that LAM was superior to traditional turning techniques, with a considerable drop in surface roughness values. Through studies on LAM of SiC_p/Al composite materials, Kong et al. [87] investigated the wear of hard alloy tools and the surface roughness of workpieces. They discovered that the surface roughness achieved by LAM under the same conditions was lower, and that the tool wear rate was reduced by 2.31 times. Deng et al. [88] suggested a novel material processing method that combines laser surface melting modification with precision milling. By controlling the laser processing parameters and enhancing the volume fraction of the material, surface laser modification experiments were conducted. The laser changed zone's milling surface and edge morphology were uniform and defect free, and the processed surface quality increased by 90.4% when compared to the original unmodified zone. Zhao et al. [9] proposed a

novel laser assisted micro milling technology, as shown in Fig. 14.

In an oxygen rich environment, nanosecond laser induced generation of easily removable metamorphic layers, combined with mechanical milling, can easily (with minimal cutting force) remove high-quality SiC_p/Al composites with high particle size ratio ($S_a = 147$ nm). The main advantage lies in the laser modification of Al matrix composite materials, which enhances workpiece machinability, reduces tool wear, and consequently improves processing integrity.

Laser can melt and evaporate SiC particles and Al substrates, making them very suitable for high feed rates and improving processing efficiency. However, due to the varying temperature rise rates and other features of the two materials, controlling the quality of the treated surface is difficult [89, 90]. Kong et al. [91] also conducted LAM experiments and found that tool wear can be significantly reduced within the preheating temperature range of 220–320 °C. From the perspective of the effect of LAM of SiC_p/Al MMCs, its advantage mainly lies in reducing tool wear, with little influence on reducing machining damage. Niu and Chen [54] found that thermal loading can also enhance surface integrity through surface defect coatings based on deformable substrates, resulting in smoother surfaces. But it will lead to a decrease in the mechanical properties of the coating surface. Wang et al. [92] studied LAM of 45% SiC_p/Al MMCs. Although the surface defects such as dents and voids were significantly reduced, thermal cracks were inevitably generated at high laser temperatures. The experiment of laser assisted high-speed cutting of 17% SiC_p/Al MMCs also showed a similar phenomenon. This method can effectively

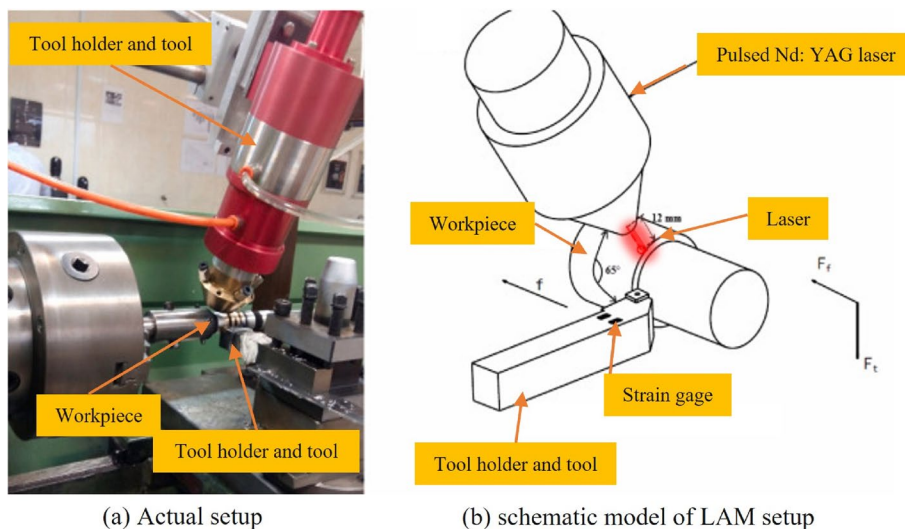


Fig. 13 Laser assisted turning device [85]

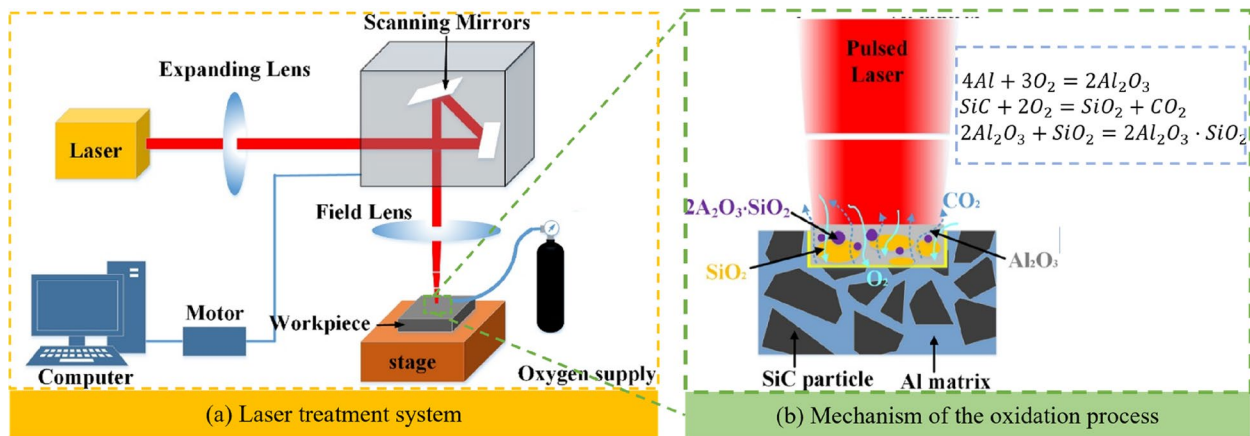


Fig. 14 Laser surface modification system and its principle [9]

improve surface quality and significantly improve production efficiency, but the laser generates thermal residue at high temperatures [93].

Table 2 shows the comparison of output parameters between the LAM processing technology of SiC_p/Al and traditional mechanical machining. However, the use of cutting fluid is often omitted in this process, and strict control over laser power is necessary to prevent the expansion of thermal impact and internal damage to the material [94]. Additionally, the softening of metal caused by high temperatures from the laser and blockage of the grinding wheel make it unsuitable for grinding operations.

3.3.3 Other auxiliary processing technologies

Ultra-low temperature assisted machining (ULTAM) is the addition of a liquid nitrogen cooling system on the basis of traditional machining techniques to achieve an ultra-low temperature environment in the cutting area. Under ultra-low temperature conditions, the plasticity of the Al matrix decreases and the supporting effect on silicon carbide particles increases [97]. Zhang et al. [98] sprayed low-temperature liquid nitrogen to the milling center in the form of spray during the PCD tool milling of 45% SiC_p/Al composites, as shown in Fig. 15a. Under low temperature conditions, using a higher milling speed (above 240 m/min) helps to reduce the micro hardness

Table 2 Laser-assisted mechanical machining processes and output parameters

Reference	Material	Hybrid process	Process parameters	Output parameters
Zhao et al. [9]	SiC _p /Al (65%, 10 μm)	Laser-induced oxidation assisted micro-milling	Laser power: 8 W Feed rate: 0.3 μm/z spindle speed: 20,000 r/min Cutting speed: 30–60 m/min Depth of cut: 2 μm	surface roughness: ↓66.7%
Zhai et al. [86]	SiC _p /2024Al (45%, 5–10 μm)	Laser-assisted turning	Laser power: 50 W Feed rate: 0.01–0.10 mm/z Cutting speed: 30–60 m/min Depth of cut: 0.05–0.20 mm	surface roughness: ↓81.37%
Deng et al. [88]	SiC _p /2024Al (15%, 30%, 40% and 55%, 10 μm)	Laser surface melting modification and precision milling	Laser power: 2000 W defocus distance: 10 mm scanning speed: 50 mm/s and scanning interval: 0.5 mm	surface residual compressive stresses: ↑52.12% and 65.83% Surface roughness: ↓ max 90.36% Tool wear: ↓ 61.03%
Wei et al. [93, 95]	SiC _p /Al2124 (17%, 0.3 μm)	Laser preheating-assisted turning	Laser power: 7.5–13 kW Cutting speed: 188, 565 m/min Feed: 0.1 mm/rev Depth of cut: 0.75 mm	Cutting force: ↓ max 62.5% Tool wear: ↓ max 65% Surface roughness: ↓ max 75.4%
Zhao et al. [96]	55% SiC _p /Al	Laser induced modification-assisted milling	Laser power: 10 W Feed rate: 5, 10, 15, 20 μm/z Depth of cut: 0.1, 0.2 mm Width of cut: 10 mm	Cutting force: ↓ max 55% Surface roughness S _a : ↓ max 12% Tool wear: ↓ 25%

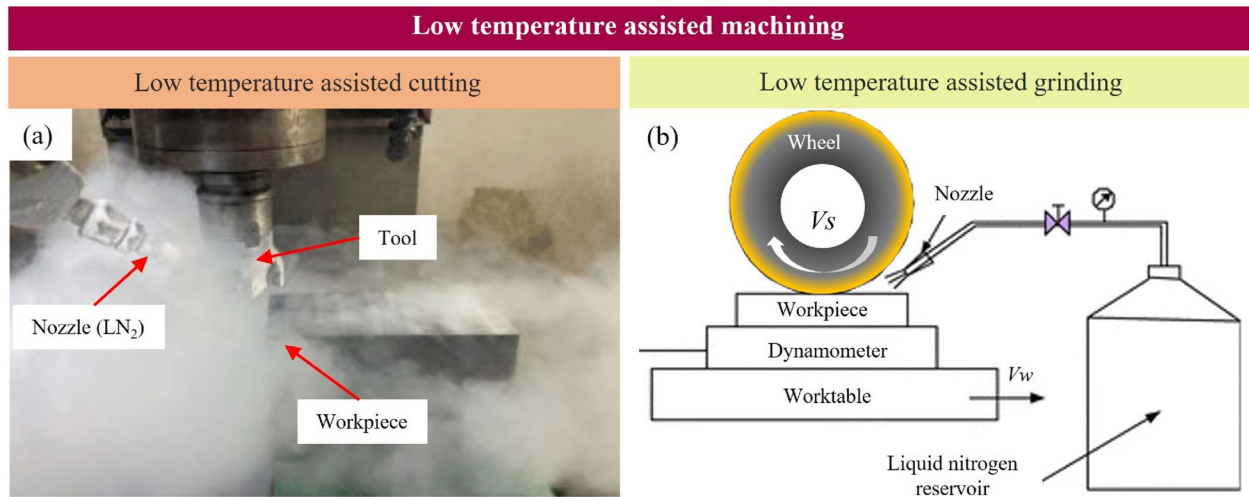


Fig. 15 Schematic diagram of ULTAM [98, 99]

and residual stress of the machined surface. Under grinding conditions, as shown in Fig. 15b, the addition of stable low-temperature conditions transforms the removal mode of SiC reinforced particles from brittle removal to plastic removal [99]. ULTAM has unparalleled advantages over conventional machining methods, including less/no environmental pollution, low health hazards, good surface integrity of parts, high machining efficiency, long tool life, and low overall machining costs. It is suitable for turning, milling, and grinding difficult to machine materials.

The surface integrity of grinding is closely related to the working surface state of the grinding wheel. For example, for super hard abrasive wheels, severe wear of the grinding wheel can cause a sharp deterioration of surface integrity. The online electrolytic dressing assisted grinding (ELID) technology is an electrochemical technique that applies current to the grinding wheel during the conventional grinding process to maintain efficient use of the grinding wheel. The schematic diagram is shown in Fig. 16. ELID is applied to ultra-precision machining of SiC_p/Al composite materials, which can increase the

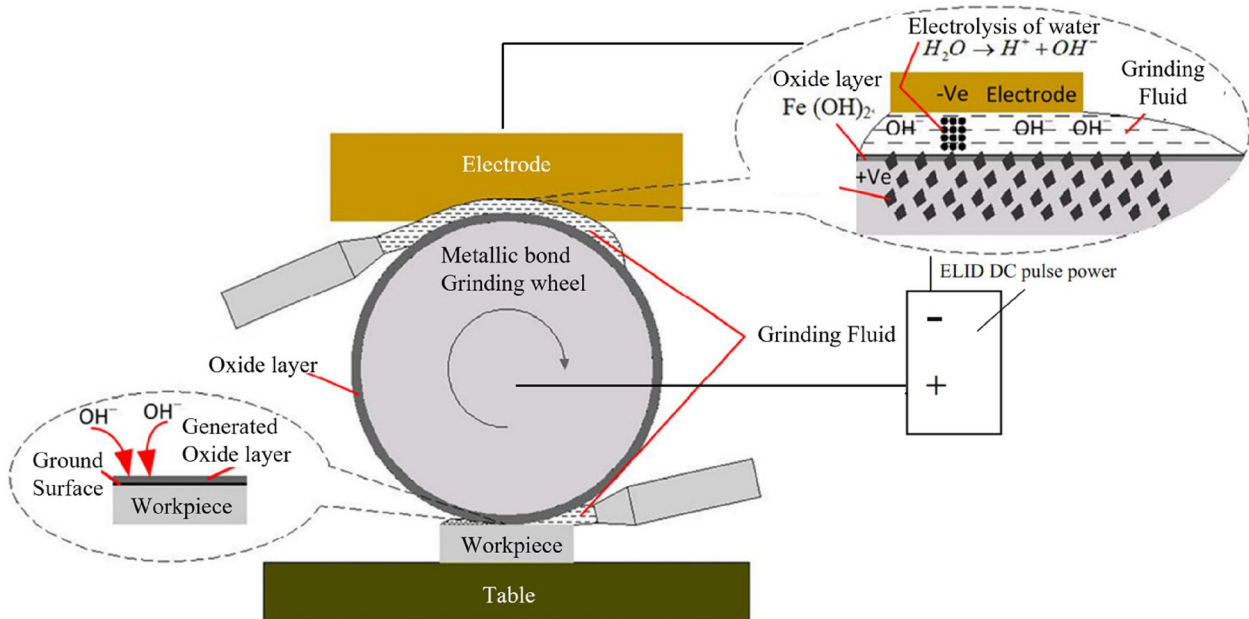


Fig. 16 ELID schematic diagram [101]

height of abrasive grains, increase the chip holding space of the grinding wheel, and greatly remove SiC particles by plasticity [100]. The common feature of both methods mentioned above is the use of grinding processing, which involves deep cutting of SiC_p/Al composite materials with very small single abrasive particles to achieve the removal of SiC particles in the ductile domain, thereby reducing machining damage. However, this technology cannot be separated from the use of a large amount of grinding fluid, which can easily cause waste and environmental pollution issues.

3.3.4 Multi energy field composite processing technology

The single energy field composite machining technology has excellent performance in cutting low particle volume fraction Al MMCs. In order to further high-quality remove (70%) SiC_p/Al MMCs, researchers have integrated ultrasonic vibration and laser into the traditional cutting process. Peng et al. [102] proposed a dual layer ultrasonic vibration composite laser assisted machining technology (L-UVAM). This multi field composite processing technology improves the plastic removal ability of (70%) SiC_p/Al composite materials, reduces surface roughness during processing, and suppresses surface and subsurface damage. Optimization of laser power is important for L-UVAM high quality machining [103]. Kim et al. [104] used L-UVAM technology to turn SiC_p/Al2124 workpiece, which reduced the chip accretion caused by turning tool in the process of LAM, reduced the cutting force and improved

the surface quality. By changing the laser power, the heat affected zone of the laser can be controlled within the cutting depth of the material. Li et al. [10] also conducted a similar study, which combines laser heating and ultrasonic vibration on the basis of conventional turning. Among them, the softening effect caused by laser heating weakens the matrix’s support for particles, reduces the overall hardness of the material, and makes it easier for the tool to push particles along the shear plane distribution. The intermittent contact separation machining method enhances heat dissipation efficiency and extends the service life of the cutting tool. As shown in Fig. 17e, it was found that there were a large number of pores on the surface of CM and a large area of matrix detachment. However, L-UVAM greatly improved this phenomenon, with only a small number of pits. In addition, the Al material was softened and coated with some surface defects by heating (Fig. 17d). Figure 17c shows that the surface roughness *R_a* of L-UVAM was significantly lower than that of CM, and the surface roughness can be minimized by optimizing laser power (200W).

In terms of grinding, Wang et al. [105] proposed a novel hybrid machining technology that comprehensively utilizes photocatalysis, electrochemistry, and mechanical grinding technology (PAECMG). The equipment schematic is depicted in Fig. 18. On one hand, this technology facilitates the electrochemical dissolution of Al to accelerate its dissolution, while simultaneously inducing abrasive particle damage to the surface passivation layer of the workpiece. On the other hand, by softening SiC

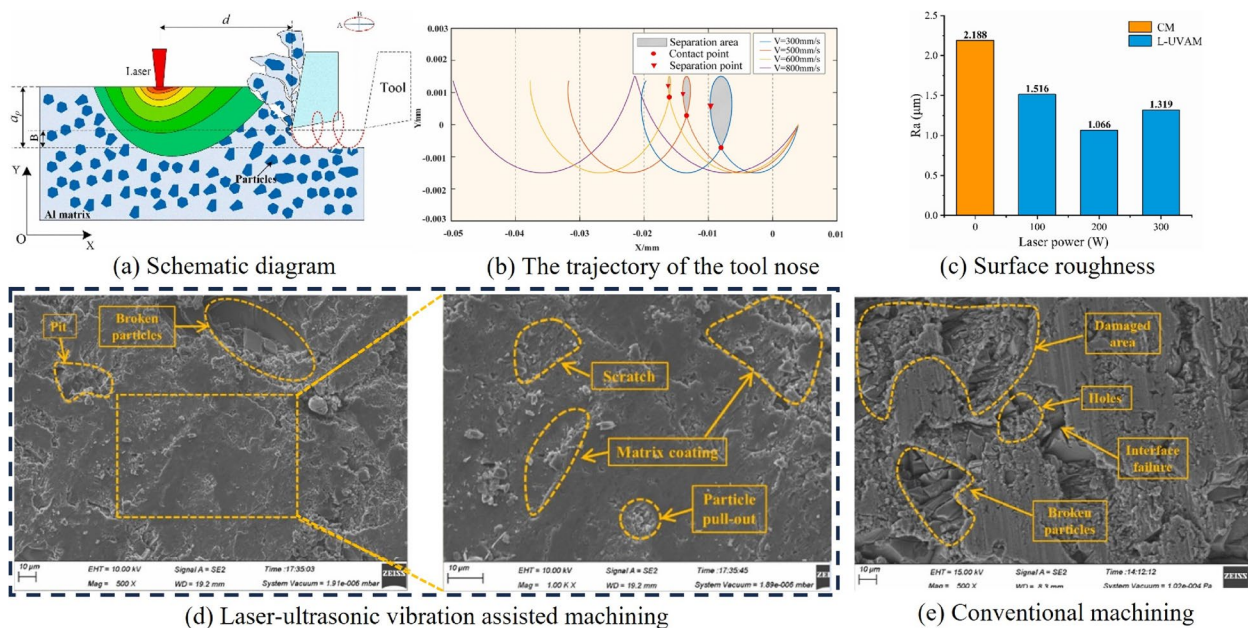


Fig. 17 Schematic diagram of L-UVAM and machined surface morphology [10]

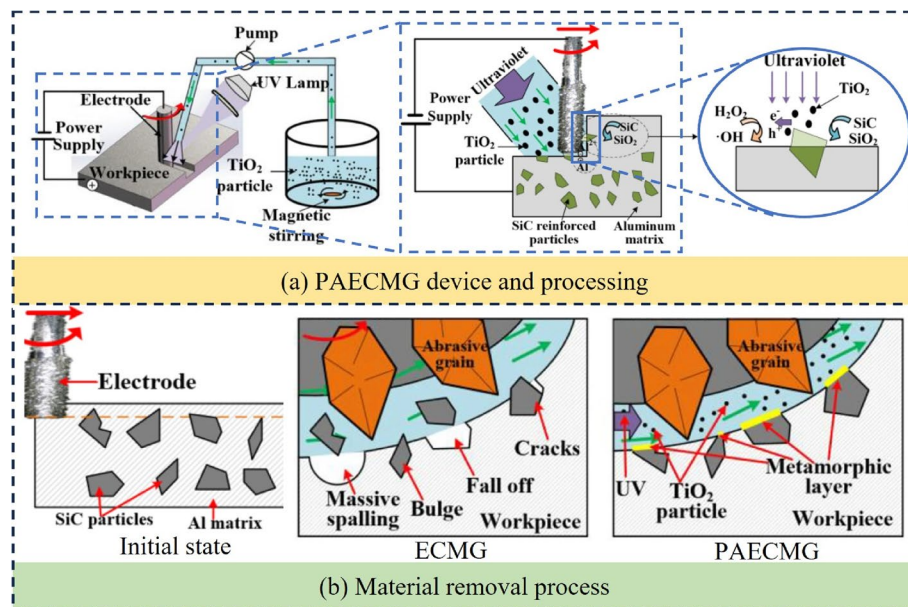


Fig. 18 Schematic diagram of PAECMG system and material removal process [105]

hard particles through photocatalytic reactions (converting SiC into SiO_2), and then cooperating with mechanical grinding, protruding SiC particles can be easily removed. From the perspective of processing effect, PAECMG technology with photocatalysis can form a neat and smooth processing surface, while electrochemical grinding (ECMG) without photocatalysis causes many pits on the processing surface.

4 Conclusion

Al matrix composites play a crucial role in various industries, particularly aerospace. This article examines the factors influencing surface integrity and damage characteristics of Al matrix composite materials during processing, providing a comprehensive review on surface creation and control technology for maintaining surface integrity throughout the process. The influence and mechanism of different energy field aids on the surface integrity of machined aluminum matrix composites were discussed. The control of surface integrity in Al matrix composites can be achieved through various methods during mechanical processing. In summary, the following points can be highlighted as follows:

- (1) To achieve high-quality processing, it is essential to focus on the suppression of processing damage. The processing damage of aluminum matrix composite materials primarily encompasses three key aspects: surface damage, subsurface damage, and edge damage. The defects generated on the processed surface

are the primary cause for diminishing the surface quality and integrity of the workpiece.

- (2) The properties of the matrix material, including its shape, volume ratio, size, and distribution state of the reinforcement, significantly impact the machinability of Al matrix composites. The mode and mechanism of removing reinforcement material are crucial factors that determine the integrity of the processed surface.
- (3) Cutting and grinding are the fundamental methods for achieving high-quality surface machining. Surface integrity can be controlled by modifying processing techniques, adjusting processing parameters, and optimizing tool (grinding wheel) characteristics. The relationship between chip state, cutting force, cutting temperature, and surface quality is inherently interconnected during the machining process. Aiming for low damage machining of Al matrix composites involves reducing both the cutting force and cutting heat.
- (4) Various energy field-assisted machining technologies, such as ultrasonic vibration, laser, low-temperature, and electrochemical methods, are effective means of enhancing the surface integrity of aluminum matrix composites during machining.

The high surface integrity processing technology of Al matrix composites has achieved significant progress. However, there are still areas with insufficient research

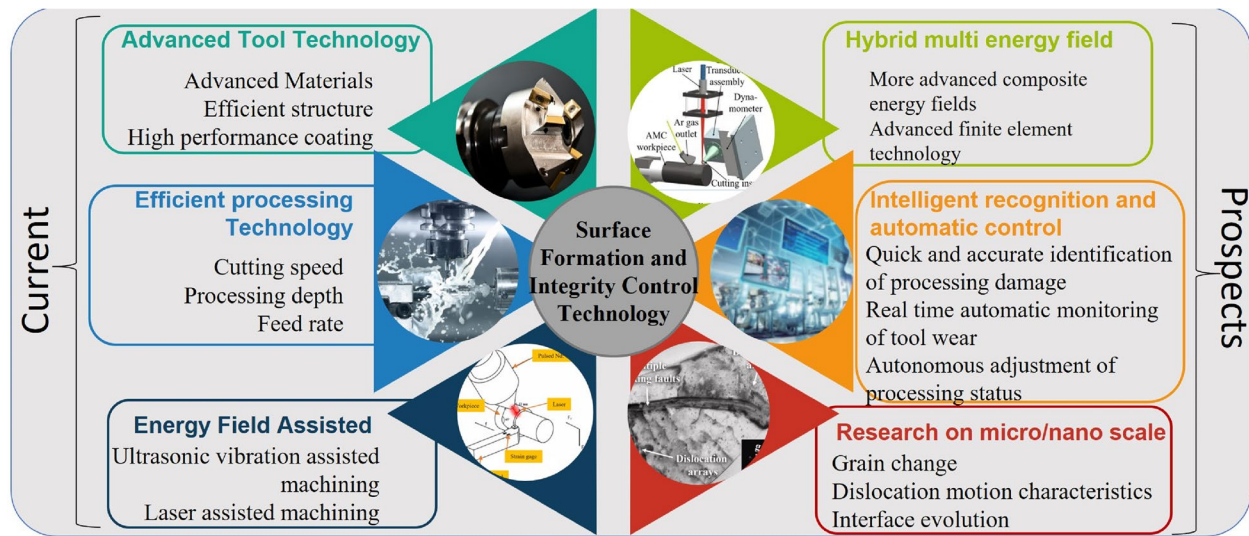


Fig. 19 Summary and prospect of surface formation and integrity control technology [3, 84, 100]

that may become future research hotspots. Figure 19 shows the summary and prospect of surface formation and integrity control technology.

- (1) There are still gaps and limitations in the research of emerging energy field-assisted technologies, such as finite element simulation of laser-assisted machining, low-temperature assisted machining, and other composite machining. Further comprehensive and systematic investigation is required to advance our understanding of these novel composite machining techniques and their impact on surface integrity.
- (2) The majority of studies primarily focus on the removal mechanism and surface integrity of materials from a macroscopic perspective, such as the evolution of damage on machined surfaces, chip states, etc. However, there is limited research that delves into material removal from a microscopic standpoint, including grain alterations, characteristics of dislocation motion, and evolution at material interfaces.
- (3) The integration of conventional processing with intelligent recognition and automated control systems may also emerge as the next prominent research direction. Enhance surface integrity through monitoring and control systems, develop intelligent technologies for monitoring and automated control of surface integrity, and enforce stringent controls on surface integrity during the production of critical components.

5 Nomenclature

SiCp/Al MMCs SiC particle reinforced Al matrix composites

- L-UVAM Laser-ultrasonic vibration-assisted machining
- Al MMCs Al matrix composites
- ULTAM Ultra-low temperature assisted machining
- PCD Polycrystalline Diamond
- PLA Laser pulse ablation technology
- PCBN Polycrystalline Cubic Boron Nitride
- FEA Finite element analysis
- UVAM Ultrasonic vibration-assisted machining
- ELID Electrolytic dressing assisted grinding
- UVAT Ultrasonic vibration-assisted turning
- CM Conventional machining
- UVAG Ultrasonic vibration-assisted grinding
- PAECMG Photocatalysis, electrochemistry, and mechanical grinding technology
- LAM Laser assisted machining
- ECMG Electrochemical grinding
- LAT Laser assisted turning

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Author contributions

Biao Zhao conducted writing (comments and editing), supervision, and visualization. Jianhao Peng conducted writing (original manuscript), and visualization. Wenfeng Ding conducted writing (review and editing), project management, and funding acquisition.

Declarations

Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article. Wenfeng Ding is a member of the editorial board of this journal. He was not involved in the editorial review or the decision to publish this article. All authors declare that there are no competing interests.

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