CIRP Annals - Manufacturing Technology 72 (2023) 645–671

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: https://www.editorialmanager.com/CIRP/default.aspx

Grinding of composite materials

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ARTICLE INFO

Article history:
Available online 7 June 2023

Keywords:
Composite
Grinding
Mechanisms

ABSTRACT

Grinding plays an important role in ensuring the final machining quality in the manufacturing process of composite parts. Problems such as grinding damage, grinding wheel wear and loading undermine the grinding efficiency and quality. This review presents relevant research progress in the field of composites grinding in recent years from the aspects of material removal mechanisms, surface integrity, and advanced grinding technologies. It further discusses the common problems of composites grinding and summarizes grinding process strategies to suppress damage. It can provide an in-depth understanding of the fundamental mechanisms involved in composites grinding and solutions to the composites grinding problems.

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1. Introduction

Continuous progress of science and technology has led to an increasing requirement for high-performance engineering materials. Traditional metals, plastics, and ceramics cannot simultaneously achieve the following mechanical properties: low weight, high strength, high stiffness, and high toughness. Therefore, engineers often employ the traditional materials as matrices and add a reinforcing phase to form composites for improving the mechanical or physical properties. Based on their matrix materials, composites can be divided into three categories: polymer matrix composites (PMCs), metal matrix composites (MMCs), and ceramic matrix composites (CMCs) [17]. The reinforcing phase of composites can be carbon materials, carbides, nitrides, and oxides in the form of fibers, whiskers, or particles. PMCs have high specific strength and stiffness but poor heat resistance and are often used in situations requiring significantly lightweight materials in relatively low temperatures [11]. MMCs have metal matrices such as aluminum, magnesium, copper, steel, and titanium alloys, which can also be manufactured in a non-traditional way such as additive manufacturing [168], and are often used in situations with higher temperatures requiring materials with higher wear resistance than PMCs. CMCs are often used for high-temperature structural parts and replace ceramic materials because of their higher fracture toughness, which is higher than that of a ceramic material [25,149].

The most prominent application of composites is in the field of aerospace. Owing to their lightweight and high-temperature resistance properties, an aircraft achieves enhanced flying performance and fuel economy. For one kg reduction in the aircraft structure weight, the annual aviation fuel consumption can be reduced by 2900 L [141]. Carbon fiber-reinforced plastic (CFRP), a lightweight and high-strength structural material, has been widely used in fuselage structures. In the latest models of the world's three major civil airliners such as the Bombardier CS300, Boeing B787, and Airbus A350XWB, composite materials account for 46%, 50%, and 52% of the total body weight, respectively [110]. Silicon carbide fiber-reinforced ceramic matrix composites (SiC_f/SiC) have been applied to high-temperature structural parts of aerospace vehicles such as nozzles and combustion chambers for an aero-engine with a high thrust weight ratio. Compared to superalloys, SiC_f/SiC can increase the working temperature by 300 – 500 °C and thrust by 30 – 100% and reduce the structural weight by 50 – 70% [199]. The application of silicon carbide particle-reinforced aluminum matrix composites (SiCp/Al) in the key parts of an aircraft can greatly improve the performance of the aircraft. SiCp/Al prepared by the U.S. military in co-operation with Lockheed Martin replaced aluminum alloy skin with the abdominal fin of an F-16 fighter, which not only increased the stiffness by 50% but also increased the service life from hundreds of hours to more than 8000 h, saving maintenance costs by more than 26 million US dollars [170]. With a gradual reduction in the material preparation cost, composites have been widely used in the field of mass consumer goods, such as sports equipment, electronic devices, and auto parts. For example, PMCs are used for boats, tennis rackets, laptop shells, automobile bodies, etc. [137]; MMCs are used for the automobile drive shaft, cylinder liner of an automobile engine, electronic packaging, thermal management components, etc. [74,115]; and CMCs can be used for the braking system of high-speed trains and racing cars [199].

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https://doi.org/10.1016/j.cirp.2023.05.001
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With the increasingly extensive applications of composites in the field of aerospace and mass consumer goods, the requirements for the processing quality and efficiency of parts increase unceasingly. The service conditions of parts in the aerospace field are extreme. These parts typically experience a long service time under the conditions of high speed, high temperature, and high load. Therefore, there is a high requirement for the fatigue performance of the parts. The dimensional accuracies, geometries, and surface integrity of the parts have an important impact on their service quality and lifetime. In the field of mass consumer goods, enterprises pursue the lowest possible manufacturing cost with high manufacturing efficiency. Some non-conventional machining methods, such as laser beam machining (LBM) [40,80,103,129,198], abrasive water jet (AWJ) machining [58,127,144,145,152], and electrical discharge machining (EDM) [54,60,172,180] have been applied in the field of composite material processing. However, LBM is only applicable to cut thin-wall parts, and it is difficult to avoid thermal damage. Although AWJ can avoid thermal damage, it has a relatively low machining accuracy and encounters problems such as trail-back, taper, striation marks, and grit embedment. EDM also encounters problems such as recast layer and thermal cracks. Owing to the above limitations of the non-traditional processing methods, the most widely used machining methods in industry are cutting and grinding with CNC machine tools. Compared with cutting, grinding provides better surface finish and dimensional accuracy for a workpiece [23,29,70,112]. Therefore, grinding has an important role in the production cycle of a composite part, which are often used to ensure the final quality of the part.

Because of the heterogeneous structure and anisotropy of mechanical and thermal behaviors, composite materials are prone to machining damage, and therefore, they fall into the difficult-to-machine materials category. When grinding PMCs and MMCs, wheel clogging occurs easily. For hard and brittle CMCs, wear of abrasive particles and material cracks in the surface/subsurface of a workpiece typically occur. A summary is presented in Fig. 1 to illustrate the classification, properties, structures, applications, and grinding challenges of the most commonly used composite materials. At present, the manufacturing industry mainly relies on the trial-and-error method to determine the appropriate machining parameters for composite materials, mainly because of the heterogeneity of the material. However, in many cases, it is still difficult to control the grinding quality and efficiency, which may result in an increased production cost. The abovementioned problems make it difficult for composite parts to achieve the expected service performance. In an attempt to address the challenges of composites grinding and realize high-quality and high-efficiency machining, the material removal mechanisms in grinding and the factors affecting grinding quality and efficiency should be intensively studied, and reasonable grinding strategies should be adopted.

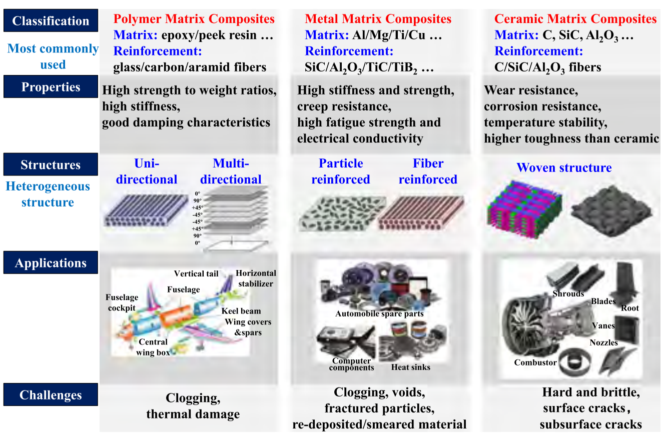

Fig. 1. Summary of the most commonly used composite materials with typical structures [26,91,110,136].

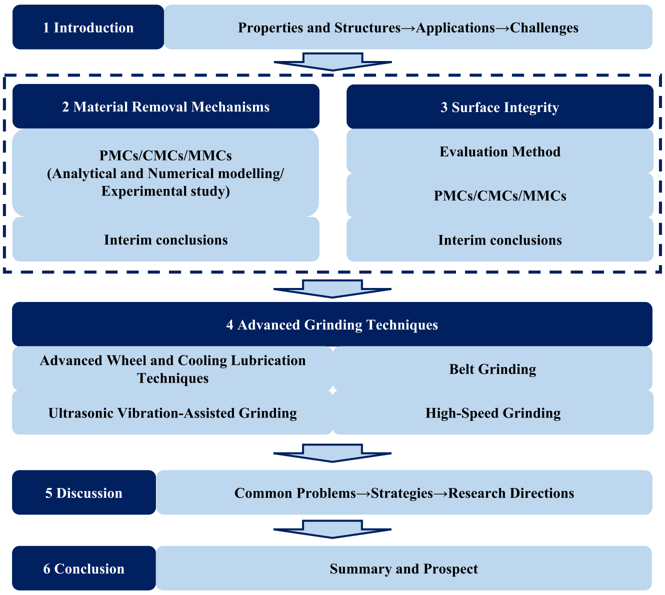

Fig. 2. The overall structure of the paper.

The published literature shows that there exist a large number of studies on composite machining [26,41,46,71,78,91,110,136,149]. However, most of the studies focus on either the cutting processes or the machining processes of composite materials. There is a lack of systematic and comprehensive review on composites grinding (using tools with fixed abrasive particles). Although there are engineering applications of particle-reinforced CMCs [51] and fiber-reinforced MMCs [21,118], but few literatures on grinding of the above two types of composite materials have been reported, therefore such composites are deemed out of the scope of this review. This review focuses on the most commonly used PMCs (fiber-reinforced), CMCs (fiber-reinforced), and MMCs (particle-reinforced) materials in engineering applications, and traces the important research progresses in composites grinding in the recent years (that is, mostly from the past 20 years). The purpose of this review is to grasp the key problems of high-quality and high-efficiency grinding of composite parts and to provide a useful reference for the industry.

The structure of this paper is shown in Fig. 2. The remainder of this paper is organized as follows. Material removal mechanisms of PMCs, CMCs, and MMCs are analyzed in Section 2. Surface integrities of the ground PMCs, CMCs, and MMCs are reviewed after introducing the evaluation methods in Section 3. Four advanced grinding techniques, including advanced grinding-wheel and cooling-lubrication, abrasive belt grinding, vibration-assisted grinding, and high-speed grinding (HSG) techniques are introduced in Section 4. Finally, the common problems involved in composites grinding are discussed in Section 5, and conclusions are provided in Section 6.

2. Material removal mechanisms

Material removal mechanisms of composite materials are more complex than those of monolithic materials because of their heterogeneous structural characteristics. An in-depth understanding of the material removal mechanisms is helpful to optimize process parameters and improve product quality. At present, the main research method is to establish analytical or numerical models based on the theory of mechanics and materials science, and to analyze the deformation and failure behaviors in the process of material removal with the help of theoretical models to explain the experimental phenomena.

2.1. Polymer matrix composites (PMCs)

Grinding can be regarded as a micro-cutting process of workpiece materials with the simultaneous participation of numerous abrasive grains. Owing to the complexities and uncertainties, it is difficult to establish a mechanical model of grinding, but cutting can be used as a reference to grasp the removal mechanisms of fiber-reinforced composites.

Xu et al. [177,178] established and analyzed a single-fiber-cutting mechanical model of unidirectional CFRP composites based on the elastic foundation beam model. They found that when the tool rake angle was γ and, the fiber direction angle (the angle between the cutting and fiber directions) satisfied the condition of $\theta<90°+\gamma$, (the cutting edge is in contact with the fiber), the failure mode of the fiber was crushing-dominated fracture. When $\theta>90°+\gamma$ (the rake face is in contact with the fiber), the failure mode of the fiber was bending-dominated fracture. Su et al. [146] observed the material removal process of in-situ orthogonal cutting of unidirectional CFRP under a microscope and confirmed that the fiber orientation had a decisive effect on the material removal mechanism and chip morphology. Through the analysis of the cutting mechanisms and experimental phenomena, it is evident that the machining damage caused by fiber-shearing fracture is lower than that caused by fiber-bending fracture. The fiber-fracture mode is closely related to the supports and constraints in the cutting direction, and a strongly supported fiber is more inclined to shear fracture. Various fiber orientations and the corresponding failure modes also have significant influence on the cutting force. Voss et al. [153] developed an analytical force model for CFRP orthogonal cutting considering the influence of fiber orientation, tool geometry, and increasing tool wear and showed that a good correlation exists between the numerical and experimental cutting forces.

In a grinding process, an abrasive grain can be regarded as a cutting tool with a negative rake angle, and the undeformed chip thickness is close to the nano/micro-meter scale. The failure mode of PMCs exhibits strong size dependence on such a small scale. Han et al. [56] elucidated the intra-laminar failure mechanisms of unidirectional CFRP under varying-load nano-scratching tests through micromechanical finite element simulations and corresponding experimental validation. Furthermore, they established a micromechanical analytical model to quantitatively characterize fiber deflection and subsurface damage (Fig. 3) and found that with an increase in the applied normal load, the scratching process could be divided into three regimes: the micro-fracture, micro-to-macro fracture transition, and macro-fracture regimes. Micro-fracture occurred at the tool–fiber contact region without the bending of the un-fractured part, whereas macro-fracture occurred in the subsurface damage layer after a strong fiber deflection. Therefore, the fiber orientation has a strong impact on the dynamic transition of the multi-fracture modes of fibers.

Man et al. [113] conducted scratch tests to study the surface deformation behavior of additively manufactured CFRP, and identified different scratch deformation modes namely mild abrasion, fiber breakage, and fiber removal, depending on the normal loads. They found that the critical loads for the transitions between various deformation modes were greatly affected by fiber orientations and interfacial bonding played a key role in determining the failure process of fiber and the size and shape of the formed fiber debris.

Investigating the cutting-force models is helpful to understand the material removal mechanisms. In the modeling process, numerous studies have made an assumption that CFRP materials are removed in the brittle-fracture mode [101,120,158,161]. However, Wang et al. [160] observed and identified through their single abrasive scratching tests that both carbon-fiber and epoxy-resin layers demonstrated the ductile-fracture removal mode at a small cutting depth. Therefore, it is not comprehensive to consider only brittle-fracture removal mode in PMCs modeling.

Shi et al. [135] considered both ductility and brittleness of CFRP composites in their grinding force model and proposed a ductile-brittle ratio K that could be obtained through experiments. Their results showed that K increased with spindle speed

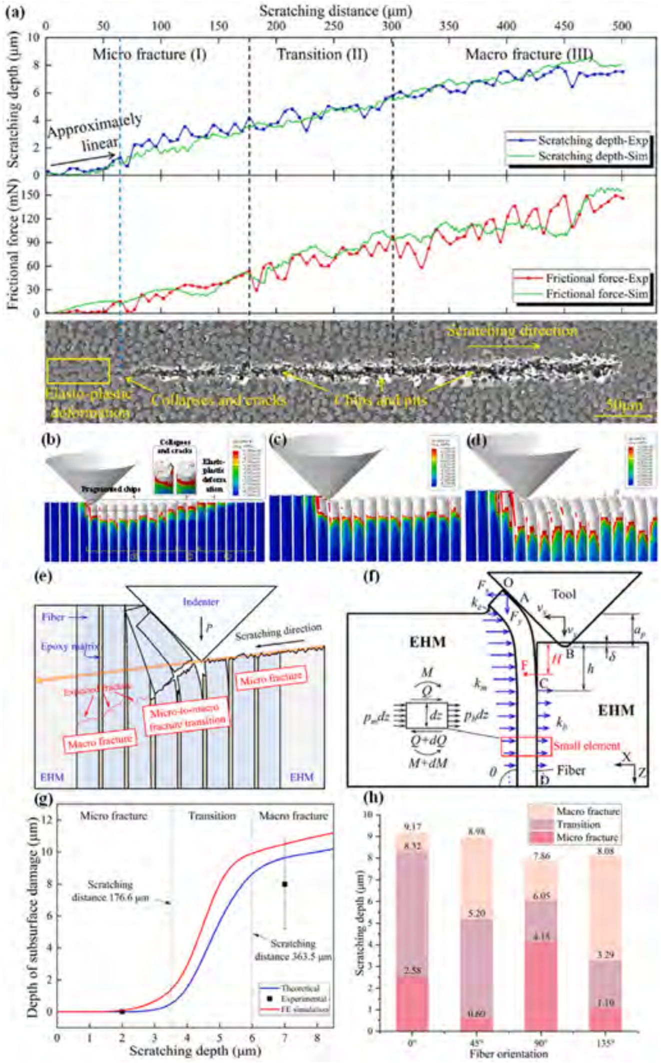

Fig. 3. Nano-scratching of unidirectional CFRP by joint analytical modeling, micromechanical FE simulations and experiments [56]: (a) observation of three fracture regimes, (b)~(d) FE simulation results of three fracture regimes with a fiber orientation of 90°, (e) schematic illustration of fiber fracture mechanisms with a 90° fiber orientation, (f) schematic illustration of analytical modeling, (g) variations of depth of subsurface damage with a 90° fiber orientation derived from the analytical model, (h) the influence of fiber orientation on proportion of three regimes.

but decreased with feed rate and cutting width. Wang et al. [162] distinguished the ductile- and brittle-fracture removal modes by introducing the critical indentation depth δ_{d_max} in their CFRP rotary ultrasonic grinding force model. When the cutting depth exceeded δ_{d_max}, the material removal mode changed from ductile- to brittle-fracture mode, as illustrated in Fig. 4. Although many scholars have applied the concept of “ductile removal” to the machining of CFRP, in fact, most studies have not reported sufficient evidence of ductile removal and have reported only based on the surface morphology.

In the aforementioned studies, CFRP was usually treated as a homogeneous material in the modeling processes. However, CFRP is typically a heterogeneous and anisotropic material. To capture the material removal behavior of CFRP accurately, Gao et al. [45] established a single-diamond grain grinding force model of CFRP (Fig. 5). Owing to the randomness of fiber distributions and abrasive grain shapes and the different contact conditions between the abrasive grains and the workpiece fibers, four sub-models were developed. (1) A contact-force model of the contact forces between the grain tip and the fibers. (2) A local contact stress

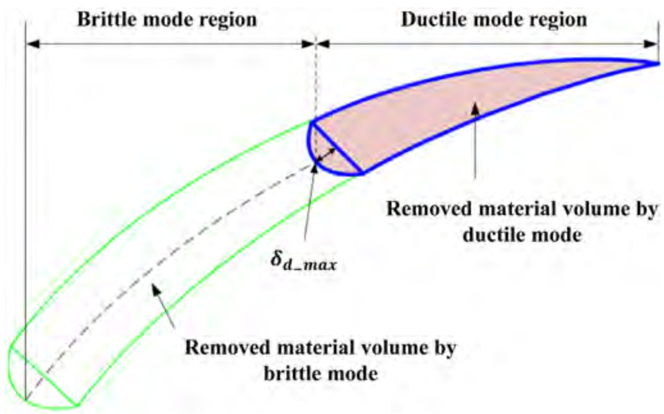

Fig. 4. Illustration of the material volume removed by one single abrasive grain in ductile mode region and brittle mode region [162].

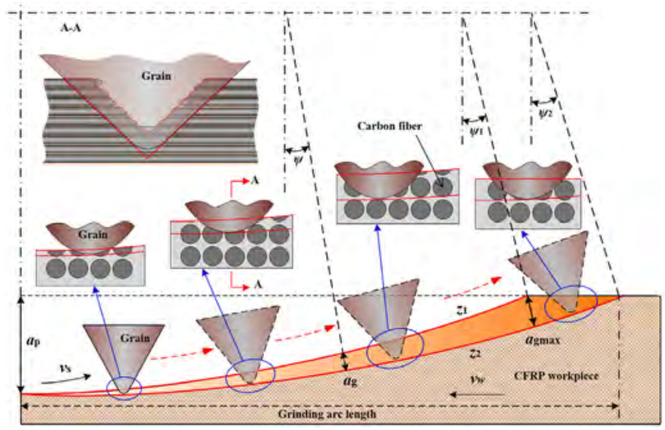

Fig. 5. Interaction modes between the single grain and CFRPs under different a_g values [45].

model of the elliptical region between spherical grain edge and cylindrical fiber. (3) A tensile fracture force model of a single fiber regarded as a bending beam fixed at both ends and constrained on the elastic foundation. (4) An extrusion and shearing force model of the cut-fiber section with a grinding groove. These sub-models revealed that the tensile fracture force on a fiber had the most contributions to the grinding force.

2.2. Ceramic matrix composites (CMCs)

CMCs are considered the most difficult-to-machine composites because of the high hardness of constituents and brittle-fracture tendency during machining [26]. The stochastic nature of the conventional abrasive particles hinders the understanding of the fundamental interaction between the abrasives and the composites. To investigate the material removal mechanisms of CMCs, Luna et al. [107] prepared abrasive grains with different geometric shapes and sizes using pulsed laser ablation and studied the effects of abrasive grain shape and fiber direction on the material removal mechanisms of the SiC_f/SiC composites by conducting single grit tests. The results showed that the shape of abrasive grains had a greater influence on the grinding force than the fiber direction. In addition, the grinding force produced by the round abrasive grains was the largest compared to those of the rectangular and/or triangular abrasive grains. The analysis of contact mechanics showed that the crack onset location was governed by the grains shape, but its direction of propagation depended on the fiber orientation, as shown in Fig. 6.

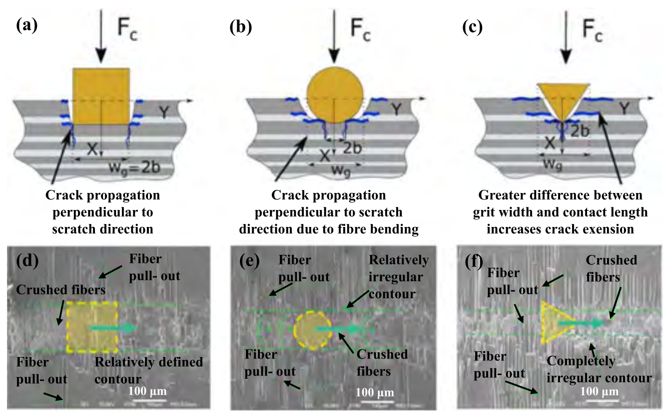

Fig. 6. Crack location and propagation direction under different abrasive grain shapes and fiber directions [107].

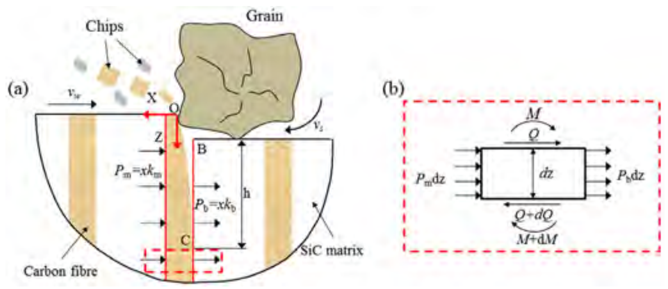

Fig. 7. Single abrasive grinding model of C_f/SiC composites [125].

In a single-point scratching test of C_f/SiC composites, Li et al. [82] showed that the failure mode of CMCs during grinding was mainly brittle fracture and the damage behaviors included matrix brittle damage, fiber fracture, fiber pullout, and interface debonding.

Regarding the analytical mechanical model, Qu et al. [125] analyzed the main differences between CMCs and PMCs and pointed out that for C_f/SiC composites, the bouncing-back phenomenon was negligible and cracks could easily propagate along the interface. Furthermore, the difference in matrix properties limited the fiber from obvious deformation, as in the case of CFRP, but the existence of interface cracks allowed the fiber to undergo a small deformation. Different from the elastic foundation beam model describing the fiber deformation of CFRP, the mechanical model of C_f/SiC composites grinding was established based on the rigid foundation beam model (Fig. 7) to analyze the effect of grinding process parameters on grinding force and interface debonding.

Researchers conducted several grinding tests to investigate material removal mechanisms of MMCs. Esmaeili et al. [36] analyzed the removal mechanisms of C_f/SiC composites and considered that composite shearing appeared when the cutting shear stress was higher than the ultimate shear strength of the entire C_f/SiC composites. Furthermore, they found that matrix shearing appeared when the cutting shear stress was lower than the composite ultimate shear strength but higher than the matrix shear strength. Finally, matrix fracture and interface crack propagation occurred when the cutting shear stress was lower than the matrix shear strength. Zhang et al. [201] conducted grinding tests of unidirectional C_f/SiC composites and found that the fiber direction had a great influence on the grinding force. The schematic of three orthogonal grinding directions is shown in Fig. 8. The test results showed that $F_{normal}>F_{longitudinal}>F_{transverse}$. It can be seen that for PMCs and CMCs, the influence of the fiber direction angle on the grinding force is not consistent, which may be related to the difference in their matrix properties. Under the condition of different fiber direction angles, the

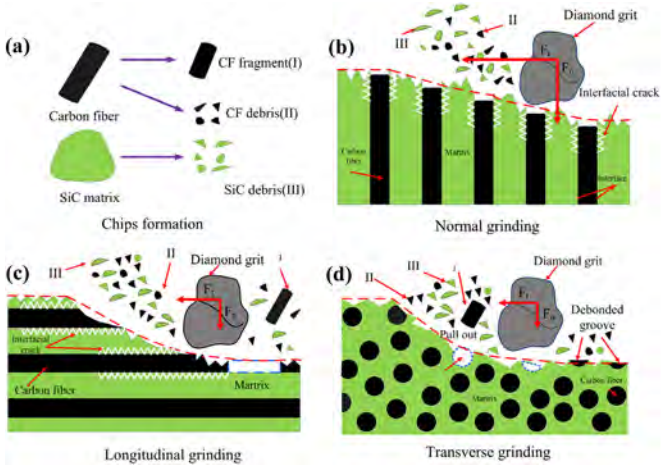

Fig. 8. Grinding diagram of three typical fiber directions of CMCs [201].

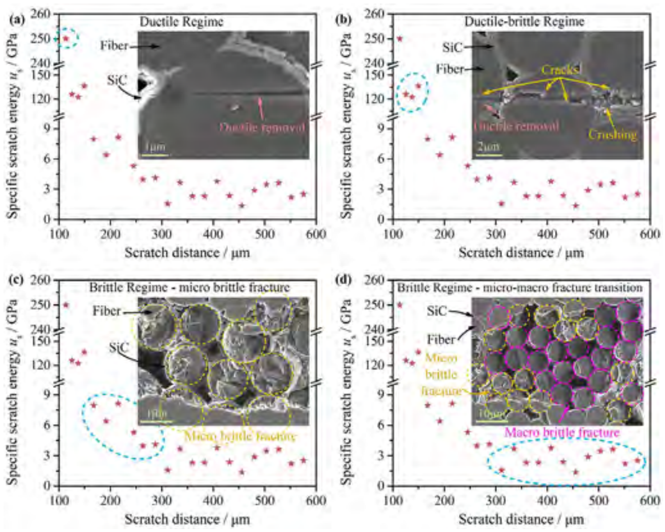

Fig. 9. Variations of specific scratch energy and micromorphology across the fibers of the C_f/SiC composites [13].

friction coefficient between the abrasive grains and the composites is different; this also affects the grinding force. The grinding force increases with an increase in the cutting depth and a decrease in the spindle speed. In addition, at the same cutting depth, the tangential force is always greater than the normal force [82]. Zhang et al. [200] analyzed the interface failure behavior in different fiber directions. They observed that when grinding in the transverse direction, the interface was subjected to the first failure mode (opening mode), and the fiber was mainly subjected to shear stress. When grinding in the longitudinal direction, the interface was subjected to the second failure mode (shearing mode), and the fiber was subjected to in-plane shear stress. When grinding in the normal direction, the interface was subjected to the third failure mode (tearing mode), and the fiber was affected by shear and tensile stresses.

Similar to hard and brittle materials such as ceramics and glass, CMCs reportedly have plastic/ductile removal mechanisms in the grinding processes under certain conditions (usually at a very small depth of cut). Mueller et al. [117] found plastic deformation in single-abrasive grinding of $(Al_2O_3)_f/Al_2O_3$ composites and confirmed the existence of plastic deformation mechanism in the material removal process by observing the changes of residual stress, material side bulge, and material melt smearing. Liu et al. [102] conducted a single-abrasive scratching test of 2.5D braided SiC_f/SiC composites. The results showed that a sharp abrasive grain could produce ductile-fracture removal and fiber crushing. The main material removal characteristics under the action of a blunt abrasive grain were fiber debonding and shear crushing, whereas the removal modes of the matrices were fracture, peeling, and pulverization. Chen et al. [13] conducted a nano-scratching test of C_f/SiC composites and found that with an increase in the scratching load, the material removal occurred in three modes: ductile-fracture, micro-brittle-fracture, and macro-brittle-fracture modes. Here, Fig. 9 shows the variations of specific cutting energy when cutting fibers in different modes of material removal. It can be seen that a “size effect” exists in grinding of composites.

The “ductile removal” mechanism of CMCs materials also has problems. The abovementioned studies all judged the ductile removal mechanism based on a “crack-free” sample surface. However, according to the research on grinding of ceramic materials, even if the ground surface was smooth and free of cracks, there might still be cracks and material pulverization hidden in the subsurface [194–196].

2.3. Metal matrix composites (MMCs)

For MMCs, it is difficult to establish an accurate analytical model to describe the grinding process. The main difficulty is that the ceramic particles are significantly different from fibers in terms of their shapes. The randomness of shape and distribution makes it difficult to describe the interaction between abrasive grains and reinforced particles accurately. To reveal the removal mechanisms of MMCs under the action of abrasive grains, the main research methods include finite element simulation, grinding-force modeling, single-point scratching/grinding tests, and observation and analysis of chip morphologies or of ground workpiece surface/subsurface morphologies.

Researchers have performed a large number of simulations using the finite element method. Dandekar et al. [22] summarized previous studies on composite cutting simulations, and pointed out that the three key elements of establishing a finite element simulation model were constitutive equation, chip-separation criterion, and tool–chip interface friction. At present, researchers have been able to reproduce all the typical machining damage morphologies of MMCs through finite element simulations, and have revealed the material removal mechanisms by analyzing the material deformations and failure processes. During grinding, the relative position between the abrasive grains and the reinforced particles in MMCs determines the mechanical behavior of the reinforced particles and affects the surface damage morphology after machining. Zheng et al. [210] performed single-abrasive finite element simulation of SiCp/Al. The results showed that with an increase in the cutting depth of the abrasive grains, the interference depth between the reinforcing particles and the abrasive grains gradually increased, and the behavior of the reinforcing particles changed from pressing to the matrix and micro-crushing to complete fracture and fiber pullout. With the plastic deformation of the matrix and the displacement and fracture of the reinforcing particles, interfacial debonding could also occur. Zhao et al. [209] established a three-dimensional (3D) finite element model of SiCp/Al, which was closer to the actual situation. Because of the negative rake-angle cutting effect of abrasive grains, particle pullout was negligible. A simulation analysis performed by Yin et al. [189] showed that the removal process of SiCp/Al could be divided into four stages: plastic deformation of aluminum matrix, crack initiation, crack propagation, and brittle fracture of the SiC particles. A grinding simulation study of the TiCp/Ti-6Al-4 V composites by Xi et al. [96,176] showed that when the undeformed chip thickness (UCT) decreased, the removal mode of the TiC particles changed from macro fracture to micro fracture. The simulation results were in a good agreement with the experimental results, as shown in Fig. 10.

The finite element simulation of cutting MMCs is similar to the single abrasive simulation, except for that the tool rake angle,

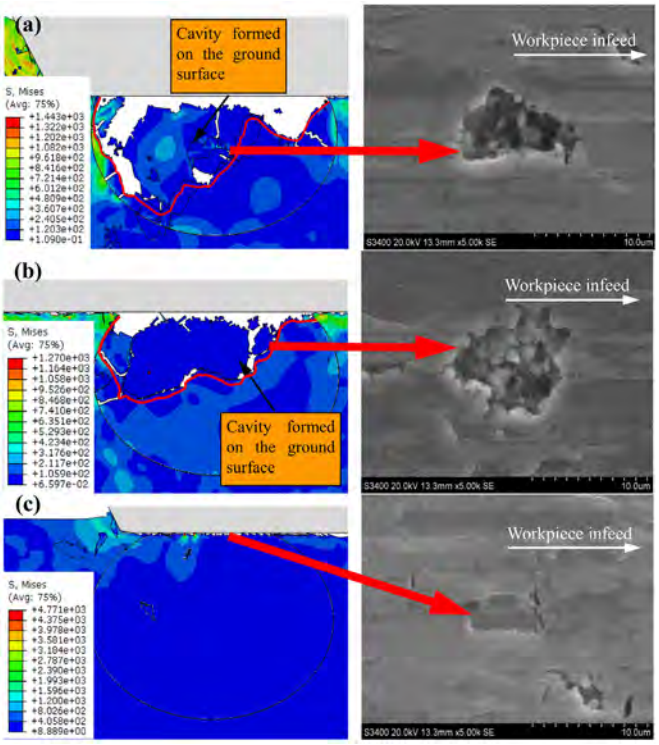

Fig. 10. Failure characteristics of the SiC particles under different grinding conditions [176]: (a) UCT=1.2 μm, v_w=12 m/min, a_p=0.02 mm, v_s=80 m/s; (b) UCT=0.7 μm, v_w=9 m/min, a_p=0.01 mm, v_s=120 m/s; (c) UCT=0.2 μm, v_w=1 m/min, a_p=0.002 mm, v_s=140 m/s.

which is generally non-negative. The damage characteristics obtained by the cutting simulation are closely related to the relative position of the reinforcing particles and cutting edges [97,123,148]. Owing to the influence of matrix plastic deformation, interface debonding occurs before the cutting edge contacts with the reinforcing particles [50]. However, when the cutting speed is relatively high, because of the work-hardening effect of the matrix, the fracture strength is significantly improved. The reinforcing particles could be subjected to a higher amount of stress, making them reach their fracture limit faster and easier. The reinforcing particle fracture occurs before debonding, and the reinforcing particles are easier to cut-off rather than being pulled out, thereby reducing large machining damage such as pits [98]. Most of the simulation studies on MMCs have been conducted under the assumption that the reinforced particles have an ideal shape and are evenly distributed in the matrix. To make the simulation realize the actual situation, some scholars have carried out simulation research based on the finite element model of the random distribution of reinforced particles [32,169,216], and the simulation results were close to the experimental results.

Prediction of grinding forces is of great significance to optimize the process parameters and improve the machining quality and efficiency. There are two types of grinding-force models: empirical and analytical. Joshi and Liu et al. [68,95] established an empirical model for predicting the SiCp/Al cutting force through regression analysis of a large amount of experimental data. A limitation to the model was that its prediction accuracy was highly dependent on the experimental conditions. An analytical model should be based on a deep understanding of the material removal mechanisms. For MMCs, it is generally believed that the grinding force should include chip-deformation, friction, and particle-fracture forces [33,105,189], and some scholars have considered the ploughing force as well [220].

The common steps in establishing a grinding-force model are as follows. First, based on the kinematic analysis of an abrasive grain, an undeformed chip model is established. Subsequently, a model for each grinding-force component is established. Finally, the overall grinding force is obtained by the superposition of each force component. Unknown parameters of a model must be determined by conducting experiments. Therefore, analytical models established for grinding-force prediction exhibit semi-empirical characteristics. Because grinding is a process of micro-cutting with a large number of abrasive grains, the shape and distribution of the abrasive grains and the hard reinforcing phase in an MMCs workpiece are random. Therefore, it is difficult to establish an accurate grinding-force prediction model. Based on the material removal mechanisms of MMCs, Gu et al. [52] first established a grinding-force model of a single abrasive grain, treated the grinding process with multi-abrasive grains as a black box, conducted grinding experiments, and obtained the grinding-force data under different grinding parametric conditions. Finally, the multi-abrasive grain grinding force model was established using the support vector machine prediction method based on the particle swarm optimization algorithm.

Single-abrasive scratch test is a typical experimental method to simplify the grinding conditions and study the grinding mechanisms. There are several relevant literatures regarding hard brittle materials and ductile materials [37,204], which can help us understanding the material removal mechanism. For MMCs, Yan et al. [181] conducted a single-abrasive scratch test on aluminum matrix composites reinforced with different ceramic particles and studied the material removal mechanisms and the relationship between the specific energy of scratching and the depth of cut (size effect). The results indicated that the scratch process was composed of rubbing, ploughing, ductile-regime cutting, and reinforcement fracture. The larger the ratio of volume fraction of reinforcement to particle radius, the higher the proportion of the energy consumed by particle fracture and sliding friction and the more obvious the size effect. Du et al. [32,34] conducted a single-abrasive scratch test on SiCp/Al (the volume fraction of SiC particles was 45%, and the average particle diameter was 5 μm). The results showed that the removal modes of the SiC particles included crushing/fracture, microcracking, shear, and pull-out (Fig. 11).

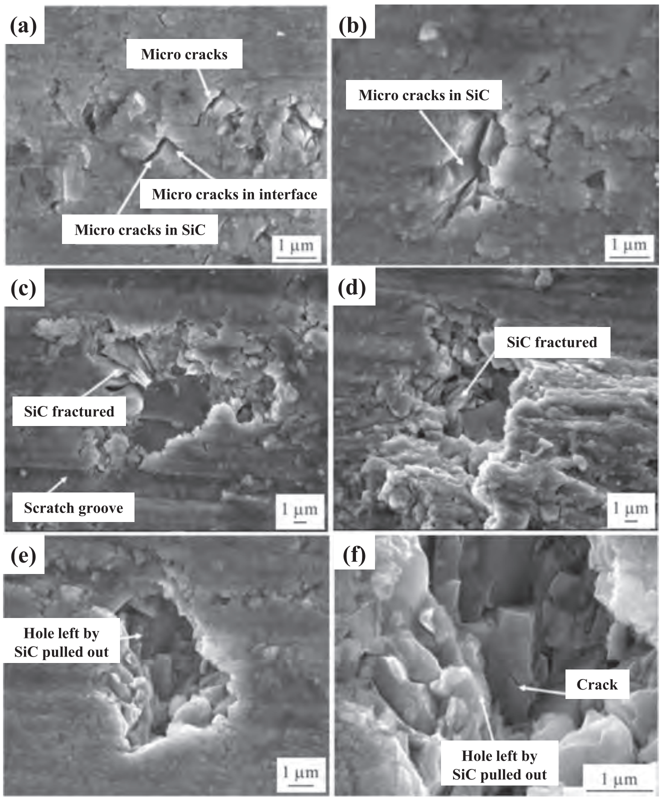

Fig. 11. SiC particle removal modes observed on the scratched surfaces of the SiCp/Al composites [34].

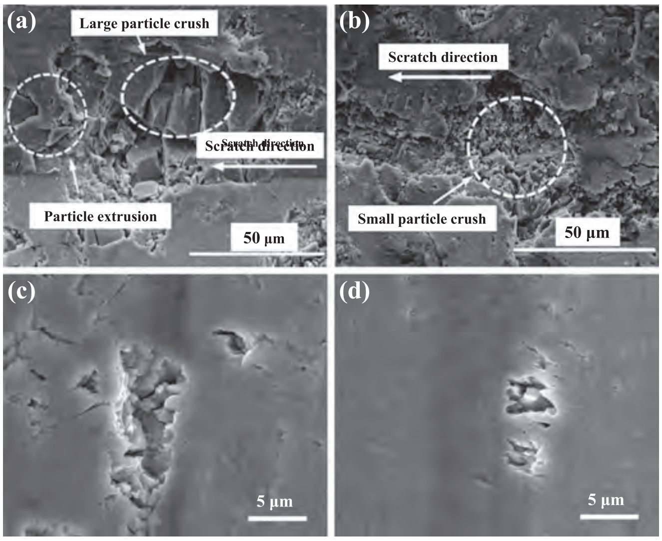

Fig. 12. Comparison of SiC particle removal modes between ultrasonic vibration-assisted scratching (US) and traditional scratching (TS) under different particle average diameter d_{av} [39,211]: (a) TS, d_{av}=40 μm; (b) US, d_{av}=40 μm; (c) TS, d_{av}=5 μm; (d) US, d_{av}=5 μm.

The smaller the cutting depth and speed, the smoother the scratch surface, the more the number of particles removed in the shear-removal mode, and the better the machined surface quality. Both Feng and Zheng et al. [39,211] conducted ultrasonic vibration-assisted scratch tests on the SiCp/Al composites with different particle sizes. The results showed that the macroscopic material removal behavior of MMCs was similar to that of metallic materials. The average load and friction coefficient of ultrasonic vibration-assisted scratch were lower than those of an ordinary scratch, whereas the material removal rate was higher than that of an ordinary scratch. When SiC particles were relatively large (40 μm), they were broken down under the ultrasonic vibration conditions to form finer debris than under the ordinary conditions. However, when SiC particles were relatively small (5 μm), they tended to maintain their complete structure under the ultrasonic vibration conditions (Fig. 12). It can be seen that the size effect of the enhanced particles in MMCs has an important impact on material removal mode.

Klocke and Wirtz et al. [72,174] conducted single-abrasive scratch tests on a tungsten carbide (WC) workpiece. They found that with an increase in cutting depth, the material removal mode

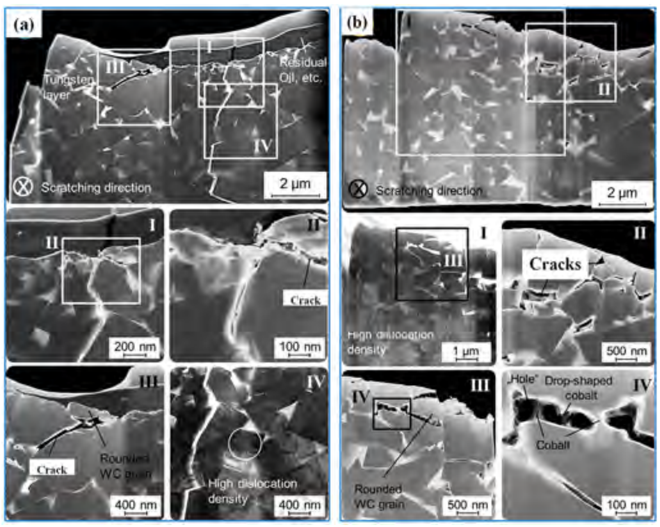

Fig. 13. Comparison of the subsurface damage characteristics of the WC–Co cemented carbide (a) before and (b) after ductile-brittle transition [174].

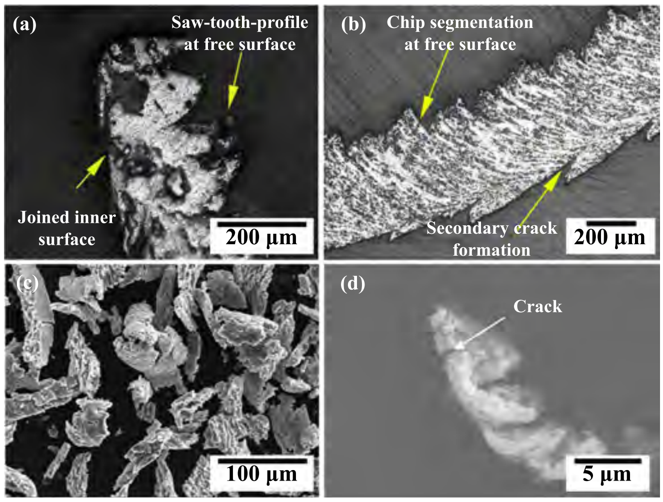

Fig. 14. Chip morphology of the SiCp/Al composites [20,35,64]: (a-b) turning chip; (c-d) grinding debris.

changed from ductile to brittle. The samples were prepared using the focused ion beam (FIB) technique, and the scratch cross-section was observed using transmission electron microscopy (TEM). As shown in Fig. 13, before the ductile–brittle transition, WC in the surface layer was locally broken, and a high dislocation density was formed in the subsurface of the WC workpiece. After the ductile–-brittle transition, the number of cracks increased significantly and tended to expand in the Co-phase, and the dislocation density in the subsurface WC particles was lower than that before the ductile–-brittle transition. Similar to PMCs and CMCs, the assertion about the "ductile removal" of MMCs is also open to discussion. The main problem was that there was no sufficient evidence to indicate the existence of a "ductile regime". For example, in Fig. 13, even in the "ductile regime" claimed by the author, there existed obvious crack damage, which just proved that the material was not removed based on the "ductile regime".

Researchers have observed the chip morphology produced by cutting/ grinding, analyzed the chip formation mechanisms, and revealed the material removal mechanisms (Fig. 14). Dabade et al. [20] established a conceptual model of chip formation on the basis of an experimental research. The model considered the influence of reinforced particle size on chip morphology. In the machining of coarser reinforcement composites, complete gross fracture occurred, generating smaller segments of chips and higher shear-plane angles. However, in the case of finer reinforcement composites, secondary crack formation was evidenced on the inner surfaces of a chip with a gross fracture on its outer surface, generating longer chip segments.

Moreover, Dabade et al. [19] established a tool–chip interface friction model for turning SiCp/Al materials. It was considered that the existence of SiC particles had an important impact on the tool–chip friction coefficient, which was mainly reflected by the embedment of the SiC particles in the chips and by the rolling of the free SiC particles at the tool–chip interface. Du et al. [35] established a basic physical cutting model for mill-grinding SiCp/Al materials. As shown in Fig. 15, a SiC particle was simplified as a sphere, whereas an abrasive grain was simplified as a cone. Similar to that in metal grinding, chip formation included three stages: scratching, ploughing, and micro cutting. The relative contact position between an abrasive grain and a SiC particle also had an important influence on the material removal and chip formation mechanisms.

Huang et al. [64] analyzed the different cutting states of an abrasive grain in the grinding process of SiCp/Al materials with a high volume fraction and considered that the different cutting states of an abrasive grain would affect the element compositions and shape of

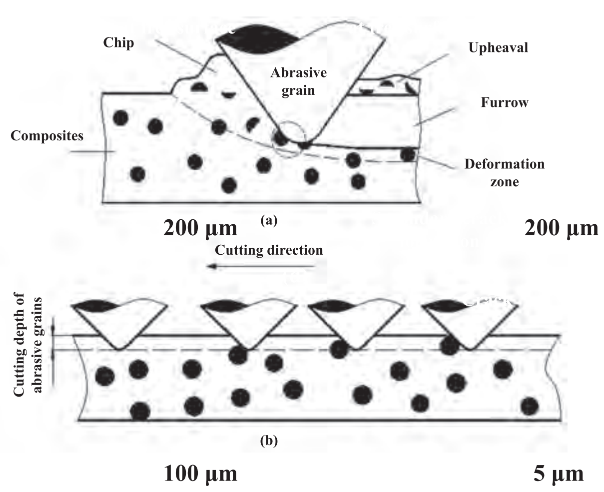

Fig. 15. Basic physical cutting model for SiCp/Al composites [35]: (a) cutting process of an abrasive grain and (b) possible contact position between abrasive grain and SiC particle.

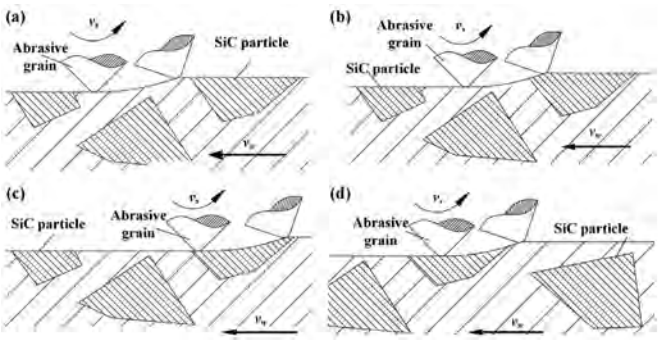

Fig. 16. Different cutting states of an abrasive grain in grinding of SiCp/Al composites [64]: (a) cut-in and cut-out of the grain above Al-matrix; (b) grain cut-in from the Al-matrix and cut-out from the SiC particle; (c) cut-in and cut-out of the grain on the SiC particle; (d) grain cut-in from the SiC particle and cut-out from the Al-matrix.

the chips. The cutting states of abrasive grains could be divided into four cases, as shown in Fig. 16: cut-in and cut-out from the Al-matrix, cut-in from the Al-matrix and cut-out from the SiC particle, cut-in and cut-out from the SiC particle, and cut-in from the SiC particle and cut-out from the Al-matrix.

2.4. Interim conclusions

The abovementioned cutting/grinding mechanical models of PMCs did not consider the effect of friction heat and the performance change of the matrix resin at elevated temperatures. Although helpful for a deep understanding of the material removal mechanisms, they are significantly different from the actual machining scenarios and need further improvement in the future.

Owing to the limitations of the material preparation process, there are various defects such as holes and original fiber damage in CMCs materials that are currently being used. However, the current CMCs mechanical modeling does not consider the internal defects of the material, which leads to a deviation between the description of the mechanical behavior of CMCs and the actual situation.

There are some shortcomings in studying the material removal mechanisms using the scratch tests. At present, the results of the scratch tests can only be analyzed by measuring the scratch force and scratch profile and by observing the scratch micro morphology. It is difficult to observe the real deformation and failure behavior of the matrix and reinforced particles directly during a scratch process. Finite element simulations are generally used to help analyze the material removal mechanisms. In addition, under the condition of very small cutting depth, the "ductile removal" of composite materials needs to be scientifically proven.

At present, there are still deficiencies in the finite element simulation methods; for example, (1) most scholars do not consider the interface problem, or they only use a simplistic interface constitutive model. (2) Generally, researchers usually directly use the data of the corresponding materials as the constitutive parameters of the matrix without considering the influence of the addition of reinforcements on the mechanical properties of the matrix. Overcoming the abovementioned two deficiencies will further improve the credibility of finite element simulations.

Although an analytical model can help grasp the essence of grinding forces, the grinding-process prediction method based on big data and intelligent algorithms should have a broader prospect in engineering applications.

3. Surface integrity

Surface integrity has a great influence on the properties of a composite part, and the poor surface integrity of composite machining significantly contributes its poor machinability. In this section, first, the evaluation methods of composite material surface integrity are introduced, and subsequently, the research status of the grinding-surface integrities of PMCs, CMCs, and MMCs is summarized, including the influence of process conditions and material characteristics on surface integrity and some attempts to improve the surface integrity.

3.1. Evaluation methods

3.1.1. Assessment of grinding-surface integrity

Assessment of grinding-surface integrity is extremely important to the research on the material removal mechanisms, optimization of grinding processes, and verification of a novel grinding processes. The assessment may include surface roughness, surface-contour characteristics, surface morphology, surface and subsurface cracks, microstructural changes, and residual stresses [76,92]. The following describes the grinding-quality assessment methods applicable to composite materials.

Two types of surface roughness assessments exist: contact type and non-contact type. The contact type includes surface profilometry and portable roughness instrumentation. The white-light interferometry is the most widely used non-contact type surface roughness assessment technique [31,134,200]. The measurement of surface-contour features is similar to that of surface roughness. Two-dimensional (2D) contour features can be measured using a surface profiler, but for composite material workpieces, more attention should be paid to the 3D contours of the machined surface. Therefore, an ultra large field-depth microscope or a laser confocal microscope is the primary choice for 3D contour measurements [89,212].

X-ray diffractometry and Raman spectroscopy are the common methods used for analyzing element compositions and detecting residual stresses [25,185]. Scanning electron microscopy (SEM) with an energy dispersive spectroscopy (EDS) function can also be used to detect element compositions of a workpiece surface [32,114].

Optical microscopy can be used to detect surface/subsurface morphologies and defects [30,140]. It has certain advantages for the detection of macro- and micro-morphologies of composites although it has limited detection resolution and magnification. For observations at a micro/nano scale, SEM or transmission electron microscopy (TEM) can be used [25,57,165]. High-resolution TEM is an effective means to observe material defects at the atomic scale and determine the crystal structure [13,184]. Electron back-scattered diffraction (EBSD) technique has made it convenient to observe the orientation and deformation of subsurface grains [57,184,185]. However, the EBSD technique has a high demand for sample preparation, and it is seriously affected by the residual stresses on the sample surface. Although the abovementioned destructive methods possess good detection accuracies, they also require complex sample-preparation processes, making them unfriendly for users and thereby impractical for quality control on a production system. In recent years, non-destructive subsurface damage detection methods, such as μ-CT technique have emerged [16]. These techniques have been successfully applied to the internal defect detection of composite materials. Unfortunately, they are still immature for industrial use owing to poor detection accuracy and efficiency.

3.1.2. Quality assessment for composites grinding

Composite materials have the characteristics of non-uniformity of composition and structural anisotropy. The mechanical behavior of the reinforcing phase in a composite material dominates the surface integrity of the material during the grinding process in terms of surface morphology, material removal mechanisms, and damage formation mechanisms. The surface morphology of a composite material subjected to grinding is largely different from that of a metallic material. The assessment method for metal grinding usually does not objectively reflect the grinding quality of a composite material, or it may mislead the interpretation of a grinding result. Therefore, it is necessary to introduce a quantitative evaluation method suitable for quality control in composites grinding. By summarizing a large number of studies, this review presents quality indicators for composites grinding in three different aspects.

(1) Composite surface characterization for grinding

The 2D surface roughness parameter Ra and the 3D surface roughness parameter Sa are still the most commonly used indicators for evaluating the surface quality of composites. The surface roughness parameters Ra and Sa are the arithmetic mean deviations of the surface profile, subject to the micro-geometric errors. They are effective in evaluating the surface quality of a metallic material subjected to a grinding process. However, because large-scale surface fractures often occur in composites grinding, Ra and Sa cannot reflect the large-scale fracture characteristics. In this regard, some scholars have used the fractal dimension to evaluate the surface quality of composites. However, the fractal dimension is independent of the scale; that is, in theory, it can be used to study the surface phenomena at any scale. Gao et al. [44] successfully combined surface roughness with 3D fractal dimension to evaluate the grinding surface quality of CFRP. The smaller the fractal dimension, the lesser the fracture characteristics of the grinding surface and the smoother the surface. Zheng et al. [212] used surface fractal dimension to evaluate the surface quality of SiCp/Al materials. They reported that the surface fractal dimension was more sensitive to the common pit defects of MMCs compared to the 3D surface roughness. The waviness of the grinding surface of a fiber-reinforced composite is an important surface feature. Cao et al. [9] proposed a new method to evaluate the surface quality of woven ceramic matrix composites by calculating the 3D surface-feature parameters. The surface waviness of a traditional metallic material is highly related to the vibration of the machine tool, whereas for braided ceramic matrix composites, the fiber direction has a decisive influence on the grinding-surface waviness.

(2) Optimization of sampling location

Owing to the anisotropy and non-uniformity of composites, the grinding surface is prone to machining damage such as pits, groove marks, and burrs. These characteristics typically exist in a small range but have a great impact on surface roughness. Therefore, the measured value of surface roughness depends heavily on the sampling position. To reflect the surface morphological characteristics of composites and improve measurement accuracy and stability more comprehensively, Shi et al. [134] proposed a new surface roughness evaluation method based on sampling array and successfully applied it to CFRP composites. Surface topography of each sample was measured and quantitatively characterized using Sa. Frequency histogram of Sa in the sampling array was fitted with a Gaussian function. The mean value and standard deviation of the Gaussian function were applied for evaluating the machined surface quality. This evaluation method reduced the changes to the surface roughness results caused by different sampling positions and reflected the spatial distribution of Sa, as shown in Fig. 17. When the number of samples was higher than 13 $\times$ 13, the stability and accuracy of the abovementioned evaluation methods tended to be stable, and the relative error was less than 1%.

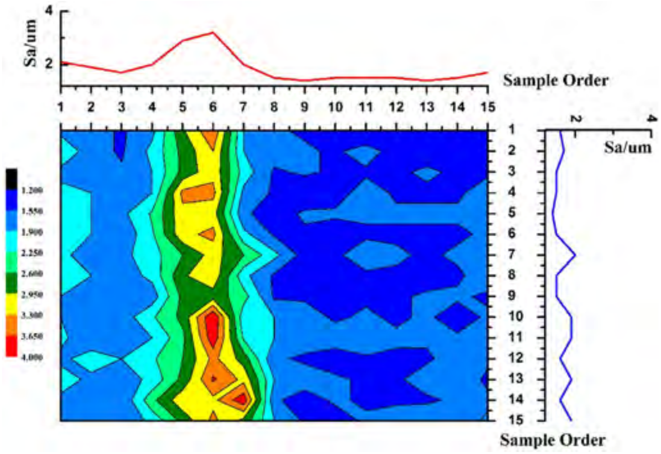

Fig. 17. Spatial distribution of Sa across surface based on sampling array [134].

(3) Comprehensive evaluation scheme

For evaluating the machined surface quality of a composite material with large-scale defects, a multi-index comprehensive evaluation scheme can be used. Zhu et al. [221] established a comprehensive evaluation scheme that considered the profile height and surface roughness of the entire topography and the profile height and equivalent surface roughness of the cavity defects, as shown in Fig. 18. The evaluation scheme could directly reflect the surface morphology with cavity defects, thereby providing a guidance for the usability performance of SiCp/Al materials.

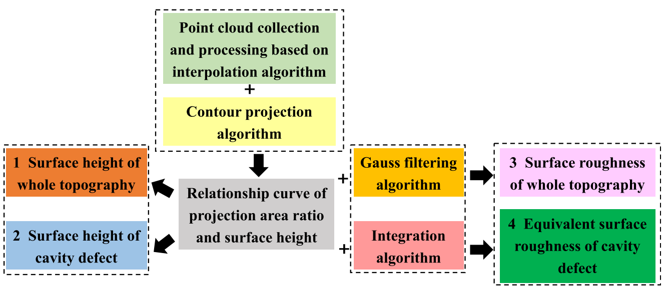

Fig. 18. Schematic diagram of the comprehensive evaluation scheme for surface morphology [221].

3.2. Polymer matrix composites

Fiber-reinforced composites have the characteristics of macro-anisotropy that imposes a great influence on the surface integrity of a ground workpiece. A large number of studies have shown that the surface morphology of a ground PMCs workpiece is closely related to the fiber direction angle [14,44,62,83]. Hu et al. [61,62] studied the surface roughness of CFRP at different fiber cutting angles. They demonstrated that when the grinding depth was small (≤0.02 mm), the influence of fiber cutting angle on surface roughness was not obvious. However, when the grinding depth increased to a certain level (≥0.05 mm), the surface roughness at a fiber cutting angle in the range of 120° – 180° increased sharply, and reached the maximum at approximately 150°, as shown in Fig. 19. According to the analyses on the material removal mechanisms of the fiber-reinforced composites presented in Section 2.1, when the fiber direction angle was $\theta > 90° + \gamma$, the fiber could bend and break with its fracture point above or below the cutting edge, resulting in an uneven fracture height. In addition, the interface debonding depth was large, and the subsurface damage was much more severe [177]. This is confirmed by the observations of the CFRP grinding sections with different fiber direction angles [61], as shown in Fig. 20. Liang et al. [89] found a similar phenomenon in CFRP grinding. When the fiber direction angle was 90°, the grinding surface was the smoothest, whereas a serrated surface profile was obtained at 135°

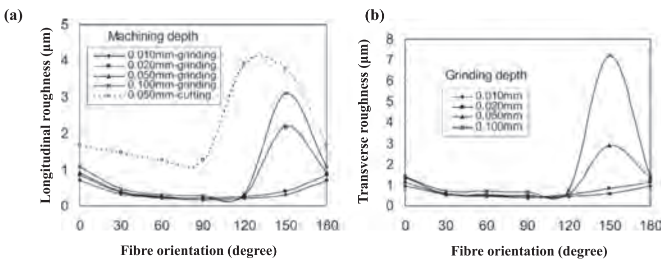

Fig. 19. Effect of fiber direction angle on surface roughness of ground CFRP: (a) along the grinding direction; (b) perpendicular to the grinding direction [61].

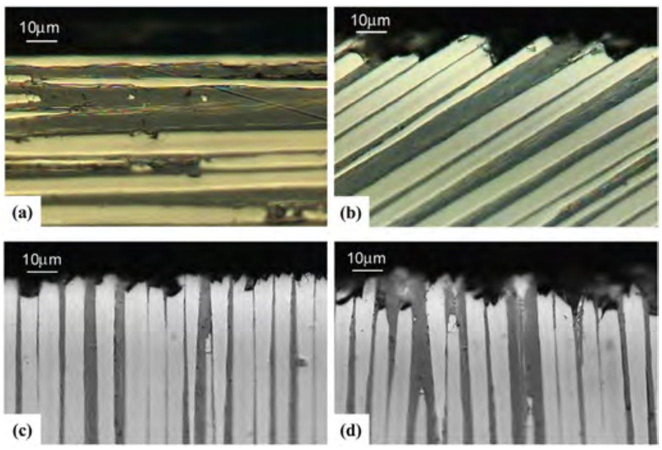

Fig. 20. Cross sectional morphology of CFRP with different fiber orientation angle θ and grinding depth d [61], (a) θ=0°, d = 20 μm; (b) θ=150°, d = 20 μm; (c) θ=90°, d = 20 μm; (d) θ=90°, d = 100 μm.

Surface roughness of CFRP can be significantly reduced using a fine grinding wheel by maintaining the sharpness of the grinding wheel and reducing the individual abrasive grain depth. Park et al. [122] realized mirror-finish grinding of CFRP using a #6000 metal-bonded diamond wheel by employing the electrolytic in-process dressing (ELID) technique and obtained CFRP surface roughness Ra_{max} below 0.65 μm. They further characterized the grinding surface using SEM and Auger electron spectroscopy, and found that the grinding debris comprised carbon fiber and carbonized epoxy resin. In addition, the workpiece surface was smeared with epoxy resin to form a smooth mirror finish. It should be noted that such a mirror-finished surface could cover up surface damage that may have been induced during the grinding process.

In fact, the resin matrix of a CFRP workpiece has a poor heat resistance and is easily affected by temperature rise. This may have an impact on the surface quality of a ground CFRP workpiece. The resin matrix is softened at the glass transition temperature beyond which thermal decomposition could occur in the CFRP workpiece, causing the carbon fibers to separate from the resin matrix and lose the protective effect of the resin [73]. Moreover, CFRP can easily absorb water and expand in a hydrothermal environment, compromising its mechanical properties [3,130]. Generally, such a material is not suitable to be applied with coolants during a grinding process. The aforementioned characteristics of CFRP are unfavorable to the surface integrity of a ground CFRP workpiece.

To suppress the grinding temperature, Zhang et al. [197] conducted a CFRP grinding test with cold air as the cooling medium (Fig. 21). The results demonstrated that cold-air grinding produced a higher grinding force but a lower surface roughness than dry grinding. The surface roughness increased with an increase in grinding depth and feed rate, and it had the lowest value in the 90° longitudinal grinding direction. The interface bonding strength of CFRP was higher at a lower grinding temperature, which helped in reducing the grinding-induced damage and improved the workpiece quality.

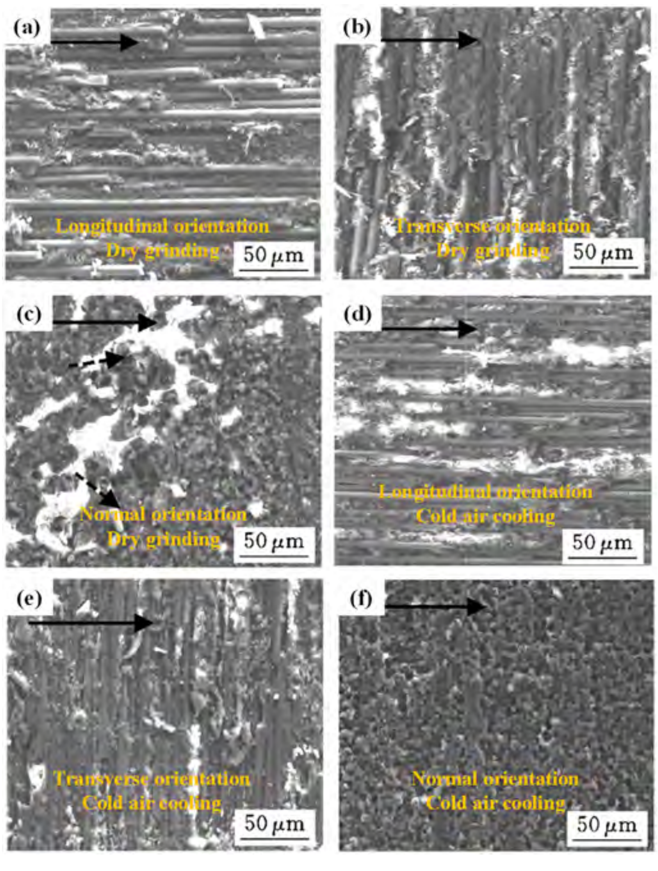

Fig. 21. Grinding surface morphologies of the CFRP workpieces under dry grinding and cold air-cooling conditions [197].

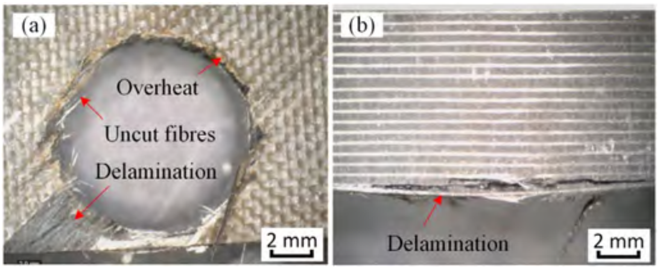

Fig. 22. Delamination and tearing damage at the rotary ultrasonic elliptical machining of thick CFRP hole exit [49]: (a) surface topography; (b) cross sectional observation.

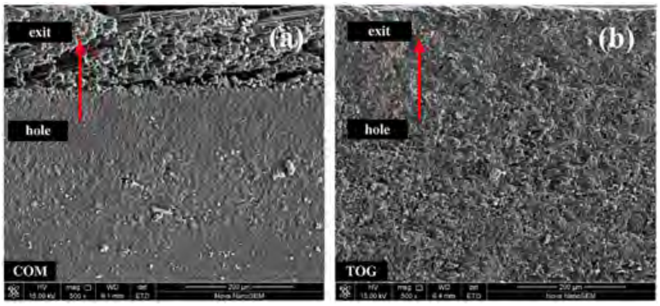

Fig. 23. Tilted orbital grinding technique for hole-making of CFRP [47]: (a) the surface of a hole made by the conventional orbital grinding, exit delamination is induced; (b) the surface of a hole made by the tilted orbital grinding, exit delamination is suppressed.

CFRPs are typically prepared as laminated plates that exhibit the characteristics of macro-anisotropy. The mechanical strength of the layer parallel to the fiber direction is much higher than that of the interlayer of CFRP. Therefore, the interlayer damage is problematic in a machining process. This is true in a hole making process that normally suffers from poor chip removal and heat dissipation conditions, as well as delamination and tear at the outlet of the hole due to the weak constraints. Similar to drilling, grinding can also cause serious interlayer damage due to temperature rise [49], as shown in Fig. 22.

To reduce damage in hole grinding, researchers have developed some new machining methods. Currently, orbital milling is one of the commonly used CFRP hole-making methods. One of its great advantages is that it does not have a zero-speed point compared to the traditional drilling processes. This can significantly reduce the axial force and increase the chip removal space [6,163]. The main and auxiliary cutting edges of the traditional spiral-milling tool are in contact with the hole-bottom and hole-wall materials simultaneously, resulting in high cutting force and temperature. To improve the hole quality further, Wu et al. [167,175] proposed to employ tilted orbital milling to mill holes in CFRP. Gao et al. [47] conducted an experiment on tilted orbital mill-grinding using an electroplated diamond grinding wheel. Compared with the traditional spiral milling, the tilted orbital mill-grinding significantly reduced the machining force and temperature and successfully suppressed the delamination damage at the exit, as shown in Fig. 23.

Kunimine et al. [75] developed a unique dual-axis grinding wheel system (DAGWS) to produce CFRP holes, as shown in Fig. 24. The grinding wheel axis was perpendicular to the hole axis. When the grinding wheel rotates, the grinding wheel axis also rotates around the hole axis. Compared to the ordinary drilling process, the dual-axis grinding wheel system continuously changes the contact angle between the grinding wheel and the workpiece surface from 0° to 90° The system is conducive to suppressing the delamination damage at the hole exit. However, the dual-axis grinding wheel system is only suitable for machining large diameter holes.

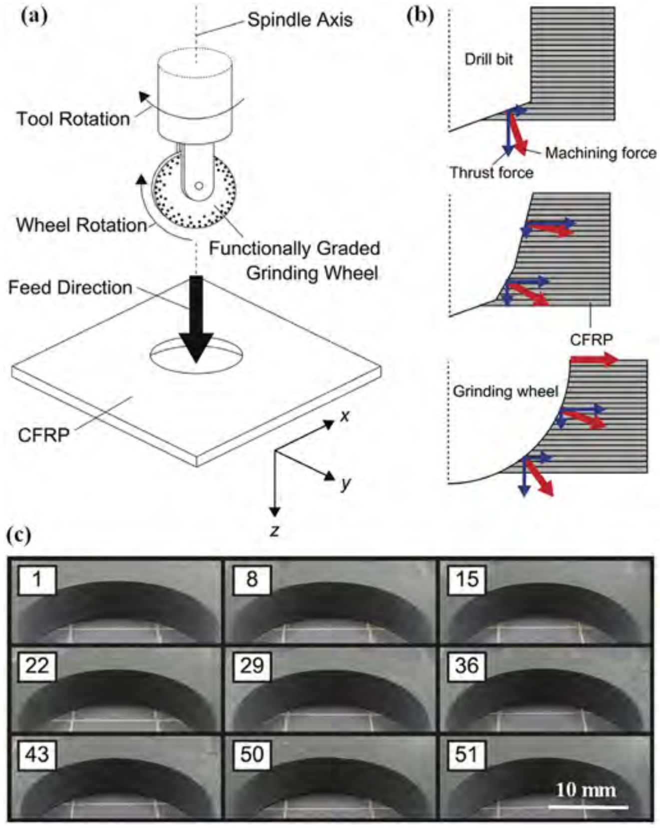

Fig. 24. Drilling CFRP by DAGWS [75]: (a) schematic diagram of DAGWS; (b) schematic diagram of reducing exit damage by DAGWS; (c) photographic views of the holes drilled by DAGWS.

3.3. Ceramic matrix composites

The main difference between CMCs and PMCs is that the CMCs matrix has better heat resistance; therefore, the effect of grinding temperature on the surface integrity of CMCs can be ignored. The main types of grinding-surface damage of CMCs are fiber fracture and pullout, matrix fracture, and interface debonding [107]. Similar to PMCs, fiber direction has an important impact on the grinding-surface integrity.

Wang et al. [165] observed the wall-surface morphology of the C_f/SiC holes after grinding and found that the hole-wall quality was the best when the fiber direction angle was 90°, whereas the surface flatness was poor when the fiber direction angle was 0°/45°/135° Zhang et al. [200] conducted a unidirectional C_f/SiC composite grinding test, and obtained the grinding-surface morphology in different fiber directions, as shown in Fig. 25. The workpiece surface roughness in the three orthogonal grinding directions was measured. The results showed that at a wheel rotational speed of 1500 r/min, the surface roughness along the longitudinal fiber direction was significantly higher than that in the other two fiber directions. At a wheel speed of 3000 r/min, the surface roughness values in the three directions had little difference. Furthermore, the feed rate and grinding depth had little effect on the surface roughness. Wang et al. [171] carried out a finite element simulation study on grinding of 2.5D braided quartz fiber ceramic matrix composites and found that the ceramic matrix was easy to be damaged and removed by the fiber extrusion caused by the grinding force, which inevitably reduced the surface quality of the composite workpiece. The fiber debonding was caused by the uncoordinated deformation of the warp and weft fiber bundles. Grinding along the fiber direction could reduce the matrix crushing, and grinding perpendicular to the weft axis could reduce the fiber debonding.

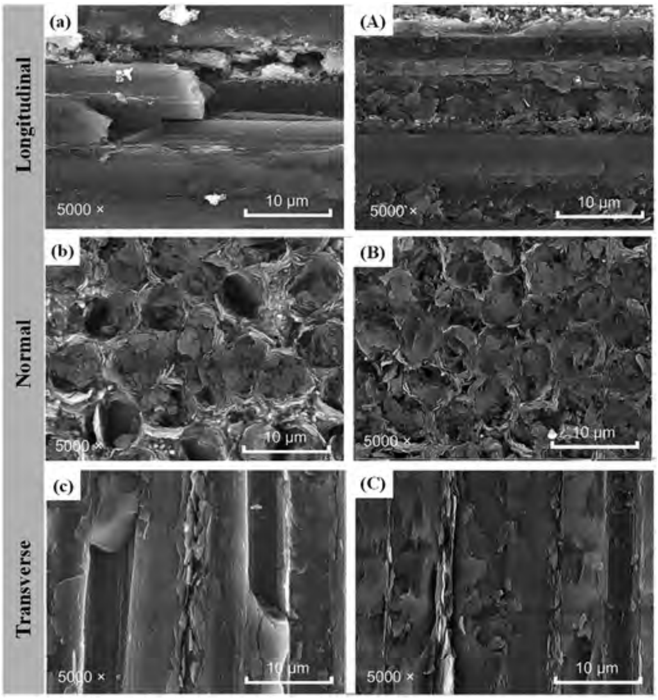

Fig. 25. SEM micrographs of the unidirectional CVI-C/SiC surfaces ground by a diamond grinding wheel [200]: (a-b-c) n = 1500 r/min, (A-B-C) n = 3000 r/min.

CMCs have been widely used in engineering applications in terms of fiber-braided structures, which often need a grinding finish. The typical morphology of a grinding surface is shown in Fig. 26. It can be seen that there are mutually perpendicular fiber directions on the same surface. At the junction of the fiber bundles, the surface morphology is different because of different fiber-bending angles [100]. Researchers have performed a large number of experimental studies on the grinding surface roughness of CMCs. Results have shown that the fiber direction plays a decisive role in the surface roughness. Liu et al. [100] indicated that the grinding force and surface roughness increased with an increase in feed and grinding depth, but decreased with an increase in grinding speed. Cao et al. [8] found that the grinding surface finish was the best when the fiber direction angle was 90° and the worst when the fiber direction angle was 0° The surface containing more parallel fibers was rougher after grinding.

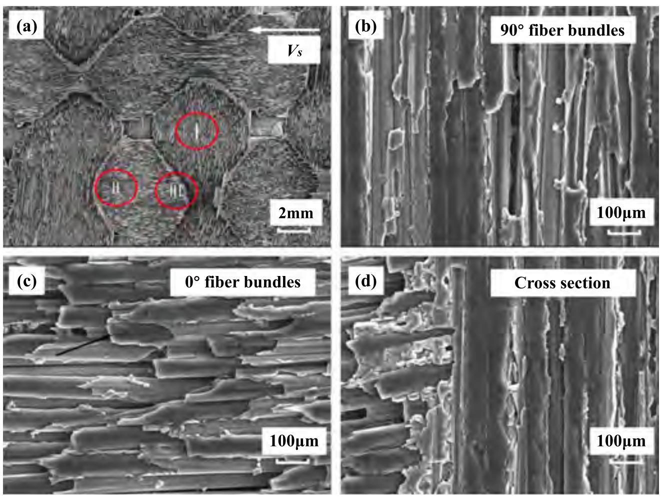

Fig. 26. SEM micrographs of the ground 2D C/SiC composites [100] (v_s=60 m/s, v_w=2000 mm/min, a_p=50 μm).

Du et al. [31] found that there were obvious differences in the grinding force and surface roughness values in different grinding directions. Compared to the grinding of a metallic workpiece, the grinding of a 2D braided C_f/SiC workpiece features a much higher tangential force than normal force. Therefore, a theoretical model of the undeformed chip thickness based on the traditional grinding scenario is no longer suitable to evaluating the surface roughness of the composite workpiece.

Studies have shown that increasing the grinding speed is conducive to reducing the influence of fiber orientation on surface roughness [100,200], which may be related to the "size effect". That is, increasing the grinding speed is equivalent to reducing the cutting depth of an abrasive grain, thereby changing the material removal mode. In a nano-scratching test of C_f/SiC, Chen et al. [13] found that by increasing the cutting depth, the material removal mode of a carbon fiber material experienced three stages: ductile regime, micro-crushing, and macro-fracture. Surface roughness was maintained at a low level as long as the macro-fracture did not occur. They also discovered that a critical load existed at which the fiber micro-crushing could be transformed to macro-fracture. According to the three typical directions in Fig. 27, the critical load and depth in the normal direction were the largest, but in the transverse and longitudinal directions, they were relatively smaller. Under the micro-crushing mode, the subsurface cracks of fibers in different scratching directions had specific characteristics. As shown in Fig. 27, the scratched fiber subsurface along the fiber axis mainly exhibited microcracks in the normal direction, cone cracks in the transverse direction, and radial cracks in the longitudinal direction [13].

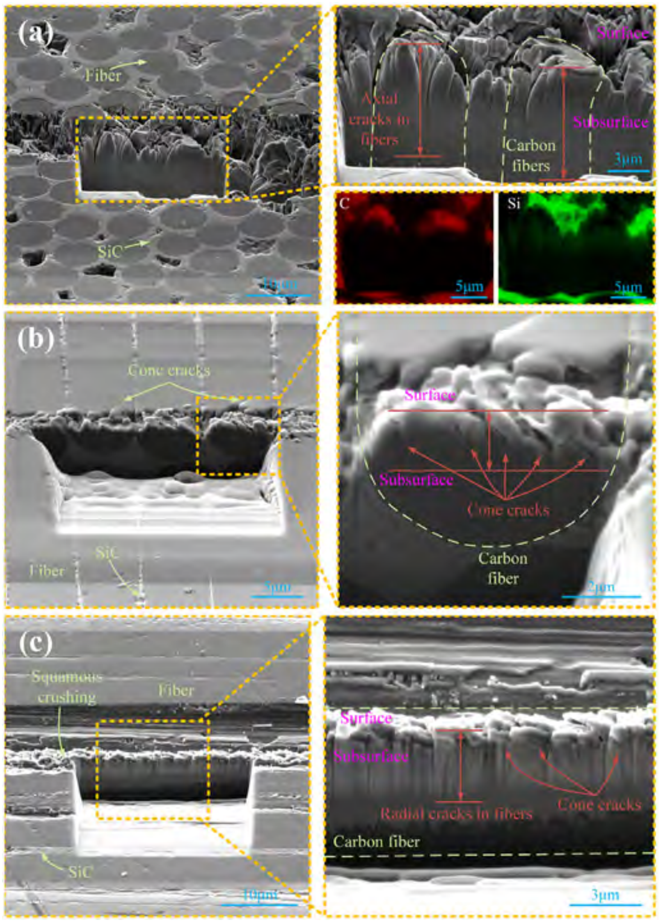

Fig. 27. Subsurface damage of micro brittle fracture along the different fiber orientations of unidirectional C_f/SiC composites [13]: (a) normal direction; (b) transverse direction; (c) longitudinal direction.

Although CMCs are not sensitive to temperature changes, owing to their poor thermal conductivity, an excessive amount of heat generated temperature during grinding leads to the rapid wear of the grinding wheel. Therefore, the surface temperature is usually reduced by flood cooling. The extensive use of a coolant reduces the economy of the machining process. Considering the economy factors and environmental protection, researchers have applied the minimum quantity lubrication (MQL) technology to CMCs grinding. Compared to flood cooling grinding and dry grinding, the MQL method can significantly reduce the grinding force, specific grinding energy, and surface roughness and improve the grinding efficiency [2,36].

3.4. Metal matrix composites

Grinding can introduce damage to an MMCs workpiece. Grinding damage is mainly influenced by the mechanical behavior of reinforced particles under the action of abrasive grains. It may include cavities formed by particle pullout and breakage and groove marks formed by particle debris sliding against the machined surface. In addition, cracks formed by interfacial debonding and tearing and smearing layers caused by severe thermoplastic deformation of the metal matrix are also important damage forms of MMCs [219], as shown in Fig. 28. Research results show that the higher the proportion of crushing and fracture of reinforced particles, the worse the surface integrity. Increasing the proportion of ductile removal mode of reinforced particles can reduce the grinding damage and improve the workpiece surface integrity.

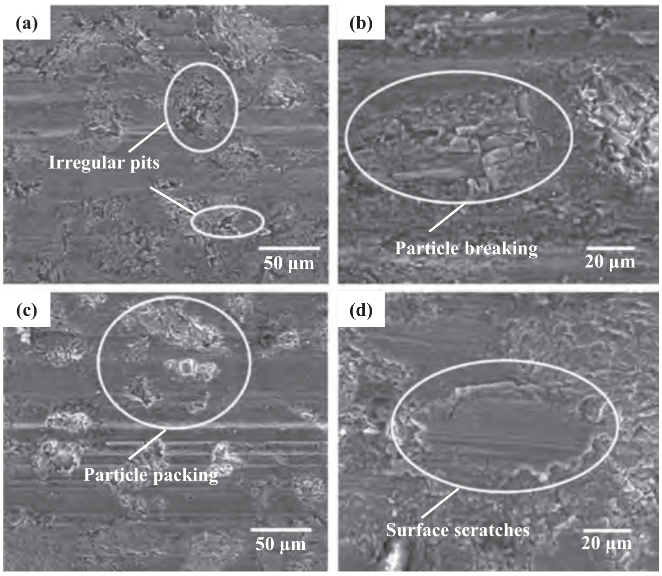

Fig. 28. Surface topographies of the ground SiCp/Al composites [219]: (a) irregular pits; (b) particle breaking; (c) particle packing and surface scratches; (d) matrix smearing.

Zhong et al. [213] conducted rough and fine grinding process tests on (Al_2O_3)p /Al materials, and found that aluminum matrix smearing occurred on the ground surface after rough grinding, but matrix smearing did not occur on the surface after fine grinding. A #3000 diamond wheel at 1 μm grinding depth was used in the tests, and they observed that the surface and subsurface of the ground workpiece were undamaged, but some ductile stripes were found on the ground surface of the Al_2O_3 particles. They recommended SiC grinding wheel for coarse grinding and super-fine diamond wheel for fine grinding to obtain good workpiece surface integrity. Enhancing the protruding height and sharpness of the abrasive grains and increasing the chip storage space of a grinding wheel are conducive to reducing the grinding damage of MMCs. Yu and Shanawaz et al. [133,191] ground SiCp/Al materials

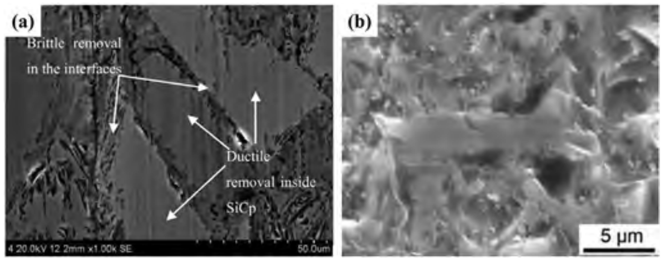

Fig. 29. Improvement of grinding surface quality by ductile removal of SiC particles [191,217]: (a) ELID grinding; (b) cryogenic grinding.

using the ELID technique to effectively improve the grindability of the SiC particles and inhibit surface damage (Fig. 29(a)). Suppressing the grinding temperature is also conducive to improving the surface integrity of MMCs. In the grinding of SiCp/Al materials, Zhou et al. [217] introduced liquid nitrogen into the grinding area by employing a cryogenic cooling method. The freezing action of the liquid nitrogen inhibited the thermal softening and enhanced the support provided by the aluminum matrix to the SiC particles. Although the grinding force was larger in cryogenic grinding than that in regular grinding, the workpiece surface integrity was significantly improved (Fig. 29(b)).

The relationship between surface roughness and grinding parameters of MMCs is relatively clear. With an increase in the grinding speed and a decrease in the feed rate and grinding depth, the surface roughness decreases. The higher the workpiece hardness value, the lower the surface roughness value [24,150,221]. Based on the statistical theory, Zhu et al. [222] combined the surface-roughness theoretical models of aluminum alloy and silicon carbide and established a surface roughness prediction model for grinding SiCp/Al materials by fitting an exponential composite function. Zhang et al. [205] developed an analytical model of the surface roughness of ground steel-based MMCs reinforced with TiC particles considering Rayleigh probability distribution of undeformed chip thickness, and the predicted surface roughness showed good agreement with the experimental results.

Subsurface damage of MMCs has an important influence on the fatigue performance of an MMCs workpiece. Dong et al. [30] microscopically observed the subsurface damage in high-volume-fraction

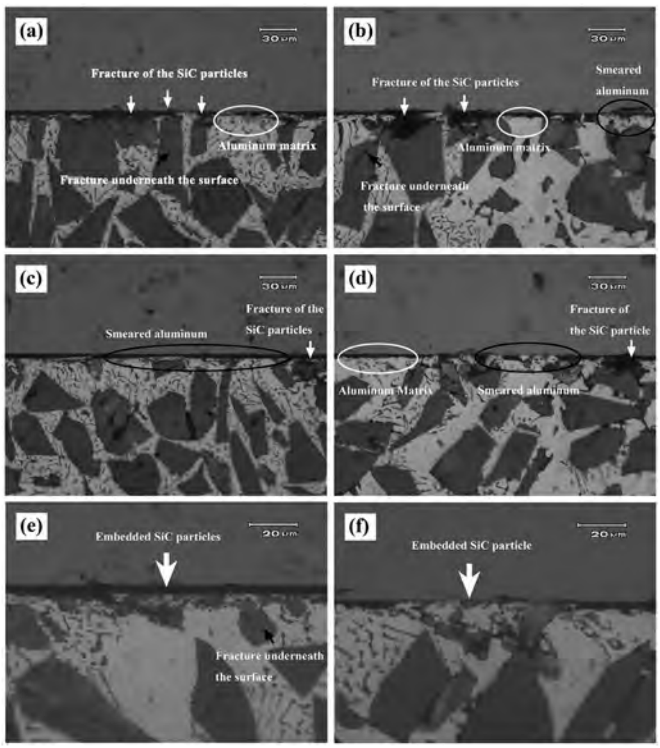

Fig. 30. Subsurface damage of SiCp/Al composites after grinding [30].

SiCp/Al grinding, and found that crushing, embedding, and cracking of the SiC particles had occurred on the workpiece surface, as shown in Fig. 30. They claimed that because the aluminum matrix was softened and smeared on the workpiece surface during the grinding process, grinding-induced damage was obscured. The grinding quality of the SiCp/Al workpiece could be fully reflected only by observing the ground surface.

Guo et al. [53] identified three different layers in the subsurface of ground SiCp/Al materials, as shown in Fig. 31. The topmost layer was a hybrid layer that featured refined Al grains and fragmented SiC particles at the nano-scale. Below the hybrid layer was the plastic flow layer, featuring fewer refined Al grains and larger broken SiC particles were observed because of the relatively less disturbance from the grinding wheel. In this layer, distinct lateral cracks were the typical features of the Al-alloy matrix. Along the depth direction from the ground surface, Al grain refinement and SiC particle fragmentation were further weakened in the plastic deformation layer, and the elongated Al grains around the migrated SiC particles were the major features and no evident broken SiC particles were found in this layer.

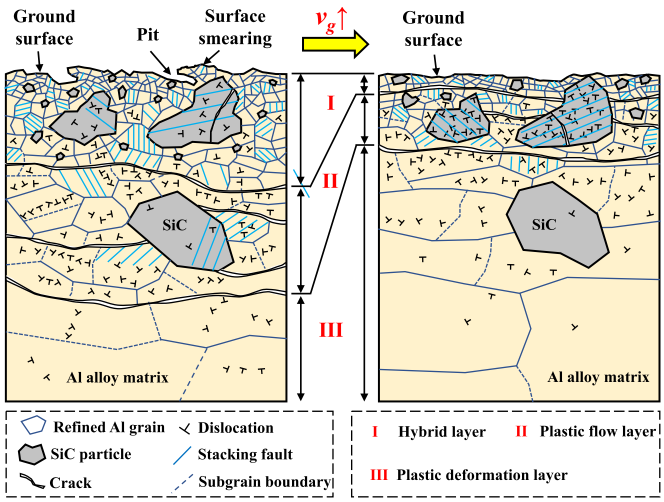

Fig. 31. Schematic of subsurface microstructural of SiCp/Al composites variation with grinding speed [53].

For cemented carbides, the content of the metal binder in the WC—Co cemented carbide was typically low, and the grinding subsurface damage was mainly characterized by the mixed deformation layer (formed by broken WC particles in the shallow surface and binder) and WC particles with plastic deformation and cracks below the mixed deformation layer [59,183]. As shown in Fig. 32, during the grinding process, slip systems inside the hard and brittle WC particles were activated and plastic deformation occurred. Experimental research showed that the surface-deformation layer of a WC—Co cemented carbide was conducive to improving the bending strength of the workpiece [183]. Liu et al. [94] established an analytical model of SiCp/Al subsurface damage. In the modeling process, the influence of the reinforcing particles, thermomechanical coupling, and tool wear were considered. In a verification experiment, the material surface-hardness change was considered as the subsurface damage depth, and the experimental results were in a good agreement with the model prediction results.

Residual stresses have an impact on the service properties of a ground MMCs workpiece. Predominantly compressive residual stress was identified in a ground WC—Co cemented carbide. Formation of residual stress was caused by the plastic deformation in the surface layer of the ground WC particles [59,183]. Yuan et al. [193] studied the grinding-surface residual stress of an ultra-finely grained WC-10% Co cemented carbide. The results showed

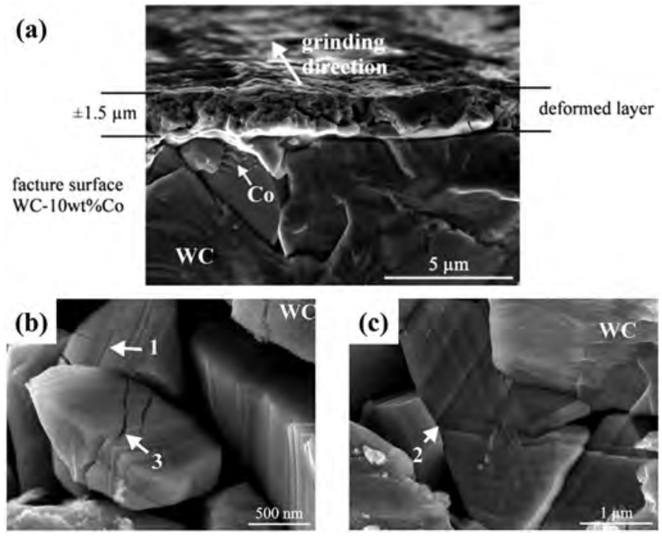

Fig. 32. Subsurface damage of the WC—Co cemented carbide after grinding [59]: (a) deformed surface layer; (b) slip lines 1 and cracks 3 on WC particles below the deformed surface layer; (c) prismatic slips 2 on WC particles below the deformed surface layer.

that the residual stress was mainly compressive stress whose absolute value decreased with a decrease in the grinding wheel grit size, and the grinding depth had little effect on the residual stress. Cruz et al. [18] studied the effects of grinding-process parameters and wheel parameters on the residual stress of the WC-5% Co cemented carbide. They discovered that the residual stress was compressive stress, and the absolute value of the residual stress perpendicular to the abrasive path was larger. With an increase in the grinding speed, the absolute value of the residual stress decreased. The coarser the abrasive grain, the greater the absolute value of the residual stress. The grinding residual stress of a ceramic-based grinding wheel was greater than that of a resin-based grinding wheel. Mao et al. [114] found that a high level of residual stress was generated in the WC phase when grinding CBN-WC-10Co composites, and its absolute value increased with an increase in the grinding depth.

Changes to the MMCs surface microstructure after grinding include plastic deformation and phase transformation. The content of TiC in titanium matrix composites is not high (10% by volume), and the plastic deformation of the surface matrix caused by grinding is obvious, which is closely related to the process parameters. Xi et al. [176] carried out experimental research on HSG of titanium matrix composites and found that when the feed speed and cutting depth were high, the workpiece surface underwent a more severe plastic deformation, as shown in Fig. 33. Li et al. [86] also observed a surface layer with plastic deformation when grinding titanium matrix composites. In addition, owing to the high strength and poor thermal conductivity of the titanium alloy matrix, grindability of titanium matrix composites was poor,

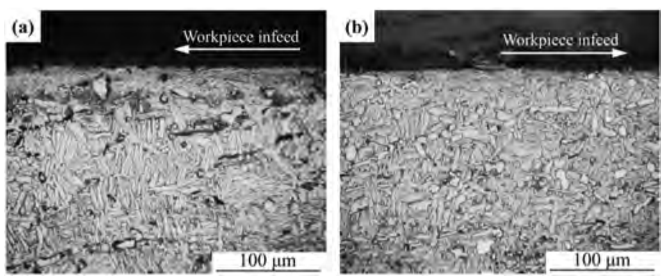

Fig. 33. Cross-sectional microstructure of the subsurface layer of TiCp/Ti-6Al-4 V composites [176]: (a) v_w=6 m/min, a_p=0.02 mm, v_s=120 m/s. (b) v_w=3 m/min, a_p=0.002 mm, v_s=120 m/s.

which was mainly reflected by the high grinding force and temperature. An experimental study conducted by Li et al. [86] reported that the grinding force and temperature could reach 400 N and 1000 °C, respectively, in creep-feed grinding. At a grinding depth greater than or equal to 1 mm, the surface residual stress changed to tensile stress. Yang et al. [184] studied the metallurgical changes of the Co binder during the grinding of WC—Co cemented carbide and found that approximately 5 μm below the grinding surface, Co binder experienced martensitic transformation from face-centered cubic structure to hexagonal close-packed crystal structure. The grain refinement of the surface layer was also observed. Furthermore, approximately 1 μm below the grinding surface, the Co binder experienced the maximum strain, resulting in the formation of nano-grains.

3.5. Interim conclusions

The characterization of surface integrity of composites grinding is a weak link in the current theoretical system. At present, the surface-integrity characterization system of conventional metal machining is still widely used. However, the heterogeneity and anisotropy of composite materials cause great difference between the characteristics of surface integrity of composite materials and that of monolithic materials, specifically for the characterization of subsurface damage. Because the transition boundary of the microstructure of each deformation layer on the subsurface of a composite material is not clear, it is difficult to identify the subsurface damage-layer depth. Therefore, it is necessary to establish a convincing surface-integrity characterization system for composite materials.

4. Advanced grinding processes

The most prominent problems in composites grinding are wheel loading and poor surface integrity. To solve these problems, researchers have pursued several process innovations and achieved quite good results. In this section, the related innovative researches are divided into four parts, including “Advanced wheel and cooling lubrication techniques”, “Ultrasonic vibration-assisted grinding”, “Belt grinding” and “High-speed grinding”.

4.1. Advanced wheel and cooling-lubrication techniques

4.1.1. Advanced grinding-wheel techniques

Under the action of grinding force and grinding heat, attrition wear, abrasive grain crushing, abrasive grain shedding, adhesion, and loading are the main mechanisms of grinding-wheel wear. Research shows that when grinding PMCs, CMCs, and MMCs, wheel loading and attrition wear are the prominent problems of grinding-wheel wear [4,30,140,219]. In the process of composites grinding, the grinding parameters [1], abrasive grain size and bond properties [81,108,109,126], and material and structural characteristics of a composite workpiece [38,42,173] have important effects on the grinding-wheel wear.

Owing to the inherent limitations, it is difficult to solve the problem of wheel loading and attrition wear of abrasives effectively when using a conventional grinding wheel to grind composite materials. The abrasive grains are irregularly arranged in a conventional grinding wheel with random protruding heights, and a small number of dynamic effective abrasive grains are observed in the grinding area. Most of the abrasive grains do not directly participate in the material removal process, with some grains rubbing and ploughing against the workpiece surface, resulting in a large amount of grinding heat. The dense distribution of a large number of invalid abrasive grains leads to the reduction of chip-storage space. When grinding composite materials with thermoplastic matrices, a grinding wheel may easily be loaded in its chip-storage space and loses its cutting ability during the grinding process. The emerging technology of the grinding tools with well-defined grain distributions subverts the concept of traditional grinding wheels. Arranging the abrasive grains in an orderly manner on a wheel surface by using special processing methods can improve the proportion of the effective abrasive grains and increase the chip-storage space. Furthermore, this prolongs the service life of the wheel and improves the integrity of the grinding surface. In addition, the grinding performance of a wheel can be controlled by adjusting the abrasive-grain arrangement parameters.

At present, electroplated and brazed grinding wheels with defined abrasive-grain distributions are being used in grinding process of composite materials, such as CFRP and cemented carbide [43,89,192,202,203]. Compared to the electroplating process, the brazing process can form a firm metallurgical connection between the abrasive grains and the metal bond and significantly improve the holding force [79].

The conventional electroplated and brazed grinding wheels with defined abrasive-grain distributions still have certain shortcoming. It is still difficult to sharpen such grinding wheels to ensure consistency in the abrasive-grain protruding height. Moreover, the manufacturing processes of these grinding wheels are time-consuming and costly. To overcome these limitations, some researchers have proposed new concepts of solid diamond engineered tools where the arrangement of the grains of controlled shapes and protrusions is created by removing the surrounding material using non-conventional techniques to customize the abrasives. Luna et al. [106] produced an engineered grinding tool (Fig. 34) on a solid piece of polycrystalline diamond (PCD) and used pulsed laser ablation (PLA) to sharpen the cutting edges (Fig. 35(a)), as well as a novel technique for grinding the SiC-based CMCs. Compared to a conventional grinding tool, the novel technique enhanced the surface integrity of the SiC/SiC CMCs and significantly reduced the wear rate by 25%.

Butler et al. [7] developed a novel micro-core drill using PLA on a solid PCD to drill micro-holes on CFRP (Fig. 35(b)). The geometry of the cutting edges was defined, and the experimental results presented a step change in the performance of small-diameter core drilling by facilitating a shearing mechanism of the CFRP workpiece. Spampinato et al. [142,143] designed and manufactured a novel roller dresser and profiled rotary dresser on a set of PCD rings or segments using wire EDM and PLA to efficiently produce precise and sharp abrasive features of uniform shape, size, and protrusion at accurately controlled locations. The successful tests of the novel

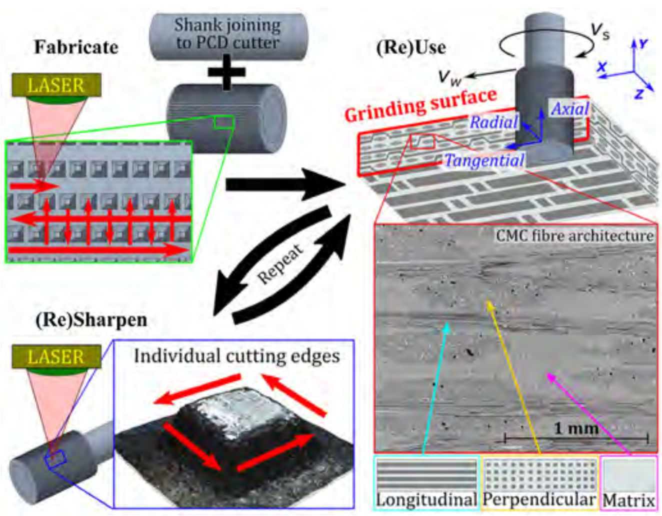

Fig. 34. Schematic representation of the engineered grinding wheel concept for CMCs with (re)sharpening capabilities for extended tool life [106].

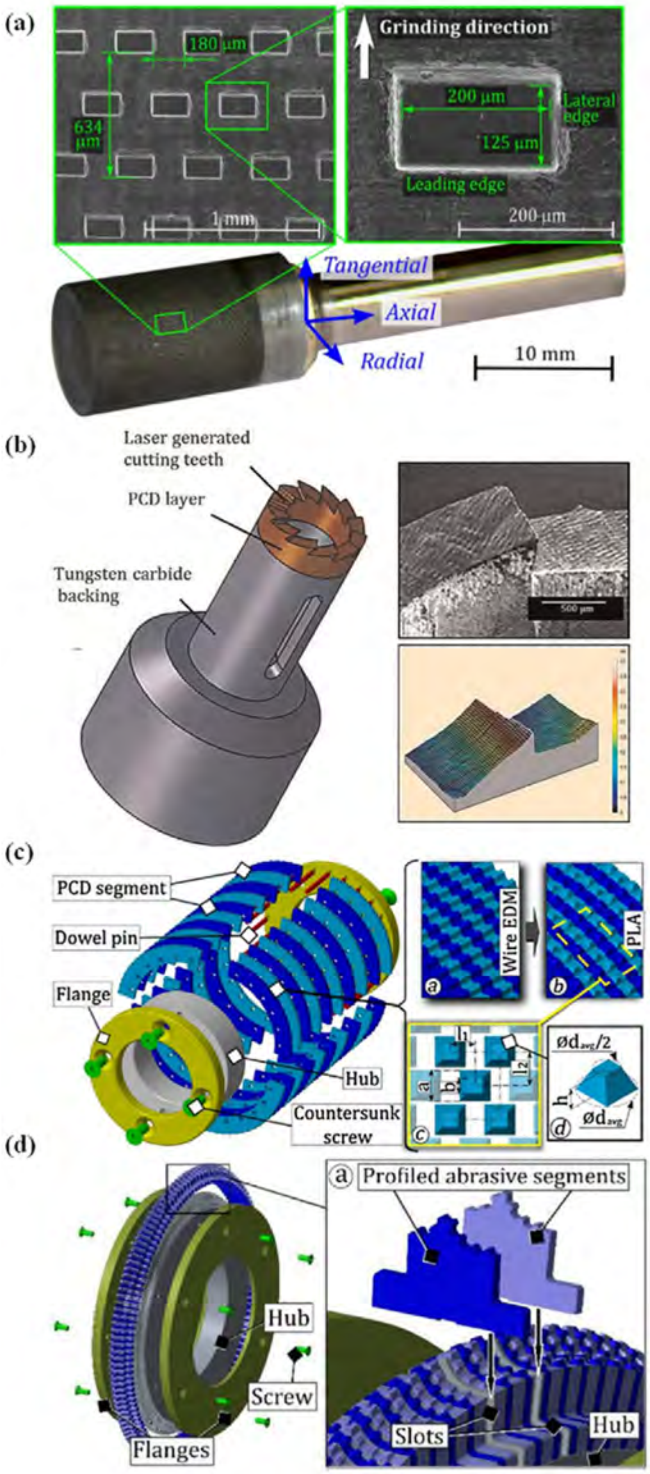

Fig. 35. Novel grinding tools with abrasive grains of controlled shape and protrusion produced by using pulsed laser ablation technique [7,106,142,143]: (a) grinding tool with square grit shape, (b) core drill with micro-cutting teeth, (c) design and manufacturing route for a novel roller dresser, (d) design details for a profiled rotary dresser.

grinding tool with controlled shape, protrusion, and location of abrasive grains demonstrated a great application potential in composites grinding.

4.1.2. Advanced cooling-lubrication techniques

In addition to developing grinding wheels with defined grain distributions, application of an effective coolant can also significantly improve the wheel performance in composites grinding. Sasahara et al. [131] ground CFRP using a ceramic bonded alumina wheel with an internal cooling structure. They found that the wheel loading was greatly improved and the surface roughness was reduced when compared to dry grinding. Wang et al. [154] developed an electroplated diamond core drill with the function of self-chip removal to produce large-diameter holes (Φ50 mm) in CFRP. They were able to reduce the temperature during hole making effectively and obtained a better grinding performance, as shown in Fig. 36. Wang et al. [154] also studied the wheel loading when machining CFRP holes with different cooling methods. As shown in Fig. 37, compared with no cooling or external cooling, the internal cooling method could effectively inhibit the wheel loading at the end face.

Dry processing has been widely applied owing to the hygrothermal aging of CFRP using flood lubrication [77,132], but the yielding dust is harmful to humans and the environment [55]. Vegetable oil-based nanofluid minimum quantity lubrication (NMQL) involving CNTs with excellent heat-transfer and friction-reduction properties could solve the abovementioned problems. Gao et al. [44,45] conducted grinding experiments under different conditions to investigate grindability and surface integrity of a CFRP workpiece with NMQL and demonstrated the feasibility of CFRP precision machining using NMQL. In NMQL grinding, CNT nanoparticles form a dense protective film at the interface between the grain and the fibers, as shown in Fig. 38. This film

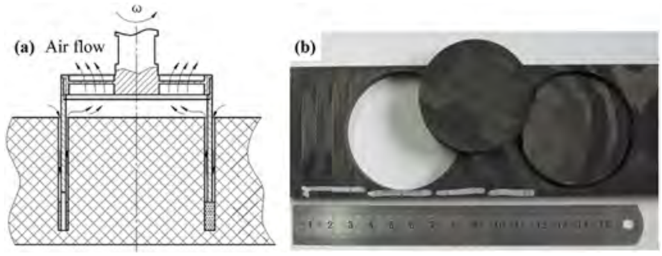

Fig. 36. Machining of large diameter CFRP holes with the self-air-cooling electroplated diamond core drill [154]: (a) chip removal mechanism of the self-air-cooling core drill; (b) CFRP large-diameter hole machined with the self-air-cooling core drill.

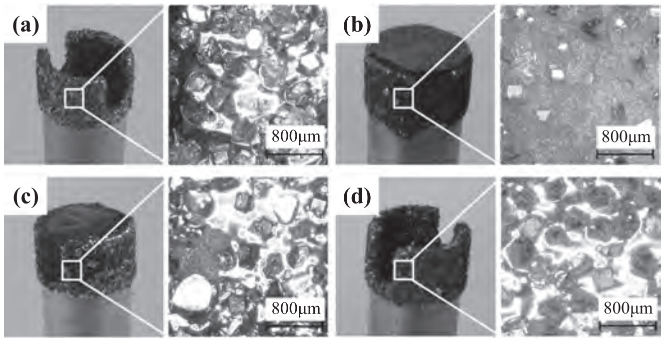

Fig. 37. Morphology of a new tool and the tools after drilling using different cooling methods [154]: (a) new tool; (b) no cooling; (c) external air cooling; (d) internal air cooling.

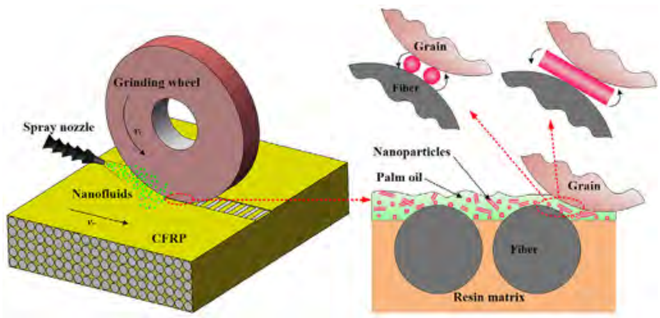

Fig. 38. Protective effect of CNT nanofluids on the grain-fiber interface [44].

prevents the grain from removing the partially exposed fibers, thereby improving the surface integrity. The NMQL technique can also be used for CMCs grinding. Qu et al. [124] proposed a method for effectively dispersing carbon nanoparticles and studied the effects of dry, flooded, MQL, and NMQL conditions on the grinding performance of C_f/SiC. The experimental results showed that the NMQL conditions could provide significantly higher surface quality and lower grinding forces than the other conditions.

4.2. Ultrasonic vibration-assisted grinding (UVAG)

Yang et al. [188] comprehensively reviewed the application of ultrasonic vibration-assisted machining (UVAM) of advanced materials. According to the different application directions and cases of ultrasonic vibration, UVAM can be divided into three categories: one-dimensional (1D) UVAM, 2D UVAM, and 3D UVAM, with various specific forms, as shown in Fig. 39. There are two types of ultrasonic vibrations in 1D UVAM: one is perpendicular to the machining surface [30,88,101,156,159,208,212,219], and the other parallel to the machining surface [14,83,89,90,135,158,166]. Elliptical UVAM [48,49,161] and longitudinal–torsional UVAM [38] are the most widely used 2D UVAMs, and 3D UVAM is rarely used. Moreover, 3D ultrasonic vibration-assisted grinding (UVAG) cases of composite materials have not been reported yet.

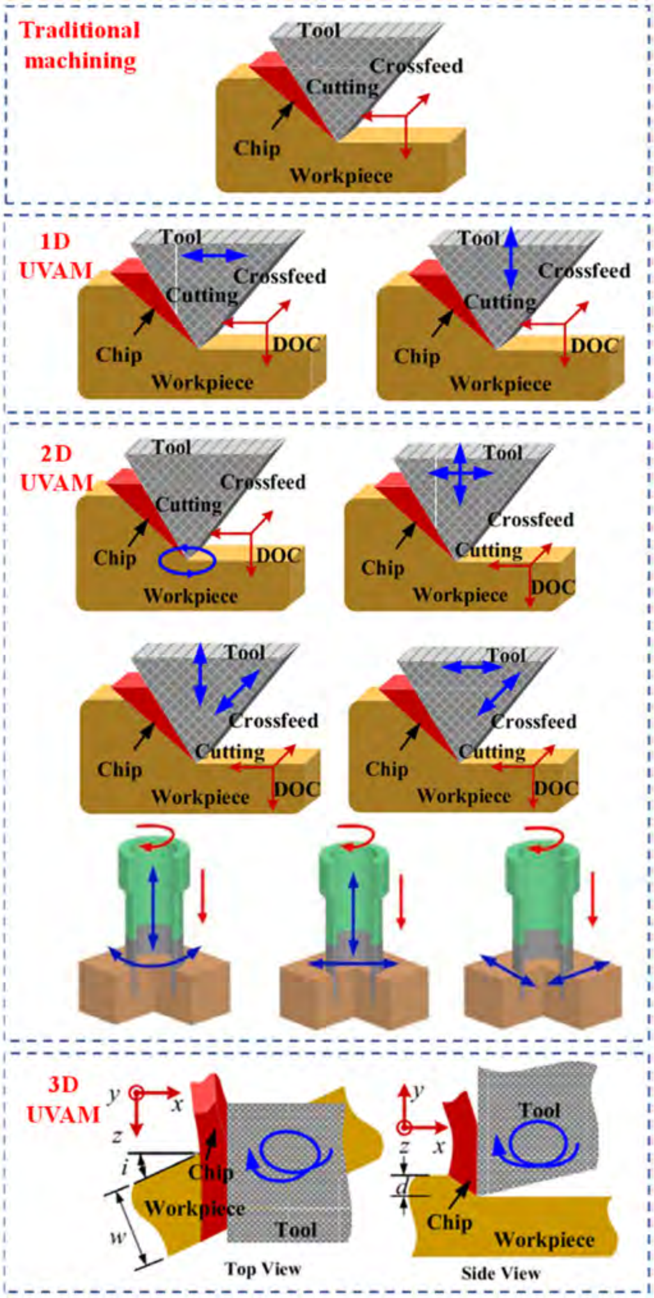

Fig. 39. Three different categories of ultrasonic vibration-assisted machining [188].

A large number of studies have shown that, when applying 1D UVAG in the PMCs grinding process with vibration direction perpendicular to the machined surface, the grinding force, grinding-wheel wear, and surface roughness are significantly reduced compared to the conventional grinding processes [12,101,119,156,159]. The 1D UVAG process can be better than the conventional grinding process in terms of the surface roughness of MMCs. However, it may sometimes be worse than the conventional grinding processes [30,208,212,219]. To reveal the mechanisms of UVAG, Feng et al. [39] conducted an ultrasonic vibration-assisted scratching test on SiCp/Al, and found that the impact of the abrasive grain against the workpiece surface could pulverize the SiC particles that were remove easily, as shown in Fig. 40. The pulverized transition layer helped reduce the friction coefficient between the abrasive grain and the workpiece. The results of the scratching test of CFRP conducted by Ning et al. [121] showed that the ultrasonic vibration-assisted scratching led to a larger crack-free removal region before the successive brittle fractures and cracks.

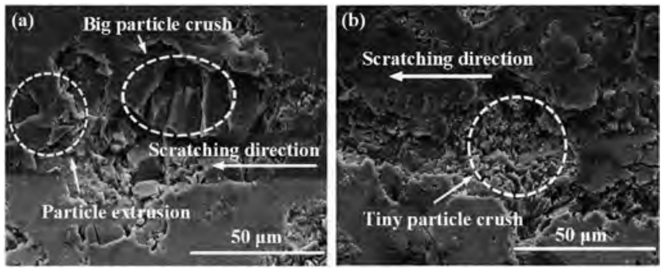

Fig. 40. Comparison of the surface morphologies between the ultrasonic vibration-assisted scratching process and the traditional scratching process [39]: (a) traditional scratching; (b) ultrasonic vibration-assisted scratching.

The most prominent feature of the 1D UVAG with the vibration direction perpendicular to the machined surface is the intermittent contact between the abrasive grains and the workpiece. The higher the ultrasonic amplitude and frequency, the shorter the effective contact time and the smaller the average cutting force [101]. The intermittent cutting characteristics of abrasive grains are also conducive to improving the conditions of chip removal and heat dissipation to suppress the grinding-wheel wear. However, the 1D UVAG process does not improve the surface flatness because of the sinusoidal motion of the abrasive grains with respect to the workpiece surface.

Two forms of 1D ultrasonic vibration exist, whose vibration directions are parallel to the machined surface, as shown in Fig. 41. As

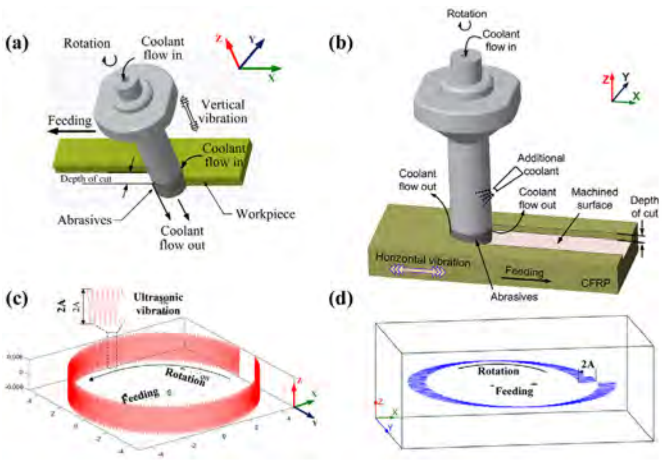

Fig. 41. The 1D UVAG process with vibration direction parallel to the machined surface [83,158]. (a) vibration direction parallel to the axial direction of the grinding wheel; (b) vibration direction parallel to the workpiece feed direction; (c, d) abrasive grain trajectories of different vibration directions.

observed from the movement path of an abrasive grain, when the vibration direction is parallel to the machining surface, the abrasive grain is always in contact with the workpiece, its movement path is longer, and the grinding traces are more intensive; these are, more conducive to reducing the surface roughness.

Sufficient literature is available on composites grinding using the ultrasonic vibration mode, as shown in Fig. 41, and most of them are on trimming and grooving of CFRP [14,83,89,90,157]. The surface quality is improved and the grinding force is reduced when applying 1D UVAG with vibration direction parallel to the machined surface.

For CMCs, the 1D UVAG process is mainly used for hole machining and surface grinding [27,88,165], and the ultrasonic vibration direction is generally along the axial direction of the grinding tool. The axial force is reduced and the hole-wall quality is significantly improved, as shown in Fig. 42. This is because the introduction of ultrasonic vibration changes the mechanism of fiber fracture. Under the condition of ultrasonic vibration, the cutting angle with respect to the fiber tended to be 90° (as shown in Fig. 43), and the cutting speed improved. However, the improvement of the hole-wall quality was more obvious only under the conditions of a relatively low spindle speed and high ultrasonic amplitude.

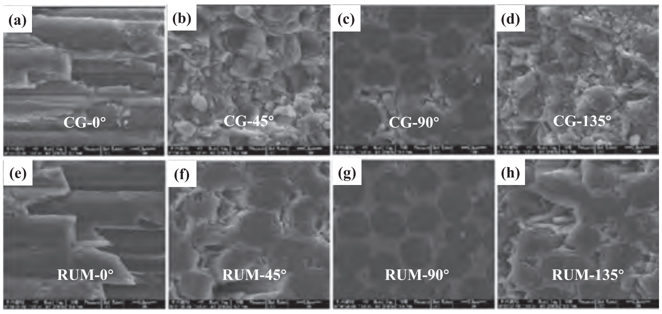

Fig. 42. Comparison of hole wall morphology between the methods of the conventional machining and RUM [165]: (a-d) the conventional machining; (e-h) RUM.

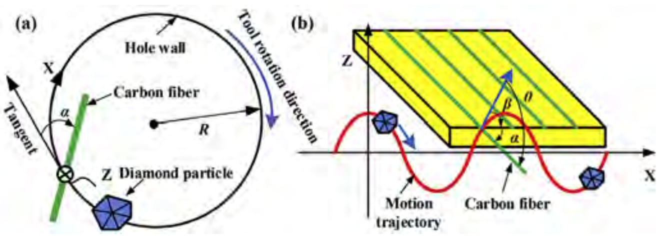

Fig. 43. Fiber cutting angle in RUM of FRCMC [165]: (a) view in X-Y plane; (b) view in X-Z plane.

The 2D UVAM technique was mainly developed to solve the problems of the 1D UVAM technique. At the stage of tool and workpiece separation in 1D UVAM, the tool flank could easily rub and damage the machined surface. In addition, the tool bears alternating tensile and compressive stresses, which may lead to an edge collapse. The 2D ultrasonic vibration can not only avoid the problem of the 1D ultrasonic vibration, but also improve the machining efficiency and tool life [188]. At present, the 2D ultrasonic vibration used in composites machining mainly includes elliptical vibration [48,49,161,177,178] and longitudinal–torsional vibration [38]. Geng et al. [48,49] used elliptical UVAG to process CFRP and achieved good results. The grinding force during the groove processing could be reduced by 43% at most, the tool life doubled, the maximum temperature during the hole machining could be reduced by 47%, and the loading of the abrasive tool was effectively suppressed. Feng et al. [38] successfully machined blind holes and internally threaded holes on cemented carbide by using the longitudinal–torsional ultrasonic vibration-assisted helical milling. The results showed that longitudinal–torsional ultrasonic vibration could significantly reduce the grinding force and tool wear.

4.3. Belt grinding

Abrasive belt grinding is a form of abrasive paper grinding. An abrasive paper is generally used for manual operations, whereas an abrasive belt is used on NC equipment [69]. Abrasive belt grinding has the advantages of fast heat dissipation, high efficiency, and low cost. It can be used for grinding the outer circle, inner circle, plane, and complex curved surfaces [65]. Specifically, with the development of robotic and control technologies, abrasive belt grinding has obvious advantages in grinding complex curved surfaces, such as aero-engine blades, impellers, and bladed disks [139,147].

Abrasive belt grinding has been used for processing MMCs, PMCs, and CMCs. Blau et al. [5] conducted a grindability test of particle-reinforced titanium matrix composites with an alumina abrasive belt and compared the wear characteristics of titanium matrix composites with different reinforced particle contents, without optimizing the grinding process. Uhlmann et al. [151] adopted the robot-guided abrasive belt-grinding method as the subsequent process of CFRP milling to meet the final processing requirements. They demonstrated the application potential of high-quality and efficient machining of CFRP at cutting speeds up to 40 m/s and material removal rates up to 193 mm^3/s. Huang et al. [66,67,138] systematically studied the phenomena of belt slip, belt loading, and attrition wear during the belt grinding of glass fiber reinforced polymer composites (GFRP), analyzed the mechanism and influencing factors of these phenomena, and effectively improved the grinding quality by adjusting the belt-grinding process parameters. Zhou et al. [215] studied the material removal behavior and abrasive belt wear of different types of abrasive belts in C_f/SiC grinding (as shown in Fig. 44). They found that the wear forms of the abrasive belts mainly included abrasive grain shedding, cleavage fracture, micro-adhesion, and abrasive clogging. An electroplated diamond abrasive belt was found to be better than a bonded diamond abrasive belt in terms of wear resistance and grinding quality. Owing to the flexible contact characteristics between the abrasive grain and the workpiece, the surface integrity of C_f/SiC was significantly improved.

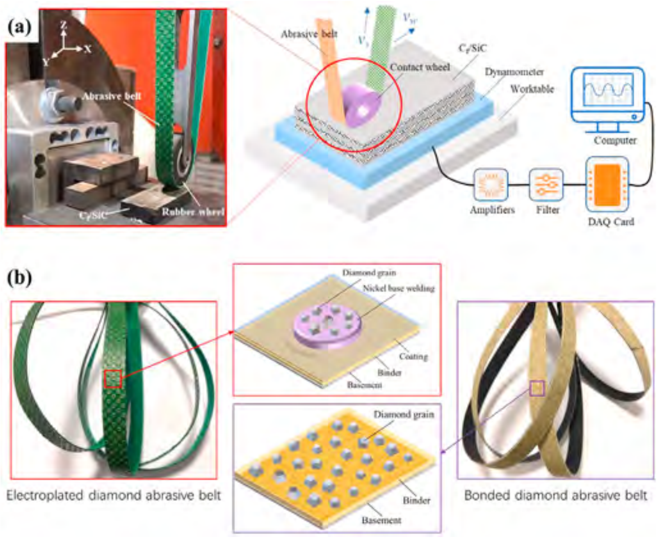

Fig. 44. Belt grinding of C_f/SiC composites [215]: (a) CNC abrasive belt grinding machine; (b) two types of diamond abrasive belts used in the experiment.

4.4. High-speed grinding (HSG)

Generally, under ordinary grinding conditions, the linear speed of a grinding wheel is lower than 45 m/s. When the linear speed is the range of 45 – 150 m/s, it is regarded as HSG, and when the linear speed > 150 m/s, it is regarded as ultra-high-speed grinding. At present, the research on high-speed/ultra-high-speed grinding of composites mainly focuses on MMCs and CMCs.

Ding et al. [28,84,85,87,93,96,176,206,207,214] have conducted tremendous research on the HSG of TiC particle-reinforced titanium matrix composites, mainly using brazed CBN grinding wheels, and have compared the grinding force, grinding temperature, surface roughness, and material removal mechanisms under both ordinary grinding speeds and HSG conditions. They found that at a grinding speed of 120 m/s, there was less lateral flow of titanium alloy matrix, and the TiC particles were mainly broken. At a grinding speed of 20 m/s, there was more lateral flow of titanium alloy matrix, and the TiC particles were predominantly pulled out [28,85]. The grinding force and surface roughness at a grinding speed of 120 m/s were significantly lower than those obtained at 20 m/s, but the grinding temperature during HSG was much higher than that during the ordinary grinding [28,84,85,87,207]. The grinding temperature at 120 m/s reached up to 700 °C, which was only 200 °C at 20 m/s [84]. Grinding burn occurred on the titanium matrix composite workpiece when the grinding temperature exceeded 640 °C. To suppress the grinding burn, grinding depth was set to less than or equal to 6 μm [93]. In the speed range of 80 – 140 m/s, the titanium alloy matrix formed serrated chips, with the removal mechanism of reinforced particles not essentially different from that in ordinary grinding. The influence of undeformed chip thickness on grinding damage was greater than that of grinding speed [96,176,214].

Guo et al. [53] performed HSG on Al/SiCp MMCs at grinding speeds ranging from 30.4 m/s to 307 m/s, which was the highest speed of machining composite materials reported so far. The results revealed that the surface quality was improved and the subsurface damage depth was significantly suppressed at higher speeds (Fig. 45, Fig. 46). In HSG, the range of plastic deformation of the Al-alloy matrix was reduced because of the larger Al grains and reduced depths of lateral cracks in the Al-alloy matrix. Distinctly denser dislocation kinks were formed at the boundary of the SiC particles in HSG, indicating the increased ductility of the SiC particles. The suppression of the plastic deformation of the Al matrix and the enhancement of the ductility of the SiC particles facilitated in reducing the property discrepancies between these two significantly different components, which improved the surface integrity of Al/SiCp.

Cheng et al. [15] conducted an experimental study on the HSG process of the YG8 cemented carbide in the grinding speed range of 80 – 160 m/s. They found that the grinding force showed an obvious downward trend with an increase in the grinding speed. In the range of 80 – 120 m/s, with an increase in the grinding speed, the proportion of plastic deformation increased and the grinding surface quality was improved. However, when the grinding speed was 160 m/s, brittle spalling occurred on the surface. Cheng [15] pointed out that under the condition of ultra-high-speed grinding, the vibration of machine tool and the effective injection of coolant had a great impact on the grinding quality.

Yang et al. [182] conducted experimental research on high-speed deep-grinding of cemented carbide with different grain sizes in the grinding speed range of 60 – 120 m/s. They claimed that with an increase in the linear speed of the grinding wheel, the undeformed chip thickness decreased, whereas the plastic removal ratio of the material and specific grinding energy increased. With a decrease in the grain size of the cemented carbides, their hardness increased, toughness decreased, and the grinding force and specific grinding energy decreased.

High-speed/ultra-high-speed grinding plays an important role in improving the grindability of CMCs. Yin et al. [190] studied the effect of grinding speed on the material removal mechanisms of SiC_f/SiC. They showed that increasing the grinding speed could embrittle the material and enhance fiber breakage. At a high grinding speed, they obtained improved surface quality and machining efficiency without matrix smearing or residual cut-off fibers, which are commonly obtained in the case of low-speed grinding. Rechenko et al. [128] carried out an HSG test of SiC_f/SiC at a grinding speed of 100 m/s and found that with an increase in the grinding speed, the surface roughness showed a significant downward trend and was reduced by

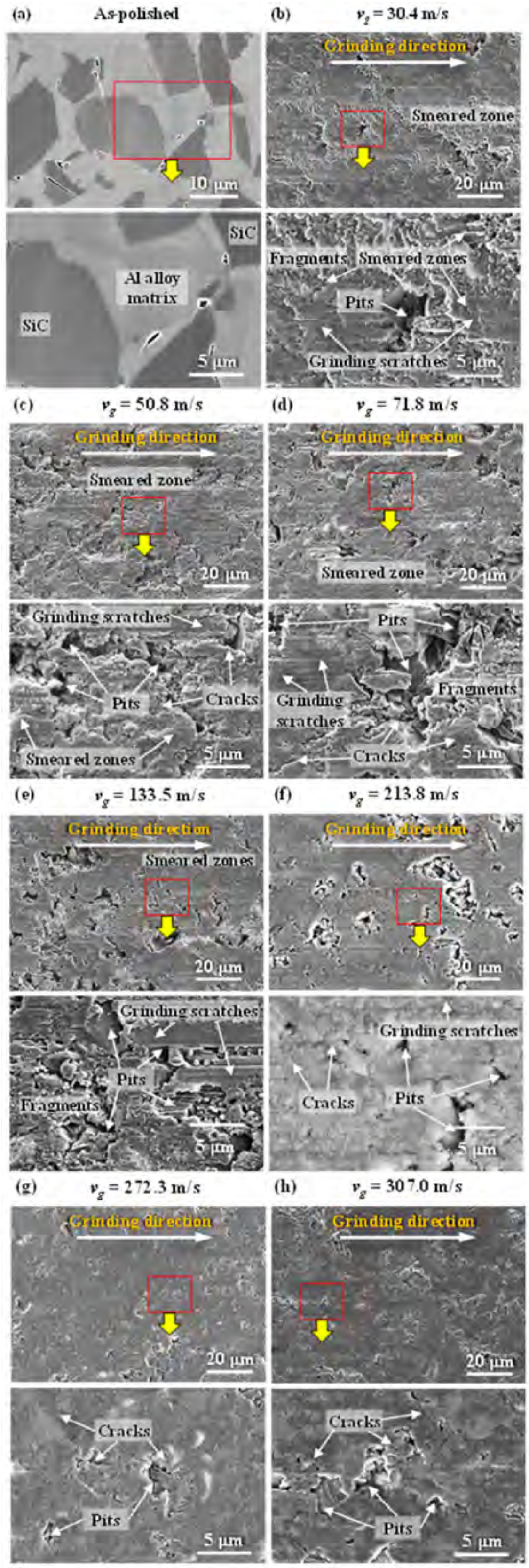

Fig. 45. Surface morphology of the Al/SiCp MMC workpieces ground at various grinding speeds [53].

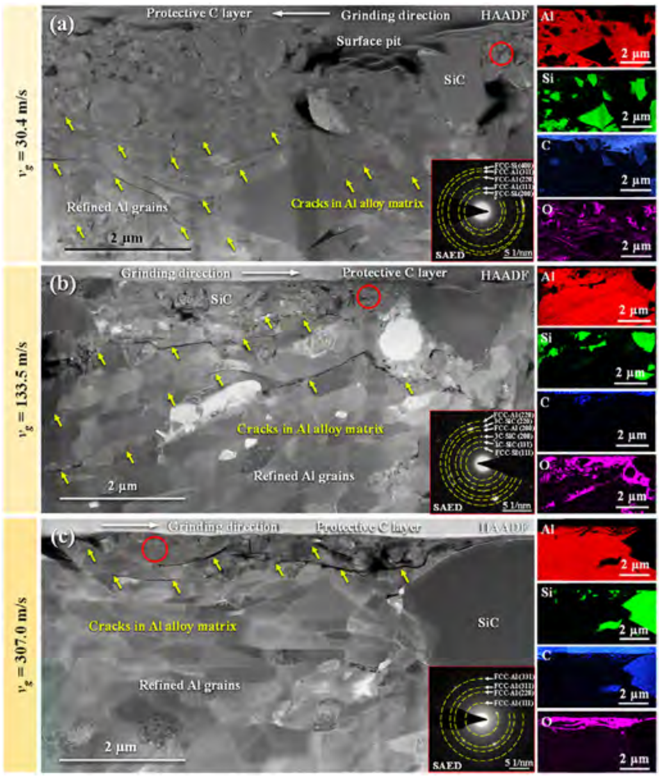

Fig. 46. HAADF images, SAED patterns and EDS images of the subsurface damage after grinding at different speeds [53].

3.3 – 4 times that at a grinding speed of 20 m/s. Choudhary et al. [16] conducted an HSG test of 2.5D braided C_f/SiC composites and demonstrated that at a grinding speed of 200 m/s, the grinding damage was reduced by 60%. This is because the high grinding speed reduced the undeformed chip thickness, the micro-cutting of abrasive grains on the fibers eliminated the influence of the fiber direction, and the material was removed through the material shear mode instead of the brittle-fracture mode.

The realization of ultra-high-speed grinding requires considerably high requirements for grinding wheel and grinding equipment. The centrifugal force generated at an ultra-high-speed may deform or even damage a conventional grinding wheel; therefore, requirements for higher strength, stiffness, and dynamic characteristics of the grinding wheel are proposed. Carbon-fiber materials have low density, high specific strength, specific modulus, and good damping characteristics. Therefore, this material is an ideal candidate for the ultra-high-speed grinding wheel matrix. Yang et al. [186] optimized the grinding wheel structure through a simulation analysis and developed an ultra-high-speed grinding wheel with grinding speeds up to 400 m/s. The CFRP wheel matrix adopted the layup sequence of $[0/\pm45/90]_{15\ s}$ to distribute the stress and deformation evenly.

Ultra-high-speed motorized spindle is a core component of the ultra-high-speed grinding equipment. The expansion and vibration of a spindle under ultra-high-speed conditions are the key problems to be solved. The application of the carbon-fiber materials to ultra-high-speed motorized spindles can improve the rotational accuracy and reduce the thermal deformation and vibration of the spindle. With the breakthroughs in the key technologies, such as ultra-high-speed grinding wheels and ultra-high-speed motorized spindles, grinding operations can reach a speed of 300 – 400 m/s, thereby significantly reducing the grinding force and temperature, preserving the workpiece surface integrity, and restraining the adverse effect of composite material anisotropy. Ultra-high-speed grinding is also expected to solve the machining problems of the difficult-to-machine materials.

5. Synthesis and discussion

By reviewing a large number of studies on composites grinding, we know that the mechanical and thermal behaviors of composites in the grinding process are extremely complex. Therefore, to understand what the core scientific issue is, in this section, the important factors that affect the grinding mechanism are presented, and the strategies for restraining the machining damage of composites are proposed.

5.1. Analysis of important factors affecting the grinding mechanism and composite material damage

There are many types of composite materials with different structures. Different composites, such as PMCs, CMCs, and MMCs, have obvious differences in the material removal mechanisms and the damage morphologies. Nevertheless, all composite materials have common characteristics, that is, they are composed of a matrix, a reinforcement phase, and an interface. The research on the mechanical and thermal behaviors of this type of heterostructural materials under the action of abrasive grains are the keys for solving the difficult problem of composites grinding. Based on the constituent elements of composite materials and their response characteristics under the action of abrasive particles, the common scientific issues of the grinding mechanism and composite material damage can be summarized into “size effect”, “anisotropic effect”, “interfacial effect”, and “thermal effect”, as shown in Fig. 47.

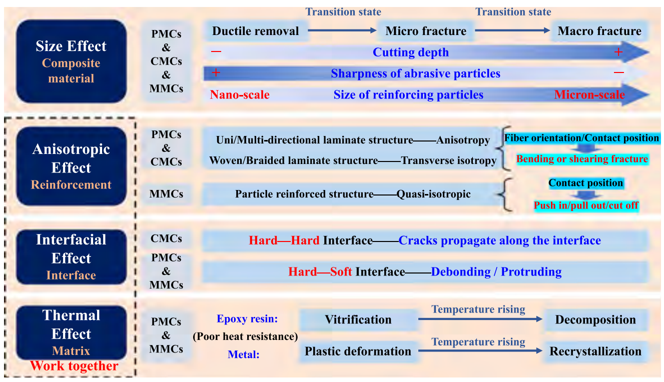

Fig. 47. Analysis on important factors affecting grinding mechanisms and damage of composite materials.

“Size effect” is an important and common issue in the grinding process of composite materials. Irrespective of being PMCs, CMCs, or MMCs, when the cutting depth of abrasive particles gradually increases from the nano-scale to the micro-scale, they undergo three main stages of material removal: ductile removal, micro-fracture, and macro-fracture. In addition, a transition state exists between two different stages. In fact, there is no obvious boundary between the characteristics of material removal at different stages, as it is a gradual process. The sharpness of the abrasive particles has an important impact on the material removal mode. A sharp abrasive particle can easily remove composite materials in the ductile regime, but a blunt abrasive particle usually causes macro-fracture. There are different definitions of “ductile regime” [63,104,187], which all emphasize the need to carefully examine whether there are cracks in the subsurface. Moreover, even if a composite material is ground in the “ductile regime" mode, one should not simply think that no damage has occurred during the material removal process. Therefore, special care should always be taken during the discussion on the ductile removal of composite materials.

For MMCs, the "size effect" is related to the size of reinforcing particles. The interaction of reinforcing particles with dislocations becomes important when the particle size is reduced to the nanoscale [10]. A matrix grain reinforced by nanoparticles is refined, and it improves the deformation resistance of the matrix. Nanoparticles have fewer internal defects and are not easy to break, but they tend to flow with matrix, which is conducive to improving the surface integrity [148].

The "anisotropic effect" is mainly reflected in the reinforcement phase of composite materials. The commonly used PMCs and CMCs are fiber-reinforced composites. Composite materials with uni-directional or multi-directional laminate structure are anisotropic. Those with woven or braided laminate structure are transverse isotropic. The commonly used MMCs are particle-reinforced composites, which belong to the class of quasi-isotropic materials. For fiber-reinforced composites, the fiber direction and contact position between a fiber and an abrasive particle determine the bending or shear fracture of the fiber. For particle-reinforced composites, the contact position between the abrasive and reinforcing particles determines whether the reinforcing particles are pressed in, pulled out, or cut off. It should be emphasized that the anisotropy is not only structural but also thermal properties. There are significant differences in mechanical and thermal properties of the constituents especially in certain specific directions, and the mismatch between these properties is an important reason for grinding damage.

The "interfacial effect" is mainly reflected in the interface position of composite materials where the mechanical–thermal mismatch occurs between the matrix and the reinforcement. According to the hardness difference between the matrix and the reinforcing phase, the interface can be divided into two types: "hard–hard interface" and "hard–soft interface". CMCs have a "hard–hard interface", whereas PMCs and MMCs have "hard–soft interfaces". Different interface characteristics have different influences on the damage modes of composite materials. For composites with "hard–hard interfaces", cracks are more likely to propagate along the interfaces, whereas for composites with "hard–soft interfaces", debonding and protruding of the reinforcement phase are easy to occur.

The "thermal effect" is mainly reflected in the matrix of composite materials. CMCs have a good heat resistance, and therefore, "thermal effect" is insignificant. For PMCs, with an increase in the grinding temperature, the resin matrix softens and even decomposes [73]. For MMCs, with an increase in the grinding temperature, the morphology of the metal matrix changes from grain elongation to recrystallization [53]. The "thermal effect" has a particularly significant effect on a matrix with poor heat resistance.

Among the abovementioned effects, "size effect" is applicable to all types of composites, which mainly depend on the cutting depth, sharpness of the abrasive particles, and size of the reinforcing phase. The manifestation of the "anisotropic effect" depends on the structural characteristics of the composite material. The manifestations of "interfacial effect" and "thermal effect" are different for different types of composite materials and depend on the mechanical and thermal characteristics of the matrix and reinforcement phase. The "anisotropic effect", "interfacial effect" and "thermal effect" always act together and affect the processing damage of composite materials.

5.2. Strategies for restraining composites machining damage

Based on the literature review on composites grinding, five strategies are suggested to restrain the damage formation in composites grinding.

(1) Reduction of undeformed chip thickness

When the scale of the undeformed chip thickness is close to the respective volume element (RVE) scale of the composite material, the influence of composite material micro-anisotropy on the machining damage formation is obvious. Because of the large proportion of the deformation range of an RVE, the interface failure is more likely to occur in a large range. Furthermore, when the scale of the undeformed chip thickness is much smaller than the RVE scale, the "size effect" can be more obvious. Within the interaction ranges of abrasive grains, most grains remove materials as if they cut monolithic materials in the ranges within their respective interactions. The influence range of material deformation and fracture accounts for a small proportion of RVE, and the influence of the interface failure is significantly reduced. The published literature showed that when the grinding depth was sufficiently small, the hard brittle reinforcement in the composites was removed in the ductile-regime mode [13,72,117,174]. However, as increasing the grinding speed is equivalent to reducing the undeformed chip thickness, the removal mode of the reinforced particles in MMCs changes from macro-fracture to micro-fracture [96,176], and the influence of the fiber direction of CMCs on roughness is reduced [100,200]. Therefore, reducing the undeformed chip thickness can significantly reduce the composites grinding damage.

(2) Processing techniques for suppressing anisotropy

Machining damage induced in a composite material is mainly affected by its anisotropy and the property differences in its component phases. The machining damage of composites can be restrained by adopting an appropriate machining process that suppresses their anisotropy. For example, for fiber-reinforced composites that have fibers perpendicular to the machining surface, if the 1D UVAG process with the vibration direction parallel to the machining surface is adopted, the sinusoidal motion trajectory of abrasive grains makes the fiber cutting angle approach 90° This aids in obtaining a good surface quality, because the machining damage under the 90° fiber cutting angle condition is the smallest among the machining damages caused under all the other angles [89,90,165]. For MMCs, the yield strength of the metal matrix in the grinding zone can increase significantly in HSG [155,218], which reduces the differences in the mechanical properties between the metal matrix and the hard brittle reinforcement. For the fiber- and particle-reinforced composites under cryogenic grinding conditions, the interfacial bonding strength under low-temperature conditions was significantly improved, and the supporting effect of the matrix on the reinforcement phase was enhanced, which helped in improving the grinding quality [197,217].

(3) Maintaining the sharpness of abrasive grains

The sharpness of abrasive grains has an important influence on the removal mode of the reinforcement phase in the composites grinding process. For fiber-reinforced composites, the contact area between a sharp abrasive grain and a fiber is small, which can increase the stress concentration in the contact area to facilitate an easy fiber cut-off [107]. In addition, sharp abrasive grains can improve the ratio of the ductile-fracture removed reinforcement phase [102], which decreases the machining damage. Sharpening the grinding wheel or controlling the abrasive grain shapes help maintain the sharpness of a grinding wheel; thus, improving the surface integrity of a ground composite workpiece [107,133,191].

(4) Optimizing the constraining state

Owing to the existence of an interface between the matrix and the reinforcement phase, the constraining state of the reinforcement phase has a great impact on machining quality of composites, with a specific example being the exit quality control in the hole making process of composites. Delamination, burr, tear, edge collapse, and other damages easily occur at the hole exit of composite materials. This is because the support stiffness of the remaining materials is insufficient when the tool is close to the hole exit. Using abrasive machining instead of drilling is helpful in reducing the hole-exit damage of composites, specifically for those hard and brittle types. The grinding process parameters and the geometry of a grinding tool can be optimized to provide a good constraining state for materials at the hole exit to achieve an improved machining quality of composite materials. One successful example is the application of a stepped-core drill that divides the hole-material removal process into two stages. The first stage is the main material removal process of a hole with the front portion of the core drill, and in the second stage, the hole damage generated by the first stage is compensated to ensure the final quality of the hole [164]. In addition to the adoption of a stepped-core drill, a dual-axis grinding wheel can also be adopted for good hole quality. The dual-axis grinding technique has a proven record in achieving good results in grinding large-diameter holes in CFRP [75]. Moreover, the helical mill-grinding method has also been adopted to purposely transform the main material removal process into the radial direction through the helical feed movement. This is because the constraint for material removal is much stronger in the radial direction than in the axial direction [81].

(5) Multi-energy-field-assisted grinding

Owing to composite anisotropy and weak interfacial constraints, composites are sensitive to force and heat, affecting the grinding quality. The multi-energy-field-assisted grinding method is used to form a weakening layer on the surface of a composite material through physical or chemical action of the applied energy fields. The material in this layer is easier to remove than the bulk material, and the force and heat generated in the removal process of the weakening layer are small for a reduced machining-damage layer of the composite material. In the UVAM process, abrasive grains impact against the workpiece surface under the action of ultrasonic vibrations to crush the surface material, generating a large number of microcracks, which significantly weaken the material mechanical properties, reduce the grinding resistance, and improve the grindability of the material [39]. Furthermore, laser-induced material softening and microcracking of a workpiece surface also weaken the mechanical strength of the surface material that can be easily removed by the subsequent grinding process [111]. In addition, electrical discharge and electrochemical assisted grinding create a high temperature or chemical reaction environment, such that the surface material can be transformed into a loose and easy-to-remove material [99,116,179]. With the introduction of the multi-energy fields, the grinding-removal efficiency of composites has significantly improved, and the machining damage has been effectively restrained.

In engineering applications, multiple strategies may be adopted to effectively improve the grindability of composite materials. Based on the in-depth understanding of the material removal and damage formation mechanisms in composites grinding, developing new grinding processes and high-quality and efficient machining techniques are the research focal points for composite materials. The future possibilities relate to composites grinding include the following aspects:

(1) With the development of composite science, there will inevitably be a large number of new ultra-high performance composite materials in the future, which will bring more new precision machining problems. Based on a deep understanding of the grinding mechanism of composite materials and a large number of studies on the factors affecting the surface integrity, some new grinding methods may also be invented in the future to improve the grindability of these new composite materials by changing the material removal mechanism to the direction conducive to improving the surface integrity. These new grinding methods are likely to be personalized, that is, developed for a special composite material or composite part with a special structure.

(2) In essence, on the condition of using conventional grinding methods, the grindability of most composites is very poor, which limits the precision and ultra-precision machining of a composite parts, and also limits the tolerance design of the composite parts, thus affecting the performance of the composite part. Through technological breakthroughs in composite grinding process, grinding tools, grinding equipment and other aspects in recent years, the machining accuracy and surface integrity of composite parts have been greatly improved, which will also promote the application of high-performance composite materials in the industry more and more widely, and more traditional materials will be replaced, thus promoting the rapid development of the composite industry chain.

(3) The development of advanced grinding technology of composite materials has greatly improved the surface integrity of products and significantly extended the fatigue life, so as to give full play to the high performance of composite materials, which is likely to set off technological innovation in aerospace, new energy, rail transit, automobiles, ships and other fields. For many fields, the fatigue life of products has been a bottleneck problem. Once the fatigue life is significantly improved, it will promote the growth of many industries.

(4) With the development of internet-of-things (IoT), big data, and cloud computing technology, the intellectualization of grinding will help solve the existing problems. The development of the digital twin technology, the use of advanced sensors to collect the grinding-state data, and the establishment of data-driven grinding digital models will become contentious research topics in the future of composites grinding.

6. Conclusion

This paper comprehensively reviewed the recent research progress in the field of composites grinding based on three most commonly used composites in engineering applications: PMCs, CMCs, and MMCs. Through a literature review on the material removal mechanisms, surface integrity, and advanced grinding technologies, the common composites grinding problems were analyzed and summarized. “Size effect”, “anisotropic effect”, “interfacial effect” and “thermal effect” were found to be important factors affecting the grinding mechanisms and damage formation of composite materials. By reducing the undeformed chip thickness, adopting the processing techniques to suppress anisotropic effect, maintaining the sharpness of abrasive grains, optimizing the constraint state, and using the multi-energy-field-assisted grinding method, machining damage to composites could be effectively restrained and grindability could be improved. A deep scientific understanding of composites grinding, the development of high-quality and efficient grinding processes, and the associated equipment were of a great significance to promoting the widespread applications of high-performance composites and accelerating the progress of composite science and technology.

Declaration of 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 paper.

Acknowledgement

This work was partly supported by Shenzhen Science and Technology Innovation Commission for the project numbered KQTD20190929172505711, JSGG20210420091802007 (the work in "Section 4.4. High-speed grinding").

Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.cirp.2023.05.001.

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