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Topical Review

Recent advances in design and preparation of micro diamond cutting tools

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Abstract

Micro diamond tools are indispensable for the efficient machining of microstructured surfaces. The precision in tool manufacturing and cutting performance directly determines the processing quality of components. The manufacturing of high-quality micro diamond tools relies on scientific design methods and appropriate processing techniques. However, there is currently a lack of systematic review on the design and manufacturing methods of micro diamond tools in academia. This study systematically summarizes and analyzes modern manufacturing methods for micro diamond tools, as well as the impact of tool waviness, sharpness, and durability on machining quality. Subsequently, a design method is proposed based on the theory of cutting edge strength distribution to enhance tool waviness, sharpness, and durability. Finally, this paper presents current technical challenges faced by micro diamond tools along with potential future solutions to guide scientists in this field. The aim of this review is to contribute to the further development of the current design and manufacturing processes for micro diamond cutting tools.

Keywords: micro diamond tool, micro cutting, diamond tool design, tool quality, wear resistance

1. Introduction

Micro-structured array surfaces with excellent quantities performances have been extended to biomedicine, environmental protection, photovoltaics, optics, flexible skin, virtual reality, military industry, and other high-tech fields [1, 2]. Achieving a micro-structured array surface with a large area in an efficient and low-cost way has been a focus in academia and industry. Mold pressing or roller-to-roller molding technique, and micro diamond cutting are recognized as effective methods. Mold pressing [3] or roller-to-roller molding technique [4] based on the replication principle transfers the microstructures on the mold to the surfaces of polymers, glass, and other materials by heating or ultraviolet light irradiation to achieve mass fabrication of microstructures. The microstructure molds are usually

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machined with micro diamond cutting technology, in which micro diamond cutting tools play an irreplaceable role in the processing of high quality microstructure array surfaces.

Micro diamond cutting, composed of micro diamond milling [5–7], micro diamond turning [8–10], and micro diamond chiseling [11, 12], which is also performed with a micro diamond turning tool and similar to the micro diamond turning except that the spindle keeps stationary. High precision micro diamond tools are indispensable to fabricate microstructure arrays on an ultra-precision machine tool. The processing technology is applicable to the machining of most materials, such as metals, ceramics, polymers, crystals, glass, etc. Microstructures encapsulated by arbitrary complex shapes can be machined with micro diamond tools through the interpolation motion of a multi-axis ultra-precision machine tool in theory, and nanometer surface roughness and sub-micrometer profile accuracy are achievable. The processed products are serviced in optics, mold, biomedical, aerospace, and other high-tech fields. It should be noted that micro diamond tools used to machine metals and other plastic materials are different from those used to machine ceramics and other brittle materials in tool geometries because the chip formation and material removal mechanisms are different for plastic and brittle materials. The differences have to be fully considered in micro diamond tool design to achieve a satisfactory quality of machined surface and high tool wear resistance.

In diamond turning, the single point cutting edge of diamond tool contacts the workpiece and realizes material removal at the nanoscale with the extremely sharp cutting edge. So diamond turning is often called single point diamond turning (SPDT) [13]. Microstructures with complex profiles can be turned using rounded micro diamond tools in two motion modes: (1) servo motion of two linear axes (X-axis and Z-axis) along the microstructure profile, and (2) servo motion of two linear axes (X-axis and Z-axis) and a rotation axis (B-axis) along the microstructure profile. The above two modes of micro diamond turning are the processes of precision transformation from the machine tool to the machined surface via a cutting tool [14]. As defined strictly, only the 3-axis turning belongs to SPDT. In this case, the position of the cutting edge engaged in cutting keeps unchanged due to the rotary servo motion of the B-axis. Meanwhile, tool alignment accuracy must be high enough, which is challenging to perform. The position of the cutting edge engaged in cutting changes with the microstructure profile in the 2-axis turning, while a certain tool alignment error is allowed, which is conducive to reducing the tool alignment difficulty and increasing efficiency, so it is commonly used in microstructure machining. At present, the position resolution of a commercial ultra-precision machine tool has been up to nanometer level and even to picometer level. During the 2-axis turning process, micro diamond tool cutting edge profile errors (i.e. cutting edge waviness) will be copied to the microstructure surface [15]. In order to transfer such a high accuracy of the machine tool to the machined surface, a micro diamond tool with equivalent accuracy is indispensable [16]. Additionally, high-end optical elements, such as optical microlens arrays, curved mirrors, and diffractive lenses, are urgently demanded in the industry to improve the imaging quality and integration of optical systems. The accuracy of micro diamond tools has to be at least half an order of magnitude higher than that of the optical elements [14, 17, 18]. According to the form error of optical elements limited to 1/10 λ, taking red laser optical elements as an example, the accuracy of micro diamond tools shall be superior to 15 nm. In summary, a high precision and performance (especially in the tool edge waviness, sharpness, and wear resistance) micro diamond tool is essential for ultra-precision machining of microstructure arrays. Moreover, compared with the common diamond tools with millimeter dimensions, the cutting edge length of micro diamond tools with micrometer dimensions is so small that stress concentration and size effect are more likely to appear due to the extremely small feed during the cutting process, resulting in serious tool wear as discussed above. Also, the cutting edge strength and impact resistance of the micro diamond tools are much weaker than those of the common diamond tools, leading to the fracture of the tool tip, so it is difficult to achieve high-precision micro diamond tools by using the common diamond tool design and manufacturing methods.

In light of the machining methods outlined above, it can be concluded that micro diamond turning and milling are essential technologies to process microstructures. As well known, high-quality machining must be based on high-precision cutting tools and process technology. However, significant challenges still remain in manufacturing high-quality micro diamond tools in large quantities, which mainly include cutting edge waviness control, cutting edge sharpness improvement, and tool wear suppression. Therefore, this work is focused on the review of current manufacturing methods and design methods of micro diamond tools, the influences of cutting edge waviness and sharpness on the machined surface quality and the improvement methods, as well as the influences of micro diamond tool wear on the machined surface quality and the restraining methods. Then, balanced design and manufacturing methods are proposed simultaneously, considering the tool accuracy or tool life based on the previous work. Finally, prospects and suggestions for the micro diamond tool design and manufacturing are proposed for further work. The aim of this review is expected to promote further development of the current design and manufacturing processes for micro diamond cutting tools.

2. Geometric design of micro diamond tools

The design and manufacture of micro diamond tools should be fulfilled in combination with the advanced manufacturing process of microstructures [19, 20] in order to efficiently realize the machining of microstructures and promote their widespread application in industry. Micro diamond tool design is crucial for micro diamond machining processes, as it requires not only high cutting edge shape accuracy but also high strength, stiffness, and wear resistance. Due to their small dimensions, these requirements have become the key issues limiting the application of micro diamond tools. The design of micro diamond tools is mainly composed of two aspects:

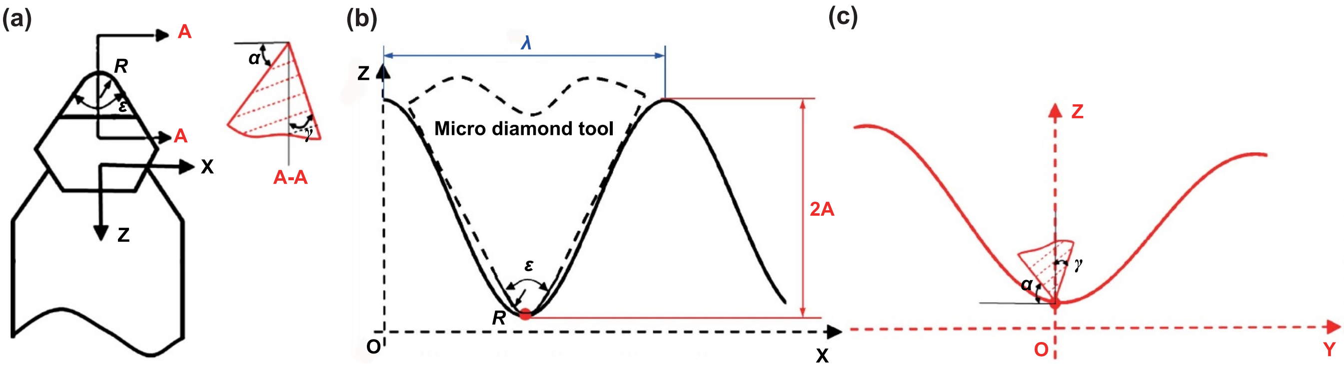

Figure 1. Geometric design of a micro diamond tool with a rounded cutting edge: (a) tool geometries, (b) design of tool nose radius and included angle, (c) design of rake and clearance angles. Reproduced from [35]. CC BY 4.0.

(1) tool geometric design, which is performed by considering the machined material properties and the shape characteristics of the microstructures to be processed, and (2) tool performance design, including manufacturability and usability, which is performed to obtain an optimal combination of the crystal orientation based on the diamond crystal anisotropy. This section only introduces the geometric design, and the performance design will be introduced in the following sections 3.3 and 4.3.

Cutting edge shape and geometries of micro diamond tools are the key factors that determine the machined surface quality, form accuracy, cutting force, and tool wear resistance in microstructure machining [21, 22]. Tool angles, cutting edge orientation, and flank face shape [23] determine the contact mode and mechanism of the tool-workpiece [24, 25], affecting the formation of chip and machined surfaces, as well as cutting force and cutting temperature [26, 27]. In micro diamond tool design, the geometries and machining process of microstructures, as well as the strength, stiffness, wear resistance, and manufacturing feasibility of the micro diamond tools, have to be simultaneously taken into account [28]. Besides, diamond crystal is a typically hard and brittle material and appears to have severe anisotropy and susceptibility to cleavage, which makes the processing of diamond crystal exceptionally difficult [29]. Therefore, micro diamond tools cannot be designed with the same complex shapes as cutting tools made of metal materials when the mechanical lapping process is selected as the tool manufacturing method [30]. Therefore, most micro diamond tools are designed with a round nosed shape to enhance the cutting edge strength and tip stiffness, which can also simplify the operation of tool alignment, be conducive to the discharge of chips, and reduce the cutting force and tool wear, obtaining excellent surface roughness [30]. Unlike the commercial standard diamond tools used to cut flat, spherical, and free form surfaces, most of the micro diamond tools require a specialized design and customization based on the microstructure geometries to be machined, which increases the difficulty of tool selection for users [31]. Insufficient design of micro diamond tools leads to overcutting and reduces the machining accuracy of microstructures. However, an excessive design will increase the manufacturing difficulty and cost of micro diamond tools and reduce their cutting edge accuracy and service life. To fill the aforementioned gaps, a design method or procedure for micro diamond tools with rounded cutting edges is reviewed, taking a micro diamond tool used for sinusoidal microstructure machining as an example, from five aspects: nose radius, included angle, clearance angle, rake angle, and flank face shape. The geometries of a micro diamond tool with a round nosed cutting edge are illustrated in figure 1(a).

(1) ***Nose radius.*** The nose radius of a micro diamond tool is a critical feature dimension that determines the minimum characteristics of machined microstructures, and it is also a main dimension that determines the manufacturing difficulty. The nose radius shall be designed in view of the minimum curvature radius (maximum curvature) of the microstructure to be machined, i.e. that the maximum nose radius cannot exceed the minimum curvature radius, as shown in figure 1(b). Otherwise, an overcutting phenomenon will appear at the position of maximum curvature. The critical tool nose radius can be expressed as [32]:

$$R_c \leqslant \frac{\lambda^2}{4A\pi^2} \tag{1}$$

where R_c denotes the tool nose radius, A and λ denote the amplitude and wavelength of the sinusoidal microstructure. Considering the manufacturability and tool nose strength of micro diamond tools, a large nose radius as much as possible should be designed while subjecting to the above constraint.

(2) ***Included angle.*** The included angle, to a great extent, determines the bulk strength of micro diamond tools. A small included angle means that the micro diamond tool has a sharp tool tip and weak bulk strength, which makes it easy to fracture and collapse. It should be properly designed in terms of the aspect ratio (i.e. the ratio of A to λ) of the microstructure to be machined, as shown in figure 1(b). A large aspect ratio corresponds to a small critical included angle. Otherwise, overcutting phenomena

will appear at the side edges of the microstructure. The critical included angle can be calculated as [32]:

$$\varepsilon_c < 180° - \frac{360°}{\pi} \arctan\left(\frac{2\pi A}{\lambda}\right) \quad (2)$$

where ε_c denotes the critical included angle of a micro diamond tool. Similar to the tool nose radius, the included angle is also increased as much as possible to improve the strength of the tool tip and reduce the manufacturing difficulty in the case of no tool interference.

(3) ***Clearance angle.*** In the machining of microstructures, apart from the interference between the flank face and microstructures [33], the flank face near the cutting edge continuously burnishes the machined surface owing to the material spring back of the machined surface [34], which has a certain impact on the quality of the machined surface. Although the interference and burnishing impact on the machined surface can be avoided and reduced by increasing the clearance angle, it also reduces the wedge angle of micro diamond tools and further weakens the already low strength of the tool tip. Currently, from the perspective of industry practice, it is generally necessary to increase the clearance angle by 2°–5° on the base of the critical value without interference, in which the tool nose radius dependent tool tip strength and the machined surface quality should be comprehensively considered. The critical clearance angle is formulated as [35]:

$$\alpha_c \geqslant \max - \left\{\arctan\left(g'_{y_q}(y_q, \rho, \theta)\right)\right\} \quad (3)$$

where $g'_{y_q}(y_q, \rho, \theta)$ denotes the first derivative of the microstructure intersectional profile on the *YOZ* plane, as shown in figure 1(c).

(4) ***Rake angle.*** The rake angle always affects the stress distribution and chip formation in the cutting area. A positive rake angle usually causes stress concentration ahead of the cutting edge, weakens tool tip strength, and is not conducive to improving tool wear resistance [36]. If a negative rake angle is used in the machining of microstructures, compressive stress in the cutting area is dominant, which is benefit to the ductile removal of brittle materials [37, 38]. However, the cutting force produced by the negative rake angle tool is larger than that produced by the positive or zero rake angle tool due to the poor chip discharge [39, 40]. Therefore, in the machining of plastic metal materials, micro diamond tools are usually designed with a 0° rake angle to achieve a high strength of the tool tip, reduce cutting force, and promote shear deformation to remove the material; in the machining of brittle materials, micro diamond tools are always designed with a negative rake angle to achieve the ductile removal mode [41]. However, an oversized negative rake angle may also cause tool interference, as demonstrated in figure 1(c). The critical value of the negative rake angle can be given by [34]:

$$\gamma_c \geqslant \max\left\{\arctan\left(g'_{yq}(y_q, \rho, \theta)\right) - \frac{\pi}{2}\right\} \quad (4)$$

where γ_c denotes the critical value of the negative rake angle.

(5) ***Flank face shape.*** There are two types of flank face shapes for micro diamond tools with rounded cutting edges, namely conical and cylindrical shapes. The clearance angle of micro diamond tools with a conical flank face is constant at any point on the rounded cutting edge, which is the nominal clearance angle. However, most micro diamond tools are designed to have a cylindrical flank face because a conical flank face results in an extremely limited width due to the geometric constraint of a small nose radius, which heavily weakens the tool tip strength. The limited width of the flank face is not only adverse to lapping in tool manufacturing but also prone to fracture in microstructure machining, while the cylindrical flank face is not subject to restriction. Generally, the flank face is designed to be cylindrical if the tool nose radius is less than 200 μm.

In addition, the finite element method (FEM) has been developed into a significant analysis technology in engineering and scientific research. More and more researches are currently reporting the use of FEM analysis in tool design [22, 42–44] to improve tool stiffness and cutting edge strength [43] and to optimize tool structures [36, 45]. FEM is also a promising complementary technology in the design and optimization of micro diamond tools, combining with the cutting simulation technology in the future.

3. Design of micro diamond tools in terms of cutting edge waviness and sharpness

3.1. Influence of tool cutting edge waviness on machining quality

In the case of two or more axes coordinated turning, such as spherical turning, free-form surface turning, fast/slow tool servo turning, and so forth, the position of the cutting edge participating in turning continuously alters, i.e. that the single point turning cannot be guaranteed, which causes the cutting edge shape error to be reproduced on the machined surface. Hence, it is significant to improve the profile accuracy of the cutting edge of micro diamond tools for improving the microstructure profile accuracy [15]. The accuracy of micro diamond tools usually refers to their dimensional accuracy and shape accuracy. For the micro diamond tools with a round nose, it refers to the dimensional accuracy of the nose radius and the profile accuracy of the cutting edge, that is, the cutting edge waviness. The dimensional accuracy is mainly guaranteed by the accuracy of the lapping machine tool for diamond tool manufacturing, and the cutting edge waviness is guaranteed by the lapping process. Cutting edge waviness is defined as the root mean square value or Peak-Valley (PV) value of the deviation between the actual tool nose profile and the ideal

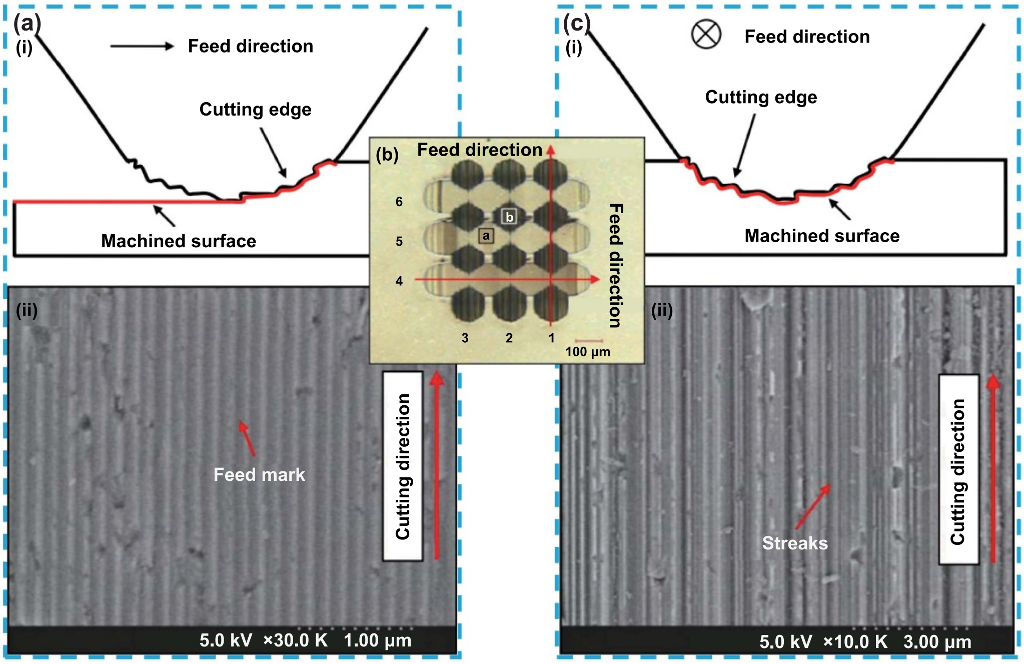

Figure 2. Influence of diamond tool cutting edge waviness on the machined surface topography: (a) parallel milling, (b) overall morphology, (c) vertical milling. Reproduced from [48], with permission from Springer Nature.

nose profile [46, 47], of which the mathematical formulae are expressed as:

$$W_{\mathrm{q}} = \sqrt{\frac{1}{R_0\theta_{\mathrm{e}}}\int_0^{\theta_{\mathrm{e}}}\left[R(\theta) - R_0\right]^2\mathrm{d}\theta} \tag{5}$$

$$W_{\mathrm{PV}} = R(\theta)_{\max} - R(\theta)_{\min} \tag{6}$$

where W_{PV} and W_{q} denote the PV value and root mean square value of the cutting edge waviness; R_0 denotes the ideal nose radius; θ_{e} denotes the opening angle of the cutting edge participating in waviness evaluation, i.e. the center angle corresponding to the cutting edge arc in evaluation; $R(\theta)$ denotes the actual tool nose radius at the position of θ; $R(\theta)_{\max}$ and $R(\theta)_{\min}$ denote the maximum and minimum radii of the actual tool nose.

The discrete expression of the root mean square can be given by:

$$\widehat{W_{\mathrm{q}}} = \sqrt{\frac{1}{n}\sum_{i=1}^{i=n}\left[R(\theta_i) - R_0\right]^2} \tag{7}$$

where $\widehat{W_{\mathrm{q}}}$ denotes the discrete root mean square value of the cutting edge waviness; n denotes the number of discrete points; $R(\theta_i)$ denotes the actual tool nose radius at the ith point.

In the machining of microstructure arrays, tool cutting edge waviness can also deteriorate the machined surface roughness [16, 30], except for decreasing the microstructure profile accuracy, as mentioned above. In 2010, Yan *et al* [48] examined the differences in surface topography caused by cutting edge waviness during the micro groove array milling process with different milling methods. The experimental results demonstrated that in parallel milling, the milling is a single point machining process, and the cutting edge waviness has little influence on the milling surface roughness. However, in vertical milling, the milling is a form machining process, and the cutting edge waviness leaves regular scratches on the machined surface, seriously deteriorating the surface roughness of the micro groove arrays, as shown in figure 2. In 2015, Sung *et al* [49, 50] reconstructed the turning surface topography by utilizing the actual profile and theoretical profile of the cutting edge, respectively, based on which they calculated the roughness (R_{t}, R_{a}, and R_{q}) of the reconstructed surface. Their evaluation results showed that the cutting edge waviness leads to an increment of R_{t}, R_{a}, and R_{q} by 40.3%, 26.1%, and 24.5%, respectively.

In optical element machining, the cutting edge waviness of micro diamond tools may lead to many negative effects on the performance of the machined optical element, such as inducing unnecessary diffuse reflection or diffraction and reducing reflectivity, etc., which are detrimental to the improvement of imaging quality. In 2016, He *et al* [34] established an analytical model to appraise the influence of cutting edge waviness on surface roughness, and subsequently, they compared the diffraction effects of metal mirrors machined by diamond tools with different waviness [51], in which a comprehensive method of theoretical and experimental analyses was employed. The investigations suggested that the diffraction effect of the turned metal mirrors gradually increases with the increment of cutting edge waviness, and diffraction spots of different orders near the specular light spot (center) gradually increase, as presented in figure 3, resulting in a serious reduction of the reflectivity. In 2017, Kurniawan *et al* [47] used a

Figure 3. Influence of diamond tool cutting edge waviness on the surface diffraction effect: (a) simulation results, (b) experiment results. Reproduced from [51]. CC BY 4.0.

similar method to study the influence of cutting edge waviness on the surface roughness during the dual frequency elliptical vibration cutting process and established a theoretical prediction model of surface roughness considering the influence of cutting edge waviness. The above results confirmed that the cutting edge waviness of a diamond tool is an essential factor determining surface roughness.

It can be concluded from the reports above that the cutting edge waviness of micro diamond tools has a significant influence on the shape accuracy, roughness, integrity, and service performance of the machined surfaces. In other words, a micro diamond tool with excellent cutting edge waviness is one of the necessary conditions to achieve a high quality surface covered with microstructure arrays. Therefore, the cutting edge waviness has to be strictly controlled to achieve super-high cutting performance in the mechanical lapping of high-precision diamond tools.

3.2. Influence of tool sharpness on machining quality

One of the important reasons why diamond tools are used in ultra-precision machining is that they have extremely high sharpness. Currently, the stable level of the edge sharpness is between 10 nm and 200 nm around the world, which is closely related to the design method and mechanical lapping process as operated. In general, tool sharpness is another important technical index to evaluate the quality of diamond tools [52].

The cutting depth in ultra-precision machining and micro machining is very small, generally at the micrometer or submicron scale and even at the nanometer scale. In this case, the chip thickness and cutting edge radius are in the same order of magnitude, leading to some experimental phenomena different from the traditional machining process, which is well known as the size effect of ultra-precision machining. It affects not only the machining process but also the machined surface quality [53–55], so many theoretical and experimental investigations on the size effect have been performed around the world. Ikawa *et al* [56, 57] examined the relationship between the minimum chip thickness and the cutting edge radius in diamond turning using the molecular dynamics (MD) simulation method, and they found that the minimum thickness was approximately 1/10 of the cutting edge radius. Subsequently, Yuan *et al* [58] established a quantitative formula for expressing the relationship between the minimum chip thickness, cutting edge radius, and cutting forces during the diamond cutting process. According to the formula, the minimum chip thickness is proportional to the cutting edge radius, with a proportion coefficient of about 1/4–1/3, depending on the friction coefficient between the machined material and the diamond tool. Son *et al* [59] investigated the influence of cutting edge radius on the minimum chip thickness based on force analysis

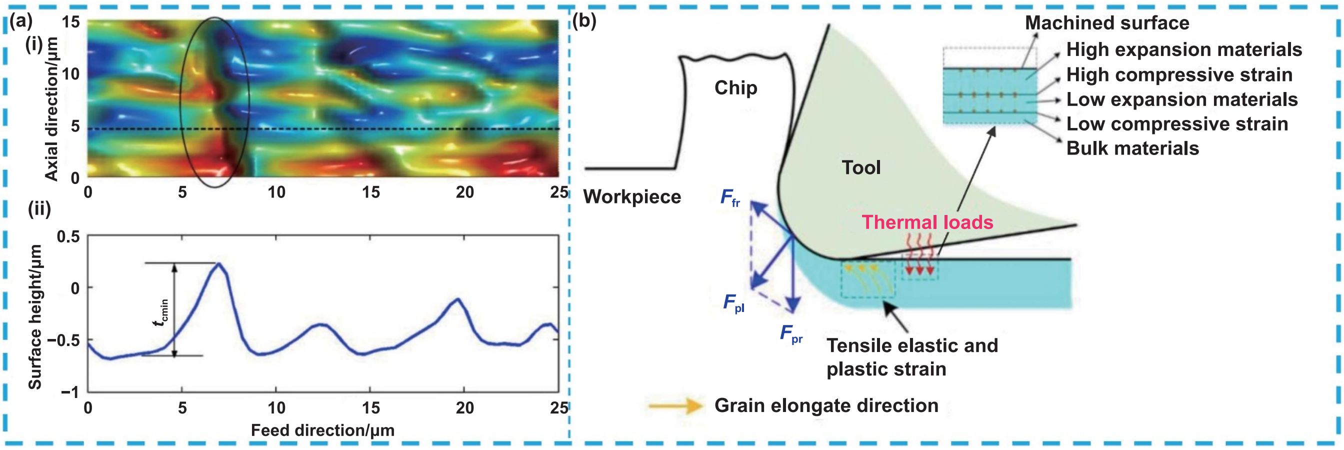

Figure 4. Formation instant of the chip with minimum thickness and residual stress formation principle: (a) minimum thickness chip formation. Reprinted from [62], © 2018 Elsevier Ltd All rights reserved. (b) Surface residual stress formation. Reproduced from [63]. CC BY 4.0.

in diamond turning with a micro diamond tool. They found that the minimum chip thickness has a negative correlation to the friction coefficient in the case of a constant cutting edge radius. Liu *et al* [60] discussed the influence of cutting edge radius on the minimum chip thickness and proposed a critical condition of cutting edge radius for the transition from cutting to plowing in diamond cutting based on the theory of friction molecular mechanics. They also captured a moment of the transition from cutting to plowing in the experiments, that is, the moment of minimum thickness chip formation, as shown in figure 4(a). Due to the minimum chip thickness phenomenon, the materials ahead of the active cutting edge cannot be completely removed, resulting in the uncut materials remaining on the machined surface under the extrusion, burnishing, and friction of the cutting edge, which makes the strain of the surface be different from that of the substrate material. Therefore, residual stress is generated on the machined surface and subsurface, as demonstrated in figure 4(b). On this topic, Nasr *et al* [53] studied the relationship between the residual stress on the machined surface and the cutting edge radius by using a combined method of theoretical modeling and experimental observations. Their findings suggested that the residual tensile stress on the machined surface and the residual compressive stress in the subsurface increase gradually with the increment of the cutting edge radius, and the affected depth of the residual stress also increases. Tao *et al* [61] analyzed the influence of the cutting edge radius on the residual stress left on the machined surface or in the subsurface with the finite element simulation method. The simulation results also demonstrated that the residual stress and its influence depth are positively related to the cutting edge radius.

In 2008, Childs *et al* [64] found that the dependence of the surface roughness R_z on the cutting edge radius (r_e) became more and more obvious with the decrease in feed rate in diamond turning of aluminum alloy. Once the feed rate was less than 10 μm r^{-1}, R_z is completely determined by the cutting edge radius, and R_z = (0.01–0.02) r_e. In the same year, Woon *et al* [65] studied the influence of cutting edge radius and cutting depth (a) on the stress distribution around the cutting edge based on finite element simulation technology. The simulation results demonstrated that: in the case of $a/r_e \rightarrow \infty$, shearing is mainly concentrated in front of the sharp cutting edge, around the chip root, and the region around the transition point of the chip free boundary, as presented in figure 5(a); in the case of $a/r_e = 3$, shearing region rapidly expands to the surroundings, as presented in figure 5(b); in the case of $a/r_e = 0.6$, shearing region expands further, resulting in a transfixion to form a non-parallel shearing zone, as presented in figure 5(c); in the case of $a/r_e = 0.262\,5$, shearing becomes highly localized and increasingly intense ahead of the cutting edge, as presented in figure 5(d).

In 2015, de Oliveira *et al* [54] examined the size effect in the micro machining process and concluded that the specific cutting force rises sharply, reaching the magnitude in grinding (70 GPa) if the cutting depth is small enough (less than 0.1 r_e). Meanwhile, the cutting process degenerates into squeezing and plowing processes without chip formation. Finally, they confirmed that the minimum chip thickness is about 1/4–1/3 of the cutting edge radius in the experiment. In 2016, He *et al* [34] studied the influence of the cutting edge radius on the stress distribution in the cutting area during diamond turning and found that a tool cutting edge with a large rounded radius has an obvious extrusion effect on the uncut material before the formation of the machined surface. They also investigated the influence of cutting edge radius on the elastic recovery of the machined surface, of which the results showed that the elastic recovery has a positive correlation to the cutting edge radius, meaning that the larger the cutting edge radius is, the more unfavorable to improve the machined surface quality. In 2017, Rahman *et al* [66] established a quantitative formula to reveal the relation between the relative sharpness (a/r_e) and the material removal mechanism in ultra-precision machining, and they predicted the transition process from cutting to plowing and further to squeezing or friction in theory. In 2021,

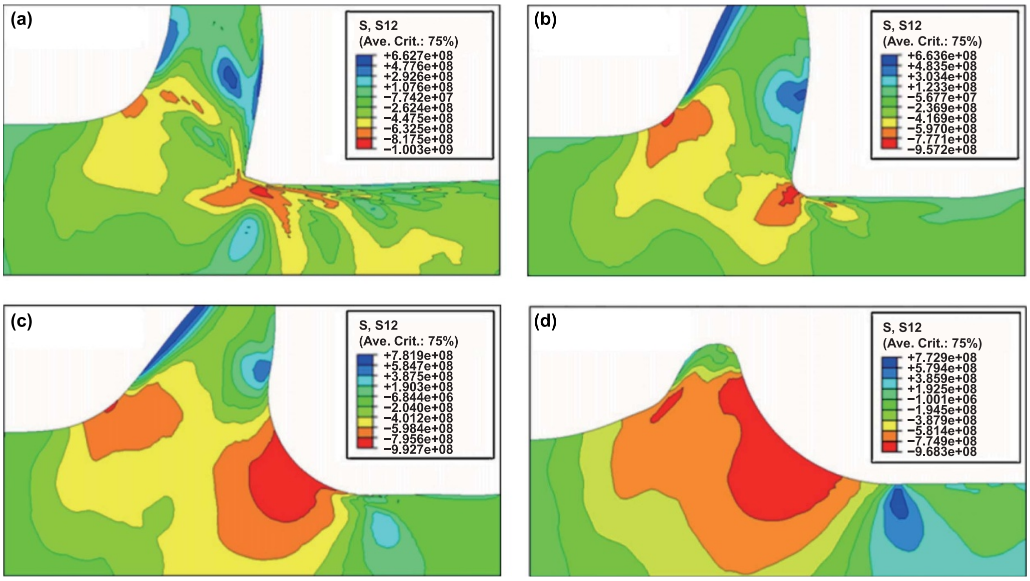

Figure 5. Influence of cutting edge radius on the stress distribution in the cutting region: (a) $a/r_e \to \infty$, (b) $a/r_e = 3$, (c) $a/r_e = 0.6$, (b) $a/r_e = 0.262\ 5$. Reprinted from [65], Copyright © 2007 Elsevier B.V. All rights reserved.

Yu *et al* [67] disclosed the influence of relative sharpness on the chip formation mechanism and surface roughness based on Ni-P alloy cutting experiments. They observed that with the decrease in relative sharpness, the chip shape changes from the initial continuous strip to the intermittent serration, and the cutting force appears periodically undulate. Moreover, the surface roughness increases gradually. They believed that the above experimental phenomena were caused by the periodic extrusion and elastic recovery of the uncut material when the cutting process degenerates into the plowing process. In 2022, Li and Chang [68] tracked the change process of the shear angle, cutting force, and stress distribution with the variation of the cutting edge radius by utilizing the FEM. They pointed out that the shear angle decreases, the cutting force increases and the stress concentration area gradually expands to the subsurface with the increase in the cutting edge radius.

It can be concluded from the above reviews that the cutting edge radius not only affects the minimum chip thickness, stress state in the cutting area, material removal mechanism, and cutting force, but also influences the surface roughness and machined surface integrity. According to the above analyses, the chip is formed mainly under the shear stress in the primary shear zone without consideration of the cutting edge radius. Meanwhile, the removal of all the material in the uncut chip layer is conducted via chip formation by dislocation motion under the extrusion effect of the cutting edge [69]. In this case, the spring back and plastic side flow effects are absent, so the machined surface morphology consists of only the feed marks [34]. However, the actual cutting edge radius is about 10–50 nm, and only the material in the uncut chip layer larger than the minimum chip thickness is removed from the workpiece surface to form chips. The material in the uncut chip layer smaller than the minimum chip thickness is squeezed by the cutting edge onto the machined surface, during which the unremoved material generates spring back and plastic side flow and finally remains on the topmost surface to form the machined surface. Moreover, the microscopic defects on the cutting edge will be copied onto the machined surface, which is not deductive to improve the machined surface finish and integrity. Therefore, during the lapping of high-precision micro diamond tools, it is of great significance to sharpen the cutting edge to improve the machined surface quality.

3.3. Design method for improving cutting edge waviness and sharpness

The machinability of the diamond crystal varies dramatically with the crystal plane and orientation due to the strong anisotropy of diamond crystal, which leads to the heavy dependence on cutting edge waviness and sharpness on the crystal plane and orientation in the mechanical lapping of diamond tools. In this regard, Liu and Zong [70] established a cutting edge strength distribution model, which was validated with MD simulations, to reveal the influence of diamond anisotropy on the cutting edge waviness and sharpness achieved in the mechanical lapping of micro diamond tools. They found a significant difference in the spatial distribution of micro diamond tool cutting edge strength with different crystal orientations, as shown in figure 6(a). In the region with high cutting edge strength, the material removal rate is obviously low, and the cutting edge profile at the corresponding region protrudes outward beyond the mean profile; on the contrary, the material removal rate is high in the region with low cutting edge strength, and the cutting edge at the corresponding region is inward concave, which leads to the cutting edge profile appearing serrate, forming the cutting edge waviness error, as shown in figure 6(b). The findings also proved that in the same lapping condition, tool sharpness is dependent on the cutting edge strength because the impact resistance of the cutting edge is related to its strength, which means that chipping defects

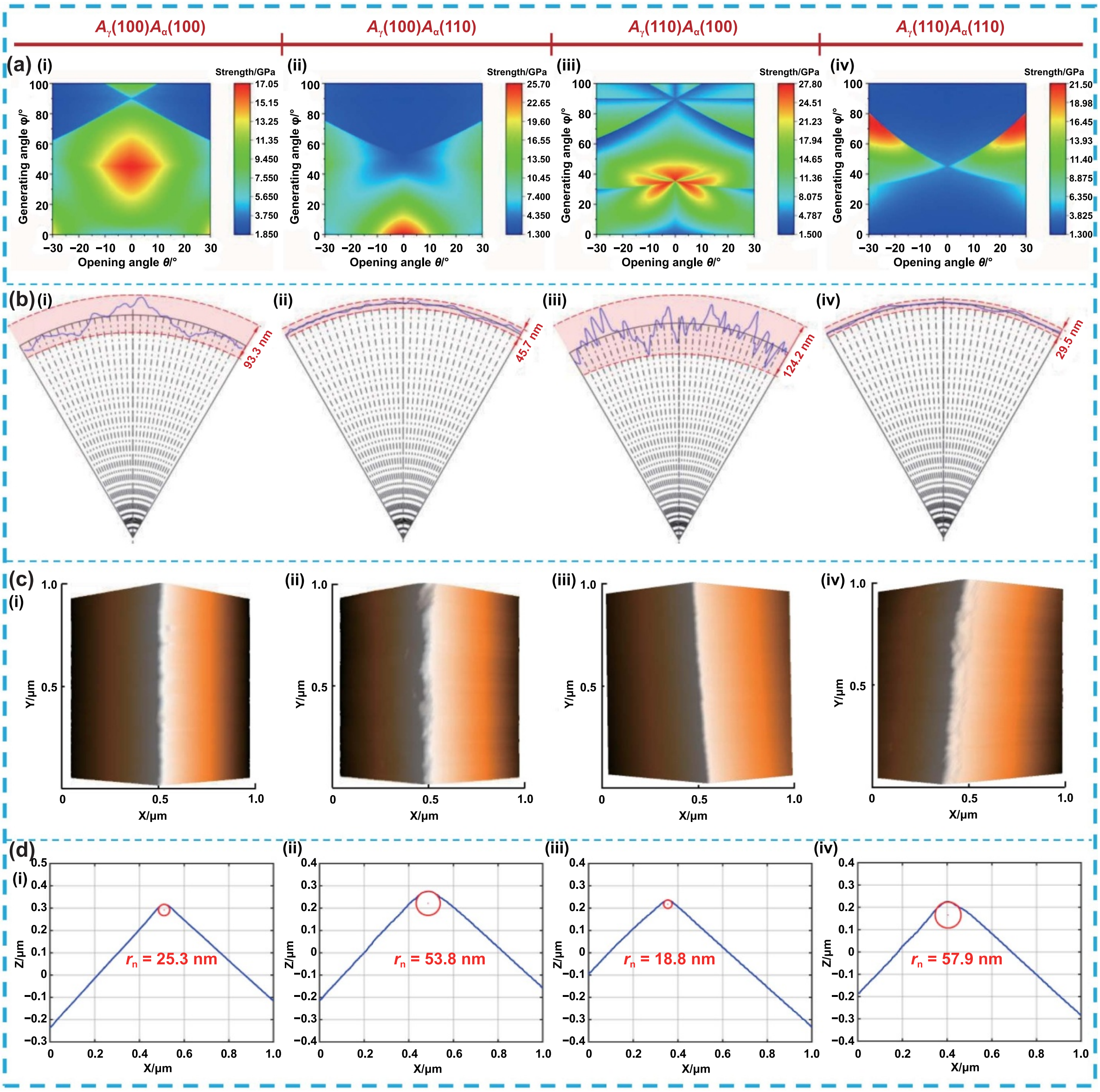

Figure 6. Spatial distribution of cutting edge strength, cutting edge waviness, cutting edge morphology, and radius of the micro diamond tools with different crystal orientation configurations: (a) cutting edge strength (θ denotes the arc angle along the cutting edge profile on the rake face and φ denotes the arc angle along the cutting edge profile on the cross section.), (b) cutting edge waviness, (c) cutting edge morphology, (d) cutting edge radius. Reprinted from [70], © 2021 Elsevier B.V. All rights reserved.

and secondary passivation can be effectively suppressed in the lapping process. Likewise, it is conducive to improving tool sharpness if the cutting edge has high strength. Cutting edge morphologies and radii of the sharpened micro diamond tools with different crystal orientation combinations are shown in figures 6(c) and (d).

In summary, the above analyses suggest that the design of the crystal orientation combination provides an effective method for controlling the waviness and sharpness of micro diamond tools to meet the various application requirements. In orientation design, the crystal orientation configuration with uniform cutting edge strength on the flank face should be selected preferentially as the oriented configuration of micro diamond tools requiring excellent waviness, for example, $A_\gamma(100)A_\alpha(110)$ or $A_\gamma(110)A_\alpha(110)$. The crystal orientation configuration with high cutting edge strength should be selected preferentially as the oriented configuration of micro diamond tools requiring excellent sharpness, for example, $A_\gamma(100)A_\alpha(100)$ or $A_\gamma(110)A_\alpha(100)$. Here, A_γ and A_α denote the rake face and flank face; (100) and (110) denote the (100) and (110) crystal planes; $A_\gamma(100)A_\alpha(110)$ denotes that the rake face is oriented as the (100) crystal plane and the flank face is oriented as the (110) crystal plane. Although the difference in the spatial distribution of cutting edge strength is one of the main origins for the variety of cutting edge waviness and sharpness of micro diamond tools, the waviness and sharpness are also closely related to the lapping parameters, such as the flatness of the iron scaife, the dynamic balance state of the spindle, the grain size of the abrasive and lapping pressure. Cheng [71] found that the differences in the cutting edge waviness and sharpness of micro diamond tools with different crystal orientations can be weakened by changing the lapping parameters.

Therefore, a specific process and optimized lapping parameters should be adopted to fabricate high-performance micro diamond tools under these extremely severe requirements. Taking the micro diamond tools applied in the ultra-precision machining of micro optical lens molds as an example, it is necessary to give priority to ensuring the cutting edge waviness and then improve the sharpness as much as possible by optimizing the lapping parameters. Whereas for the micro diamond tools applied in the ultrathin cutting, it needs to give priority to ensuring the cutting edge radius and then try the best to improve the waviness by optimizing the lapping parameters.

4. Design of micro diamond tools in terms of improving tool wear resistance

4.1. Influence of tool wear on machining quality

Tool wear resistance is another critical factor determining the cutting performance and machined surface quality, in addition to the cutting edge waviness and sharpness. Tool wear not only induces edge defects that will be copied on the machined surface, leading to a deterioration of the surface roughness and integrity, but also reduces the original accuracy of the cutting edge profile, resulting in the shape and dimension errors of the machined microstructure. The cutting depths used for both micro diamond tools and conventional diamond tools are usually in the range of 2–5 μm in micro diamond machining. Although the feed of micro diamond tools is much smaller than that of conventional diamond tools, the ratio of the active cutting edge to the whole cutting edge of micro diamond tools is still much higher than that of conventional diamond tools. Compared with conventional diamond tools, it is easy to generate stress concentration and wear on the round nosed cutting edge of micro diamond tools. Therefore, the wear suppression of diamond tools has always been a technical difficulty in the field of ultra-precision and micro machining, especially for micro diamond tools.

In 2012, Park *et al* [72] examined the wear characteristics of the 90° V-shaped micro diamond tool and its influence on the shape accuracy of microstructures in the machining of light guide plate molds. The experiment results illustrate that side edge wear and nosed edge wear are the main origins of the shape and dimension errors of the shaped light guiding microstructures. Moreover, the side edge wear also leads to burrs on the sidewall of the shaped microstructures, and the nosed edge wear leads to fillet errors on the bottom of the shaped microstructures. Subsequently, Yoshino *et al* [73] and Cui *et al* [74] reported a similar phenomenon in machining micro groove arrays on the quartz glass and Al 6061 substrates, respectively, with a V-shaped micro diamond tool. They also reported that tool wear leads to the intensification of the plastic side flow of the workpiece material so that a large amount of material accumulation appears on the groove sidewall, as shown in figure 7(a). In 2015, Zhang and To [75] found that tool wear marks copied on the machined surface and chip surface directly determine the machined surface integrity and chip morphology in ultra-precision raster milling, and they finally proposed a tool wear identification method to *in-situ* evaluate the achieved surface roughness. Zareena and Veldhuis [76] also found that the chip morphology is closely related to the tool wear condition when turning the titanium alloys with a diamond tool, i.e. the chip generated by a sharp tool appears smooth ribbon, while the chip generated by a worn tool appears rough crimp. They pointed out that tool wear impedes the timely discharge of chips, and the plastic side flow induced material accumulation on the machined surface becomes more and more prevalent, resulting in a rapid deterioration of the machined surface quality. In 2016, Mir *et al* [77] found that the material removal mode gradually changes from ductile removal to brittle fracture removal with the gradual flank face wear of the diamond tool during the ultra-precision turning process of monocrystalline silicon, resulting in serious damage to the surface finish and integrity. In 2017, Mukaida and Yan [78] observed the experimental phenomenon that the material removal mechanism changes and the machined surface roughness deteriorates due to the flank face wear and micro chipping wear of the micro diamond tool when turning the microlens array on the monocrystalline silicon substrate, as shown in figure 7(b). In 2019, Wu *et al* [79] examined the influence of micro diamond tool wear on the machined surface morphology and optical performance in the ultra-precision turning of large scale optical molds. They concluded that tool wear and micro cleavage of the cutting edge lead to the intensification of plastic side flow and the increment of scratches on the machined surface, both of which cause an increase in periodic residual height and unnecessary optical diffraction effects on the machined surface, resulting in a decrease in optical performance. In 2020, Sharma *et al* [80] monitored the change of principal cutting force and thrust cutting force with the gradual tool wear process when diamond turning oxygen free high conductivity copper. The results indicated that the cutting forces, especially the thrust force, increase rapidly with the diamond tool wearing, as presented in figure 7(c), which is not conducive to the smooth progress of ultra-precision turning.

The cutting edge and nose shapes of micro diamond tools engaged in the machining of microstructure arrays are specially designed according to the microstructure shape, as discussed in section 2. In the process of ultra-precision machining, micro diamond tool wear inevitably leads to not only the decrease in size and shape accuracy of the machined microstructures, but also the serious deterioration of surface roughness and integrity, which finally produces a sharp decline in the performance of the microstructure array surface. Currently, severe wear of micro diamond tools has become an intractable technical difficulty that restricts the improvement of the machining accuracy of large scale microstructure array surfaces [79].

4.2. Restraining methods for tool wear

Multitudinous studies on the diamond tool wear mechanism have been performed, and different wear mechanisms have been put forward for different processing conditions and

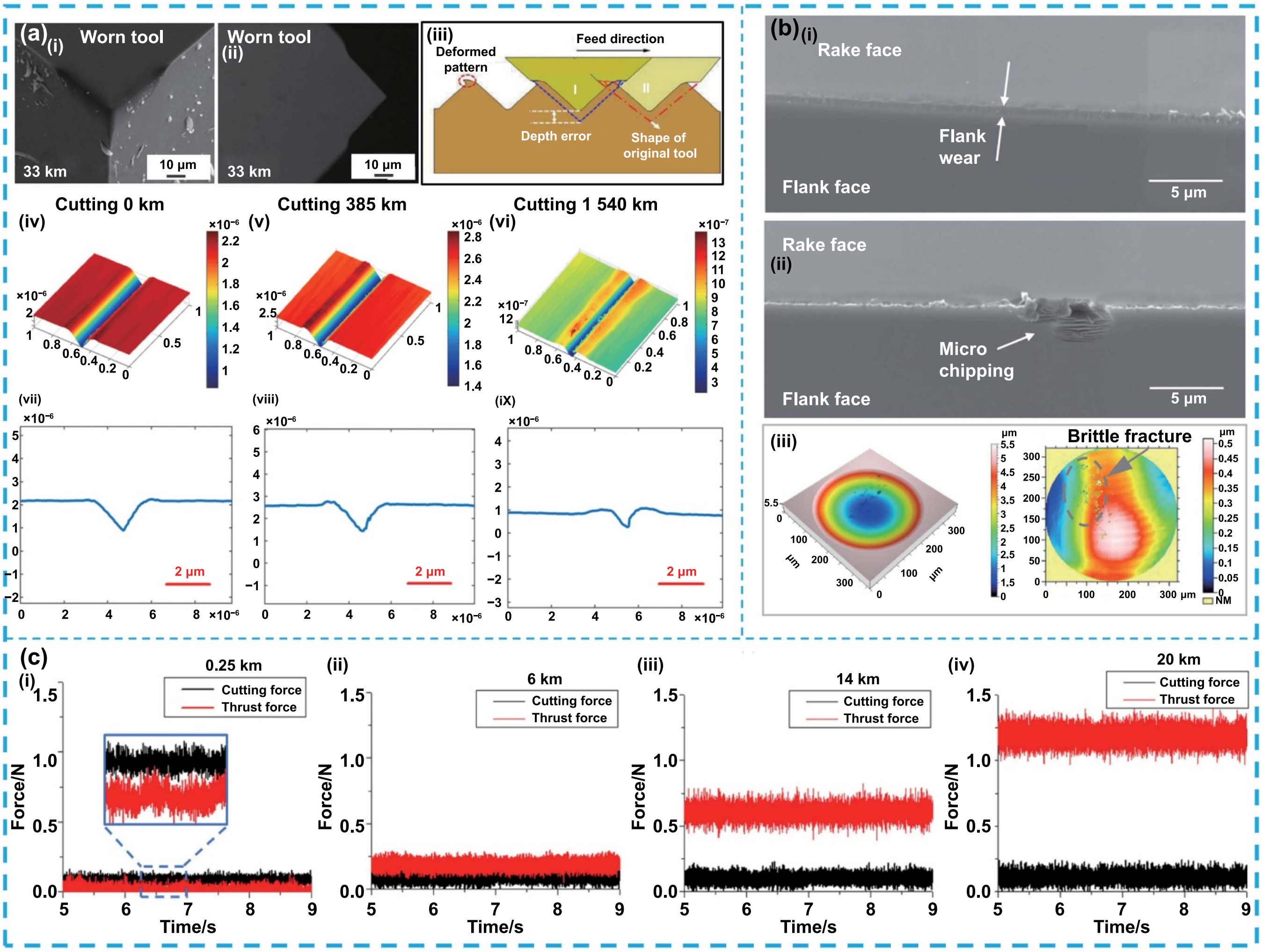

Figure 7. Micro diamond tool wear and its influence on the surface quality and cutting forces: (a) influences of tool wear on the microstructure shape. Reprinted from [72], Copyright © 2012 The Nonferrous Metals Society of China. Published by Elsevier Ltd All rights reserved. Reprinted from [74], © 2021 Elsevier B.V. All rights reserved. (b) Influences of tool wear on the material removal mode. Reprinted from [78], © 2016 Elsevier Ltd All rights reserved. (c) Influences of tool wear on the cutting force. Reprinted from [80], © 2020 The Society of Manufacturing Engineers. Published by Elsevier Ltd All rights reserved.

materials. Currently, the widely accepted wear mechanisms are summarized as follows: (a) mechanical wear, including fracture wear [75, 81], abrasive wear [82–85], and micro-cleavage wear [78, 84]; (b) chemical wear, including amorphous wear [86, 87], graphitized wear [88, 89], and oxidative wear [90, 91]; (c) thermal wear, including adhesive wear [92, 93] and diffusion wear [89, 90].

Different suppressing methods, as listed in table 1, were proposed for the corresponding wear mechanisms to mitigate the negative influences of diamond tool wear on the machining process and surface quality. In the aspect of the machining process, Zhou and his co-workers [32] optimized the machining parameters to slow down the wear rate of micro diamond tools when turning sinusoidal microstructures. Chon *et al* [85] achieved the goal of suppressing diamond tool notch wear with a method of dual feed rate. Song *et al* [94] and Brinksmeier *et al* [95] alleviated the chemical wear and thermal wear of diamond tools effectively by increasing the milling speed and flying cutting speed to reduce the contact time of the tool-workpiece. In the aspect of cooling and lubricating, Durazo–Cardenas *et al* [96] and Yoshino *et al* [73] found that adding cutting fluid could significantly reduce friction wear and thermal wear, prolonging tool life in the diamond turning of monocrystalline silicon and quartz glass. Zhuang *et al* [97] reported that minimum quantity lubrication (MQL) is an effective way to reduce the cutting temperature and tool wear. In addition, MQL technology is more conducive to sustainable development than flood fluid lubrication. Evans and Bryan [98] and Brinksmeier *et al* [99] respectively pointed out that the ultra-low temperature could effectively suppress the graphitized wear, thermal diffusion wear, and adhesive wear of diamond tools based on their cryogenic diamond turning experiments. Shimada *et al* [100] declared that the oxidation wear of diamond tools could be alleviated to a certain extent by continuously inpouring high-pressure nitrogen into the cutting area to reduce the oxygen concentration around the tool tip in diamond turning of oxygen free high conductivity copper. In the aspect of ultrasonic vibration cutting (UVC),

Table 1. Diamond tool wear mechanisms and suppressing methods.

Wear mechanism	Suppressing method	References
Fracture wear	UVC, electrochemical softening	[101, 105, 109, 111, 112]
Abrasive wear	Adding cutting fluid, increasing cutting speed, UVC, laser assisted cutting, magnetic assisted cutting, tool surface treatment, adopting dual feed rate, tool surface treatment	[73, 85, 95, 96, 102, 103, 106, 107, 113]
Microcleavage wear	Optimizing feed rate	[32]
Amorphous wear	Increasing cutting speed	[95]
Graphitized wear	Increasing cutting speed, inpouring liquid nitrogen, UVC, implanting Ga^+	[94, 98, 99, 101, 114–116]
Oxidative wear	Increasing cutting speed, inpouring high-pressure nitrogen, electric assisted cutting, nitriding treatment	[93, 94, 100, 108, 110]
Adhesive wear	Inpouring liquid nitrogen, UVC	[98, 99, 104]
Diffusion wear	Increasing cutting speed, inpouring liquid nitrogen, UVC	[98, 99, 101, 104]

Zou *et al* [101] carried out numerous diamond turning experiments for die steel materials by utilizing the uniaxial UVC technology, based on which they pointed out that diamond tool wear can be effectively restrained because the lubrication and heat dissipation conditions in the cutting area are improved due to the introduction of ultrasonic vibration. In addition, the contact time between the diamond tool and the chip could be shortened by introducing ultrasonic vibration, which is significant for suppressing chemical and thermal wear. Nath *et al* [102, 103] introduced elliptical ultrasonic vibration into the ultra-precision turning of tungsten carbide (WC) and realized the ultra-precision cutting of WC in a ductile regime and suppression of mechanical wear to a certain extent. Zhang *et al* [104] found that elliptical vibration cutting can significantly reduce the adhesion between the diamond tool and the workpiece material in the machining of WC, which is conducive to reducing thermal and chemical wear. Wang *et al* [105] put forward a method of multi axis ultrasonic vibration turning, which is capable of improving the effective sharpness of diamond tools in turning, and suppressing mechanical wear. In the aspect of multi physical field assisted cutting, Shahinian *et al* [106] adopted micro laser assisted cutting technology to heat the monocrystalline silicon surface in a localized area to increase its plasticity and reduce hardness, followed by SPDT, which is conducive to reducing mechanical wear. They extended tool life by 1.5 times and achieved ultra-precision turning of monocrystalline silicon without brittle fracture. Yip and To [107] reported that they improved the wear resistance of diamond tools in the turning of difficult-to-machine materials with the magnetic field assisted turning method. Zhang [108] invented a method of using an electric field to restrain the chemical wear in the machining of materials that chemically react with diamond. In the aspect of processed material modification, Zhang *et al* [109] modified the WC surface with electrochemical methods to decrease the hardness and brittleness of the surface to be machined, realizing the suppression of mechanical wear. Brinksmeier *et al* [93] and Wang *et al* [110] passivated the catalytic effect of die steel on the chemical wear of diamond tools by nitriding the surface to be machined and achieved the goal of inhibiting the graphitized wear and diffusion wear of diamond tools. All the methods reviewed above belong to indirect methods by changing the external cutting environment or conditions to achieve the purpose of restraining diamond tool wear.

Recently, more and more attention has been paid to the wear resistance of micro diamond tools by improving the mechanical properties of the tool surface and changing the external cutting environment or conditions. For example, Lee *et al* [114] and Du *et al* [115, 116] implanted gallium (Ga) ions into the diamond tool surface through FIB technology to change the surface energy, friction coefficient, and other properties of the diamond material. Their wear experiments indicated that the existence of Ga ions increases the graphitization temperature of diamond by 40%, and the friction and cutting temperature of the modified tool decrease greatly, which is conducive to improving the friction wear resistance and graphitized wear resistance. Chen *et al* [117–119] modified the diamond tool surface by laser induced graphitization to strengthen the wear resistance, and the experiments showed that their approach was effective. Kawasegi *et al* [111] and Wang *et al* [112] textured microstructures on the rake face with FIB micro milling and femtosecond laser ablation to modify the contact state between the diamond tool and the chip. Their cutting experiments showed that microstructures on the rake face can effectively reduce tool-chip friction, cutting force, and cutting temperature, which also relieves mechanical and thermal wear. Zong *et al* [113, 120] repaired the subsurface damage to the tool surface that is induced by mechanical lapping with a thermo-chemical treatment method to improve the strength and hardness of the rake and flank faces of the diamond tool. Cutting experiments proved that the treatment method can also extend the life of diamond tools. Zhuang *et al* [121] suppressed the wear of micro diamond tools by selecting the material type of diamond crystal, and they found that micro tools made of type Ia natural diamond have a higher wear resistance than other types of diamond crystal. The above methods directly strengthen the cutting performances of diamond tools and effectively inhibit tool wear, and they can be collectively called direct suppression methods.

In addition, advanced polishing methods, e.g. chemical polishing [122], plasma assisted polishing [123], ultraviolet light assisted polishing [124], and so on, also have access to lessen the subsurface damage of micro diamond tools for improving their service life. In fact, how to efficiently remove

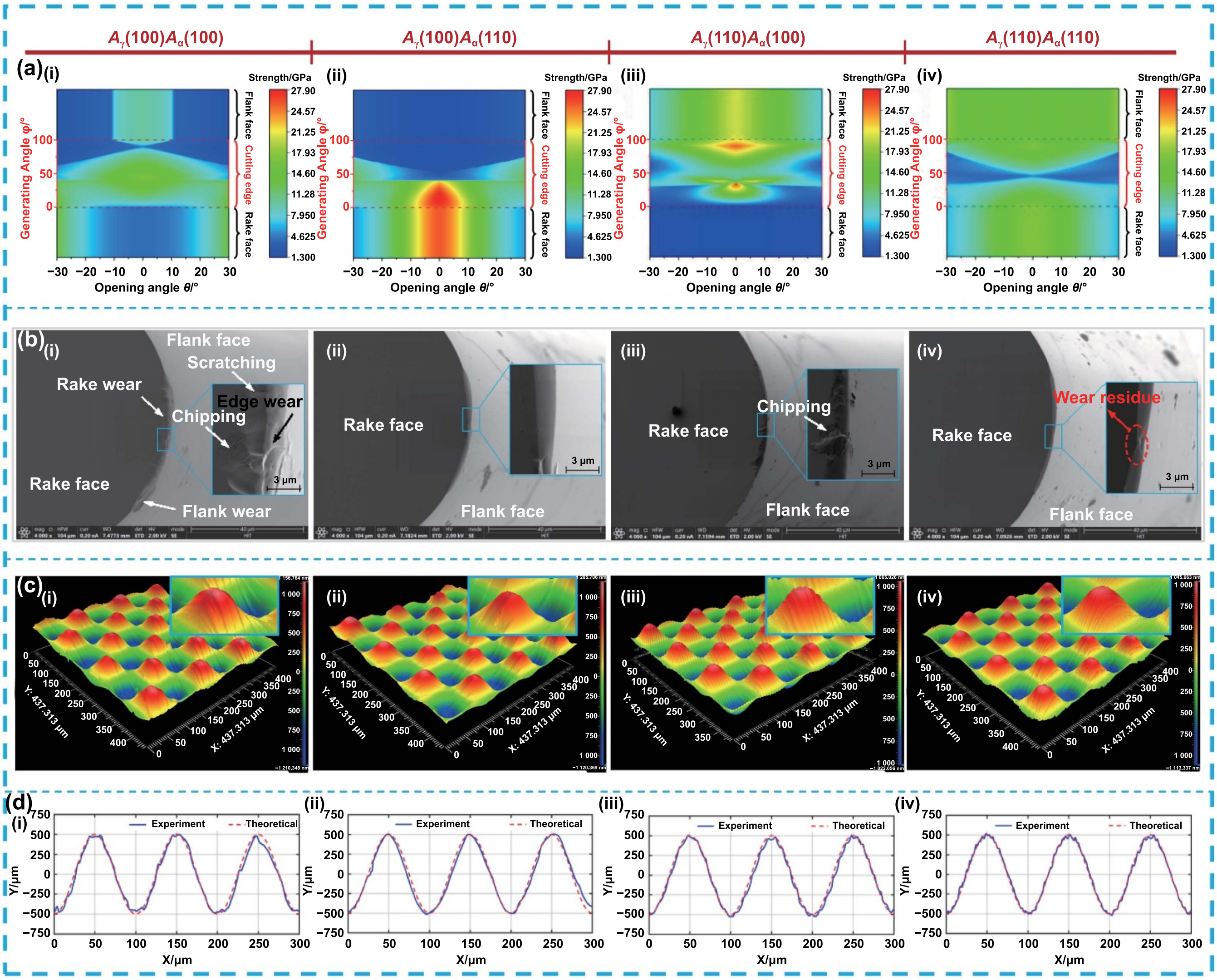

Figure 8. Tool nose strength distribution and wear morphology of the micro diamond tools with different orientations, and the machined microstructure arrays: (a) tool strength in the cutting area, (b) tool wear morphology, (c) microstructure morphology machined by micro diamond tools with different orientations, (d) microstructure profiles extracted from the corresponding surfaces in (c). Reprinted from [133], © 2022 Elsevier B.V. All rights reserved.

subsurface damage with those advanced polishing methods is an important development direction for the diamond tool manufacturing industry.

4.3. Design of micro diamond tools by utilizing diamond crystal anisotropy

A large number of simulations and cutting experiments [92, 125–132] proved that diamond tool wear resistance is closely related to the crystal orientation configurations on the rake and flank faces, but the conclusions drawn by different scholars are different [92, 128]. Except for ferrous metal machining, mechanical wear is the dominant wear mechanism, which is determined by the mechanical and physical properties of diamond tools, such as the strength of the active cutting edge and tool-chip friction property, etc. In order to improve the wear resistance, Liu *et al* [133] established a nosed cutting edge strength model of micro diamond tools with different crystal orientation configurations, and subsequently, they analyzed the spatial distribution characteristics of cutting edge strength in relation to the actual cutting area, as presented in figure 8(a). It can be seen from figure 8(a) that the strength distribution in response to the active cutting area of the cutting edge varies sharply with the crystal orientation changing, meaning that the nosed cutting edge strength has a strong anisotropy. The experimental results demonstrated that the wear morphologies, as presented in figure 8(b), are consistent with the strength distribution characteristics. That is to say, the active cutting area with large strength corresponds to high wear resistance, and the cutting area with small strength corresponds to low wear resistance. Therefore, they proposed a crystal orientation design method to improve the wear resistance of micro diamond tools, considering the strengths of the rake face, flank face, and cutting edge. In brief, the hard orientation of the flank face, i.e. the direction with high strength, should be configured along the cutting direction as much as possible through a reasonable orientation design by taking advantage of the diamond anisotropy. The wear experiments proved that the service life of micro diamond tools designed with this new method is three times longer than that of the tools designed by the traditional method. The microstructure morphologies machined with micro diamond tools with different orientations after cutting 30 km are presented in figures 8(c) and (d), of which the profile error variations further validate that the orientation dependent design method is effective in improving the wear resistance of micro diamond tools.

5. Manufacturing of micro diamond tools

Diamond crystal materials with super-high hardness, high thermal conductivity, high wear resistance, ultra-low friction, and other excellent properties are widely engaged in industry and high-tech fields. Therefore, numerous processing methods for diamond crystals have been developed, such as mechanical lapping [134], chemical assisted polishing [135], thermochemical polishing [136], laser processing [137], plasma etching [138], FIB etching [139], oxidative etching [140], and other methods [141]. However, only three of them are applicable to the manufacturing of micro diamond tools, namely laser processing, FIB etching, and mechanical lapping, and the comprehensive comparisons of these three methods are summarized in table 2. The rest of the processing methods are mostly utilized as an assistant means to improve the machined surface roughness, so this section is mainly focused on the three methods.

5.1. Laser processing

Laser processing is based on a laser beam with an extremely high energy density irradiating the diamond surface. When using a long pulse laser, the laser beam irradiating generates a localized instantaneous high temperature, which makes the material ablate, melt, vaporize, oxidize, graphitization, amorphization, and cavitate to achieve rapid removal of diamond material. When using an ultra-short pulse laser, the irradiating makes the diamond surface atoms absorb the photon energy of the high energy laser to escape from the surface and achieve slow material removal [165]. According to the length of the pulse width, lasers are generally categorized into nanosecond lasers, picosecond lasers, and femtosecond lasers. Laser processing is an essential technology in micro machining, especially for difficult-to-machine materials [166, 167] and micro cutting tools [168]. Suzuki *et al* [144] produced a diamond milling tool with 10 edges using a nanosecond laser to machine binderless tungsten carbide molds. Afterwards, they also tried to process several types of micro diamond milling tools with 20 cutting edges using the same method to realize the ultra-precision milling of SiC micro lens molds. However, the experiment results suggested that the cutting edge quality of the milling tool processed with a nanosecond laser is unsatisfied because of the obvious collapses on the cutting edge, and the sharpness was blocked at the micrometer level. The error averaging effect of the multi edge tools allows the micro grinding tools and milling tools above with insufficient shape accuracy to be applied in ultra-precision machining or to obtain a machined surface with high accuracy. However, single edge tools, for instance, single bladed milling tools and turning tools, are impotent in ultra-precision machining due to the copying effect of defects on the tool cutting edge. Consequently, Xia *et al* and Zhao *et al* [145, 169] tried to manufacture a single edge micro diamond milling tool with a picosecond laser by optimizing the laser energy density, pulse wavelength, scanning spacing, and other parameters to improve the cutting edge sharpness and accuracy. Although the surface quality of picosecond laser machining is improved compared with nanosecond laser machining, obvious ablation marks still exist on the flank face, and the cutting edge sharpness of 1.9 μm is inferior to the 100 nm generally required for ultra-precision machining. As reported by Dold *et al* [146], the same ablation marks also existed on the polycrystalline diamond turning tool fabricated with a picosecond laser. Oliaei *et al* [26] decreased the laser pulse width to a femtosecond scale, by which they processed a ball end diamond milling tool with a single edge. They declared that the shape accuracy (i.e. tool cutting edge waviness) and sharpness of the cutting edge were greatly improved, reaching 0.7 μm and 0.8 μm, respectively, which remains difficult to meet the precision requirements of the tools for ultra-precision machining.

In order to ameliorate the cutting edge accuracy and sharpness, Takayama *et al* [148] used a picosecond laser to process a sub-cutting-edge array on the straight cutting edge of a diamond tool by optimizing the laser pulse width, repetition rate, and energy density, which was prepared for the turning of microstructures to improve the processing efficiency. Their experiment results showed that the consistency of the sub-cutting-edges processed by picosecond laser needs to be further improved, and obvious fractures are also present on the cutting edges, as presented in figure 9(a). Zhao *et al* [147] used a femtosecond laser, belonging to the ultra-short pulse laser, to fabricate a micro diamond forming tool with arrayed edges and different shapes, as demonstrated in figure 9(b), and they optimized the laser ablation strategy in an effort to improve the cutting edge quality. The experimental observations proved that laser beam processing has a high flexibility in the preparation of micro arrayed diamond forming tools, and the shape accuracy and sharpness of the sub-cutting-edges processed by femtosecond laser are obviously enhanced compared with nanosecond and picosecond laser beams. Chen *et al* and Jin *et al* [170, 171] proposed a method to process super-hard cutting tools by precision shaping and polishing the rough tools fabricated with femtosecond laser forming with FIB technology. In such a way, they achieved a micro turning tool with a nose radius of 13.8 μm and a sharpness of 60 nm. Furthermore, they also manufactured a diamond turning tool by directly optimizing the laser scanning path, which has a cutting edge waviness of 15 μm in an opening angle of 66° and a sharpness of 0.47 μm, as shown in figure 9(c). The instantaneously high temperature generated in the subsurface of micro diamond tools after laser irradiation and energy absorption reaches up to 1800 K, which is much higher than the temperature of diamond graphitization (1050 K) [172].

Table 2. Comparison of micro diamond tool manufacturing methods.

Method	Advantages	Disadvantages	Applications	References
Laser	High efficiency, free of mechanical force, achievable for sub edges	Poor surface quality and shape accuracy	Rough forming	[26, 137, 142–148]
FIB	Free of mechanical force, high precision, achievable for sub edges	Extremely low efficiency, poor edge waviness	Laboratory research	[149–152]
Lapping	High efficiency, high precision	Existence of mechanical force, impossible for sub edges	Industrial production	[14, 70, 134, 136, 153–164]

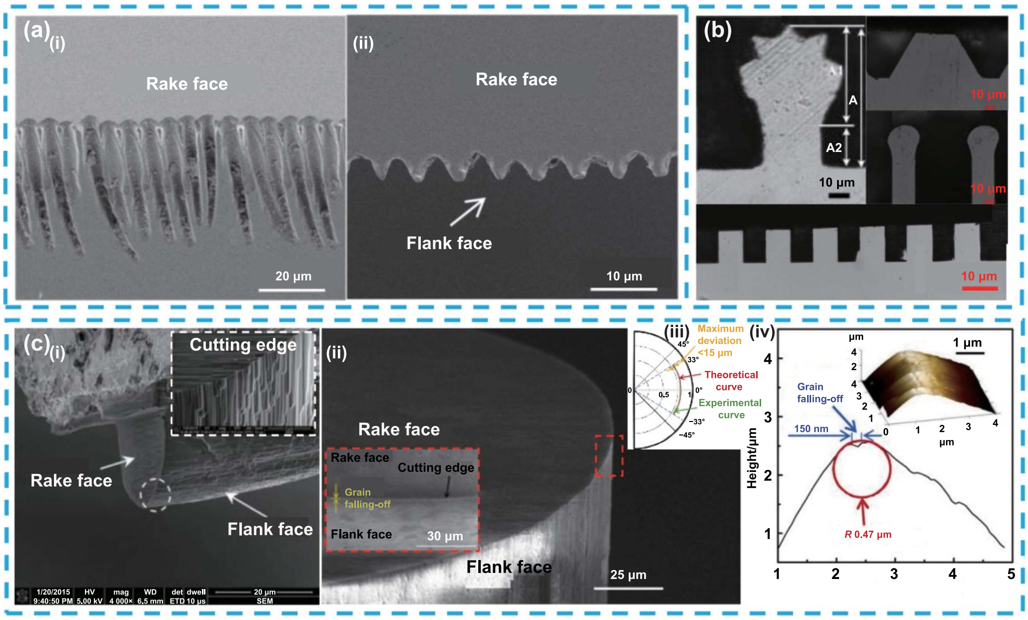

Figure 9. Micro diamond turning tools machined with laser: (a) sub-cutting-edge array. Reprinted from [148], © 2018 Elsevier Inc. All rights reserved., (b) micro diamond forming tool Reprinted from [147], © 2021 Elsevier Ltd All rights reserved., (c) micro turning tool. Reprinted from [171], © 2021 Elsevier B.V. All rights reserved.

Diamond graphitization occurs subsequently and reacts with oxygen in the air to generate carbon oxides, which are partially removed. Meanwhile, the instantaneous high temperature generates an uneven temperature field in the diamond subsurface, causing severe thermal stress and resulting in cracks on the surface of micro diamond cutting tools. Some materials are removed in the form of brittle fractures, leading to a significant decrease in cutting edge accuracy and tool surface quality. In addition, due to the interference between the incident laser and the scattering wave, periodic ripple structures with submicron dimensions usually form on the cutting tool surface, which is detrimental to the surface quality of micro diamond cutting tools and the control of cutting edge waviness [173]. Moreover, the heat affected zone (HAZ) depth of laser processed diamond can reach 40 μm. The HAZ is mainly composed of graphite, amorphous carbon, and oxidized deposited metamorphics, of which the hardness and strength are much lower than those of diamond matrix. Therefore, the micro diamond cutting tools processed by laser have the disadvantage of seriously insufficient lifespan.

In light of the above review on laser ablation of micro diamond tools, reducing pulse width [26] or optimizing ablation strategy [174–176] might lessen the HAZ and improve the processing accuracy, but the laser processing efficiency goes down sharply with the reduction of laser pulse width. So, the advantages of processing efficiency will be weakened or even disappear. And cutting edge sharpness and waviness of micro diamond tools fabricated by laser processing are just reaching micrometer or submicron levels, which are currently unable to meet ultra-precision cutting requirements. In addition, a conclusion might be drawn from the above results of laser processing with different pulse widths, i.e. the diamond tools processed with laser are hard to be directly used for ultra-precision machining, and generally, they need to be further shaped and polished by other precision methods [172], such as mechanical lapping, and FIB shaping.

5.2. FIB processing

FIB processing of micro diamond tools is achieved via the high speed bombardment of the focused gallium (or xenon) ion beam upon the diamond crystal surface, during which the kinetic energy of the high velocity moving ions transfers to carbon atoms on the diamond crystal surface through inelastic collision, leading to carbon atoms sputtering away

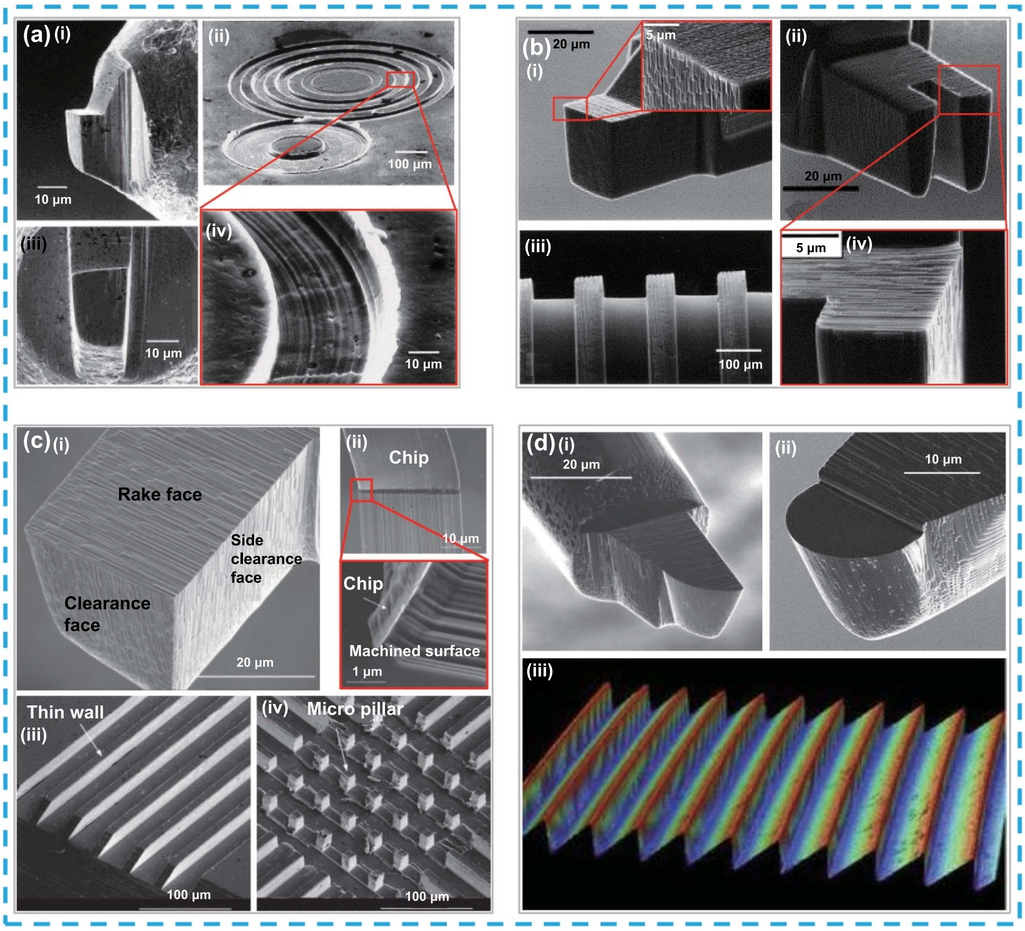

Figure 10. Different micro tools fabricated by FIB technology and their application in the machining of micro structured arrays: (a) micro cemented carbide turning tool and the machined microloops. Reprinted from [179], Copyright © 2000 Elsevier Science Inc. All rights reserved. (b) Micro diamond turning tool and the machined grooves. Reprinted from [149], Copyright © 2002 Elsevier Science Inc. All rights reserved. (c) Rectangular micro diamond turning tools and the machined microstructures and chip. Reproduced from [150]. © IOP Publishing Ltd All rights reserved. (d) Round nosed micro diamond turning tools and the machined Fresnel microstructures. Reproduced from [151]. CC BY 4.0.

from the binding of the diamond lattice and realizing material removal at the atomic scale [177]. FIB processing, with a very high resolution owing to the unique material removal mechanism, is available to realize material removal of several atom layers in a single processing operation, so the processing method is often applied in fabricating micro tools. Two decades ago, the first micro milling tool with a nose radius of 24 μm was successfully fabricated by using FIB technology at Sandia National Laboratory (SNL) in the United States for the machining of polymethyl methacrylate (PMMA) [178]. Subsequently, the cemented carbide [179] and diamond micro turning tools [149], which have a minimum characteristic dimension of 13 μm and a cutting edge radius of 40 nm, were also fabricated in SNL with the FIB processing method. The morphologies of the micro tools and the corresponding machined structures on the PMMA were illustrated in figures 10(a) and (b). Since then, FIB processing technology has been gradually promoted in the manufacturing of micro diamond tools. Singapore Institute of Manufacturing Technology [150] and Tianjin University [151] successively processed rectangular micro diamond turning tools and round nosed micro diamond turning tools by utilizing FIB technology, achieving a cutting edge radius of 30 nm. The micro diamond tools and the machined micro structure arrays are shown in figures 10(c) and (d). Sun *et al* [152] adopted FIB technology to prepare sub-micron cutting edge arrays on the cutting edge of a diamond tool, which was used to machine nano gratings efficiently.

FIB processing technology has flexible micro operability and is capable of fixed-point material removal, resulting in the convenience of preparing special-shaped micro tools or structured tools, that is, shaping the micro structures on tool cutting edges to form sub cutting edges or cutting edge arrays, as presented in figure 10(b). Compared with laser processing technology, the accuracy of arrayed micro diamond tools machined by FIB is greatly improved. However, the extremely insufficient material removal rate of FIB processing seriously restricts industrial applications [180]. In addition, due to the channeling effect [181] of FIB processing, obvious stripes remain on the micro diamond tool surface machined, as shown in figures 10(b)–(d), leading to a serious reduction of the tool surface finish and the cutting edge waviness. The

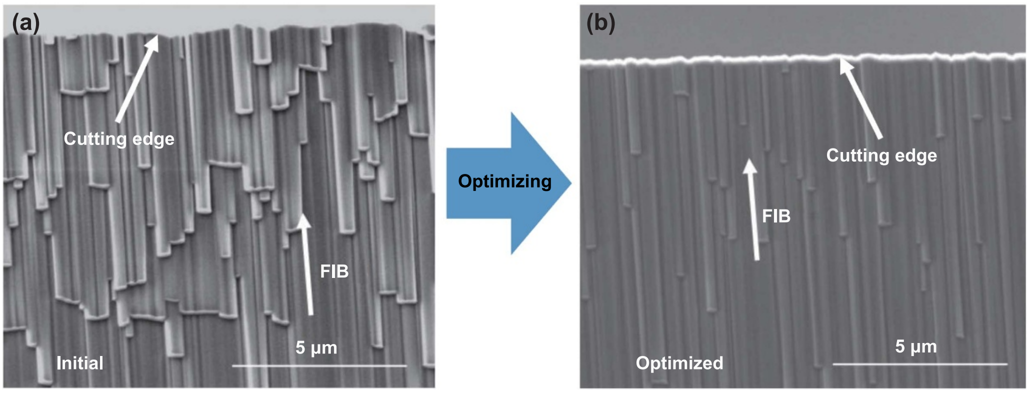

Figure 11. Surface texture of micro diamond tools induced by the channeling effect of FIB technology: (a) pre-optimized, (b) optimized. Reproduced from [150]. © IOP Publishing Ltd All rights reserved.

cutting edge sharpness and profile accuracy of the micro diamond tools are sharply reduced, and the cutting edge waviness increases correspondingly [182].

Imperfect cutting edge shape is duplicated onto the machined surface during the cutting process, forming the irregular tool marks and leading to an increase in machined surface roughness, as shown in the close-up view presented in figures 10(a) and (c). Although the channeling effect may be alleviated to some extent by optimizing the ion beam parameters, which yields the cost of further reducing the processing efficiency, the effect may not be removed completely, as shown in figure 11. For this reason, the poor consistency of cutting edges induced by FIB processing is another probable difficulty that restricts the industrial applications of FIB technology in micro diamond tool manufacturing. Moreover, limited by the principle of FIB processing, massive impurity atoms are implanted into the topmost surface of a diamond tool while high-velocity moving ions bombard the diamond surface, which distorts the lattice structure and forms amorphous defects. As a result, tool life shortens radically [183, 184].

5.3. Mechanical lapping

In the 16th century, mechanical lapping technology for diamond crystals was developed to process gems and jewelry for royal nobles. In 1901, a diamond crystal was made into a cutting tool with the mechanical lapping method to finish the optical components in ZEISS Co., Ltd [153]. From then on, a precedent was set for using diamond tools for machining. In the 1920s, Dr Tolkowsky treated the mechanical lapping of diamond crystals as a branch of science for deep investigation [185]. Because of the backward technique of machine tools, the performance advantages of diamond tools could not be perfectly utilized, and the mechanical lapping technology of diamond tools developed slowly at that time. Until the SPDT technology was invented and a classic ultra-precision machine tool, namely the hemispherical lathe, was successfully developed by Union Carbide Co., Ltd in 1962, diamond tools were gradually applied in the field of ultra-precision machining. After that, the industrially developed countries, including Europe, America, and Japan, vigorously developed the mechanical lapping technology of diamond tools [134, 154, 156]. In 1980, Wilks [186] analyzed the influence of diamond crystal anisotropy on the quality of mechanically lapped diamond tools and pointed out several technical issues and suggestions that should be paid attention to when designing and lapping diamond tools. Even now, those suggestions are still adopted as an important technical reference for diamond tool manufacturing engineers. In the 1990s, Yuan and Zhang were also engaged in the development of mechanical lapping technology for diamond tools in China [157–159]. Thereafter, the mechanical lapping technology was inherited and developed by Sun and Zong *et al* [70, 157, 160, 161] until now.

Mechanical lapping technology is the oldest and most mature processing method for diamond tool manufacturing. Up to now, it is also the only processing method that gives consideration to both efficiency and quality. Therefore, mechanical lapping technology is the most popular processing method for the current industrial production of diamond tools. Mechanical lapping of diamond tools is a compound process coupled with chemical, thermal, and mechanical effects, which adopts a high-speed rotating cast iron disc coated with diamond abrasive to ceaselessly grind the diamond tool faces to remove the material precisely. During the lapping process, the material of the topmost diamond surface undergoes squeezing, scratching, friction, thermal corrosion, and chemical diffusion [141, 187], which cause elastic deformation and lattice distortion on the topmost surface of the diamond tool to store the deformation energy. When the stored deformation energy of the C–C covalent bond reaches up to 5.5 eV [188], the breakage of C–C bonds takes place, causing a single C atom or cluster to separate from the surrounding C atoms. In such a way, the single C atom or cluster is plastically removed by the mechanical effect of the diamond abrasive to form chip fragments that remain on the iron disc surface or diffuse into the iron disc. In addition, the graphitization removal of diamond tool surfaces also occurs due to the shearing stress induced by squeezing and friction [189]. The above removal processes will continue until smooth tool surfaces and sharp cutting edges are prepared.

Xie and Bhushan [190] experimentally examined the dependence of material removal rate and surface quality on the grain size of diamond powder, lapping parameters, and properties of scaife in mechanical lapping of diamond crystals in 1996. Their experiment results demonstrated that the material removal rate and surface roughness are positively correlated with the grain size of diamond powder, lapping pressure, and the hardness of the scaife, while they are negatively correlated with the elastic modulus of the scaife. According to the experimental findings, they finally optimized the mechanical lapping process of diamond crystals. Field *et al* [134, 191, 192] summarized the development history of diamond crystal mechanical lapping technology over half a century and proposed a modern operation process for the mechanical lapping method in 2000. To date, all the process technologies for mechanical lapping of diamond tools widely used in industry are almost developed from the modern mechanical lapping method. In 2006, Higuchi *et al* [136, 162] replaced the traditional cast iron disc with a pure copper disc and conducted a series of mechanical lapping experiments to investigate the influence of lapping time on the diamond tool surface quality with the assistance of a heat source. Their experimental results proved that the improved lapping method is able to effectively diminish the micro chipping defects on the cutting edge that are induced by mechanical lapping. In 2008, Yasuo [163] achieved a rounded diamond turning tool with a nose radius of 3.9 μm and a cutting edge waviness of 50 nm on a special machine tool, according to his extensive experiences in mechanical lapping. In 2016, A.L.M.T. Corp. [14] reported that they were capable of machining micro diamond tools with different cutting edge shapes by utilizing mechanical lapping technology. The cutting edge sharpness of different tools for optical molds is superior to 50 nm, and the minimum nose radius of rounded tools is as small as 0.2 μm. Ultrahigh precision on-line measurement and calibration of the rotary center while manufacturing the rounded tool with a 0.2 μm radius are mandatory with the assistance of a special optical measurement system. In addition, the variation of ambient temperature has to be controlled superior to $\pm$0.03 °C, which is a rigorous condition and difficult to achieve. It should be noted that the rounded diamond tools with a nose radius of less than 1 μm are usually used as a V-shaped forming tool to fabricate the pyramid microstructures, V-shaped micro-groves, and cubic microstructures. Therefore, the tool feeding motions are usually intermittent, responding to the microstructure periods. The shaping of a rounded cutting edge is to improve the cutting edge strength and wear resistance. Besides, Yan *et al* [15, 48] used the micro diamond tools fabricated by the mechanical lapping method, as shown in figures 12(a) and (b), to manufacture microspheres and V-groove arrays on the oxygen free copper and NiP alloy, as shown in figures 12(c) and (d). Brinksmeier *et al* [12] also adopted mechanically lapped micro diamond tools with a nose radius of 1–10 μm to chisel cubic micro retroreflective mirror arrays on the 10 mm $\times$ 10 mm NiP alloy substrate. The reported investigations reviewed above confirmed the feasibility of the mechanical lapping method to process diamond tools for microstructure mold manufacturing and application.

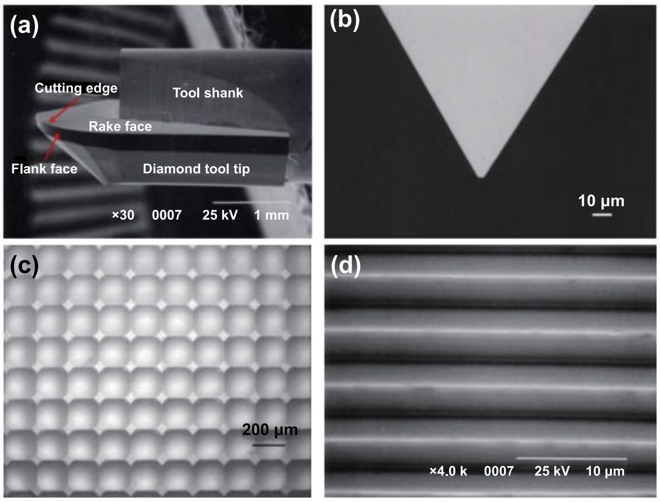

Figure 12. Micro diamond tools fabricated with the mechanical lapping method and the corresponding machined microstructured arrays: (a) micro milling tool. Reproduced from [48], with permission from Springer Nature. (b) Micro cutting tool. Reprinted from [193], Copyright © 2009 Elsevier B.V. All rights reserved (c) Microsphere arrays. Reproduced from [48], with permission from Springer Nature. (d) V-groove arrays. Reprinted from [193], Copyright © 2009 Elsevier B.V. All rights reserved.

Yuan *et al* [125, 158] proposed an optimized crystal orientation design method for diamond tools based on the anisotropy of the friction coefficient between diamond and different materials as well as the material removal rate in the mechanical lapping of diamond tools. Zhang *et al* [159, 164] examined the influence of lapping parameters on the diamond tool quality experimentally and found that the rotation accuracy of the spindle-scaife system is the essential factor affecting the lapping quality. As indicated by the findings, they invented a precision hydrodynamic spindle for mechanical lapping of diamond tools and performed an optimization of lapping parameters. Since the new millennium, research and production establishments ranging from colleges to factories have been involved in developing mechanical lapping technology, owing to the increasing demands for ultra-precision machining technology in different high-tech fields [194–198]. In 2010, Huang *et al* [199] carried out copious mechanical lapping experiments of diamond crystals on the reactive metal disc. The experimental results suggested that diamond crystals are more likely to react with titanium metal activated by the lapping heat, which is enormously conducive to improving mechanical lapping efficiency. However, the reactive metal disc was applied only to the rough lapping of diamond tools because of their underperforming surface quality. In 2019, inspired by the mechanical polishing process of single crystal silicon, Lu *et al* [200, 201] replaced the cast iron disc with a gel bonded disc, realizing the flexible consolidation of diamond powders to polish diamond crystal. The lapping experiments performed with the gel bonded disc demonstrated that flexible consolidation effectively reduces the subsurface damage of diamond crystal. Gel bonded disc polishing can be treated as a post-processing technology for mechanically lapped diamond tools

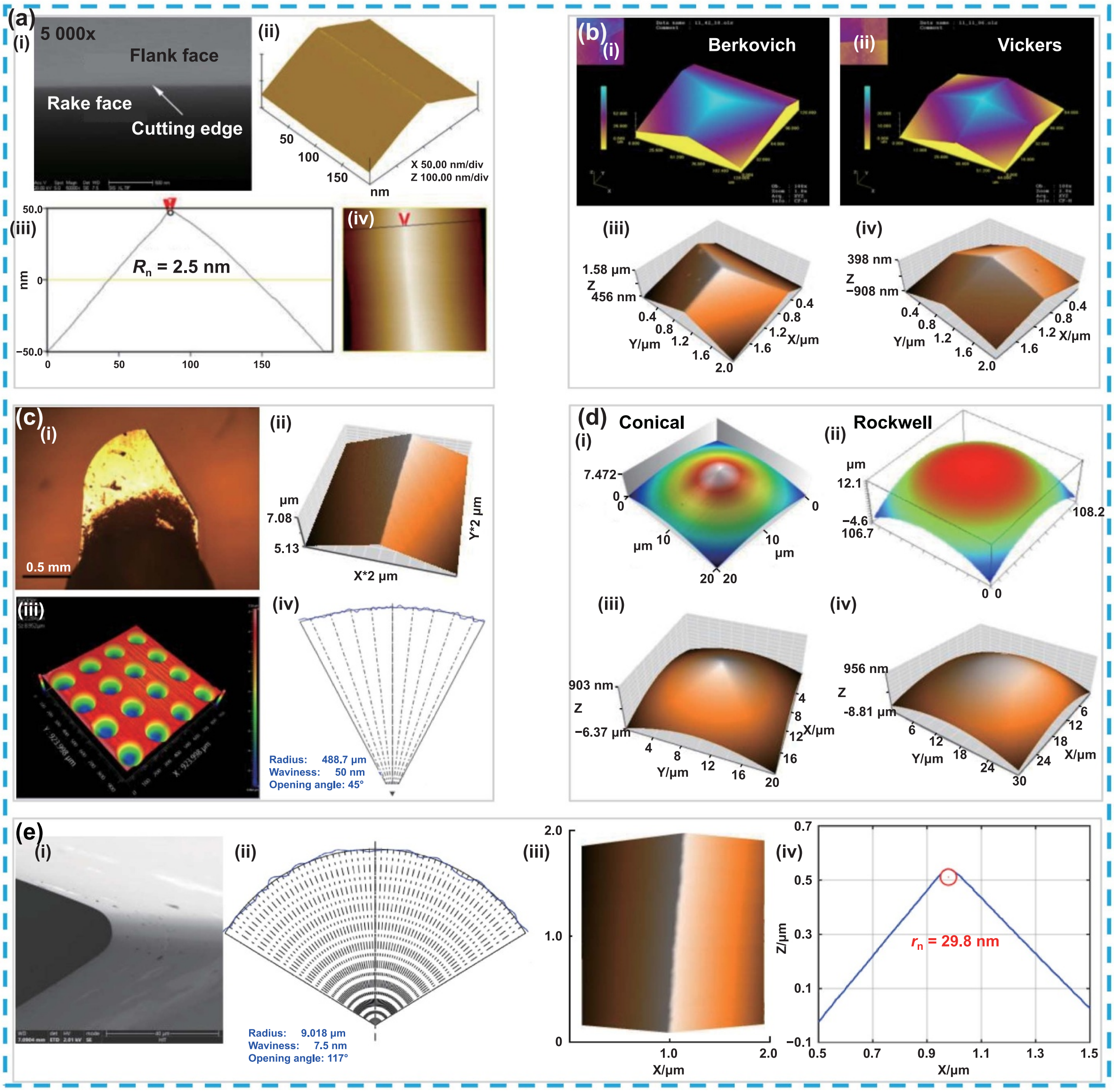

Figure 13. Research progress on mechanical lapping of diamond tools: (a) conventional diamond turning tool. Reprinted from [206], Copyright © 2006 Elsevier Ltd All rights reserved. (b) Pyramid diamond indenters. Reprinted from [207], Copyright © 2015 Elsevier Ltd All rights reserved. Reproduced with permission from [208]. Reprinted from [213], © 2017 Elsevier Ltd All rights reserved. (c) Micro diamond milling tool. Reproduced with permission from [71]. (d) Conical and spherical tipped conical diamond indenters. Reprinted from [212], © 2022 Elsevier B.V. All rights reserved. (e) Micro diamond turning tool.

to further improve tool surface quality. Recently, Zheng *et al* [202] carried out relevant research on the subsurface damage during the lapping process of diamond crystal with the high-speed dynamic friction lapping method. They found that the cleavage induced damage depth in the subsurface is up to 10 μm, which means their method can also be applied to the rough lapping of diamond tools.

In addition, systematic research on the mechanical lapping of diamond tools has also been performed in China. For example, the research groups of Sun and Zong developed a thermo-mechanical lapping method for diamond tools based on steel scaife to improve the lapping accuracy and efficiency [203] and proposed a generating method for complex lapping trajectory to improve the roughness of rake and flank surfaces [204]. They optimized the crystal orientation configuration scheme of diamond tools to increase the cutting edge sharpness and achieved the manufacturing of large nose radius diamond turning tools (nose radius: 0.5–2 mm) with a sharpness superior to 10 nm by adopting an extremely harsh lapping condition [205, 206], as presented in figure 13(a). Subsequently, they developed a semi quantitative control technology to improve the cutting edge of large nose radius diamond turning tools, which can be further used to regulate the cutting edge radius to restrain the severe tool wear. According to the theoretical calculations and mechanical lapping experiments, they disclosed the dependency of diamond material removal rate on the crystal plane and lapping direction during the mechanical lapping process and built a design method for diamond indenters, with which the Berkovich indenter [207] with an edge radius less than 25 nm and the Vickers indenter [208] with an intersection edge length less than 60 nm were shaped by utilizing the mechanical lapping method, as shown in figure 13(b). The Berkovich and Vickers indenters can be used for nanomachining [209, 210]. Besides, they have been capable of fabricating micro ball end diamond milling tools [71], conical diamond indenter used to manufacture nano arrays [211], and spherical tipped conical indenters [212], as demonstrated in figures 13(c) and (d). Recently, two kinds of components have been needed to realize specific physics experiments. One is a sphere component covered with an arrayed spherical dimple with a radius of less than 10 μm. The other is a planar component covered with sinusoidal grids with a wavelength of less than 50 μm and an amplitude larger than 3 μm. Both components have to be fabricated by a micro diamond tool with a radius of less than 10 μm. In response to this demand, the research groups of Zong have been able to manufacture the micro diamond turning tools with a sharpness of 20–40 nm and a cutting edge waviness of 10 nm over an opening angle of 117° by using the mechanical lapping technology, as presented in figure 13(e).

It should be noted that mechanical force (or grinding force) always goes with the material removal process in mechanical lapping. Therefore, subsurface damage to the cutting edge and tool surface is inevitable, such as micro-cracks or micro-cleavage and amorphization or graphitization, which is harmful to the improvement of tool wear resistance. Moreover, the grinding force is to the detriment of the tool tip integrity because tool tips, especially those with a large aspect ratio, will fracture in the action of the grinding force. In addition, during the mechanical lapping of micro diamond tools, lapping heat is generated due to the friction between the scaife and diamond tools, resulting in the amorphization and graphitization on the micro diamond tool surface and decreasing the tool wear resistance. Therefore, coolant has to be used to reduce the thermal effects of the mechanical lapping.

6. Conclusions and future directions

6.1. Conclusions

In summary, the manufacturing methods of micro diamond tools mainly include laser processing, FIB milling, and mechanical lapping. Laser processing with high efficiency can be used for the preparation of sub cutting edges and submicron cutting edges owing to the absence of mechanical force, but the tool edge quality is not good enough for ultra-precision machining. Therefore, laser processing is usually used as a rough forming method. FIB milling is free of mechanical force, so it can also be employed for the fabrication of sub cutting edges and submicron cutting edges. As compared to the laser processing method, the cutting edge quality produced by FIB milling is greatly improved. Unfortunately, the cutting edge consistency is poor because of the channeling effect. What's worse, the processing efficiency is so low that it is difficult to promote industrial applications. The mechanical lapping method has satisfactory quality and efficiency, and it is currently the most popular solution for the manufacturing of micro diamond tools in industry. However, mechanical lapping also has some shortcomings, such as the appearance of tool tip fracture and qualification rate reduction, due to the negative effect of mechanical force as the characteristic dimension decreases, resulting in an increment in lapping difficulty, which may be solved by the force feedback sharpening technology. In addition, it is also difficult to acquire multi sub cutting edges.

The design of micro diamond tools has to consider the application backgrounds, which have different requirements for tool geometries and performances. Tool geometry design shall comprehensively consider the shape of the microstructures to be processed and the properties of the workpiece material. Under the condition without tool interference, tool geometric parameters that are conducive to improving tool edge strength should be selected in order to increase tool durability. Tool performance design is relatively complex. In the case of micro diamond tools used for large size component machining, such as roller molds, tool wear resistance is more crucial for the consistency of machining quality. The orientation configuration should ensure that the hard direction of the diamond crystal is parallel to the cutting direction over the whole cutting edge, in order to achieve the best wear resistance. Moreover, the cutting edge waviness and sharpness should be improved as much as possible by optimizing the lapping process. In the case of micro diamond tools used for small size component machining, such as mold inserts for mobile phones, the negative influence of tool wear on the machined surface quality can be ignored due to the limited cutting distance. In this case, the cutting edge waviness is more important than the wear resistance to meet the high requirement for form accuracy of the machined inserts. In addition, the orientation configuration of micro diamond tools should ensure that the whole cutting edge has a uniform strength distribution along the lapping direction to achieve excellent cutting edge waviness. In the case of micro diamond tools used for ultrathin cutting, the utmost attention should be paid to the cutting edge radius, because the minimum undeformed chip thickness is proportional to the cutting edge radius. The orientation configuration should ensure that the whole cutting edge has the highest strength in the lapping direction to obtain an extremely sharp cutting edge. The summary of the work is expounded in figure 14.

6.2. Future directions

Currently, suppression for the heavy wear of micro diamond tools is an urgent technical difficulty, which seriously limits the development of large-scale microstructure surfaces. In the future, more efforts need to be made in this field. The authors believe that the following aspects are worth concerning:

(a) ***Tool orientation design.*** The existing tool orientation design method is mainly based on several typical crystal orientations, which means that the current design method is a locally optimal solution. However, in order to further improve the performance of micro diamond tools,

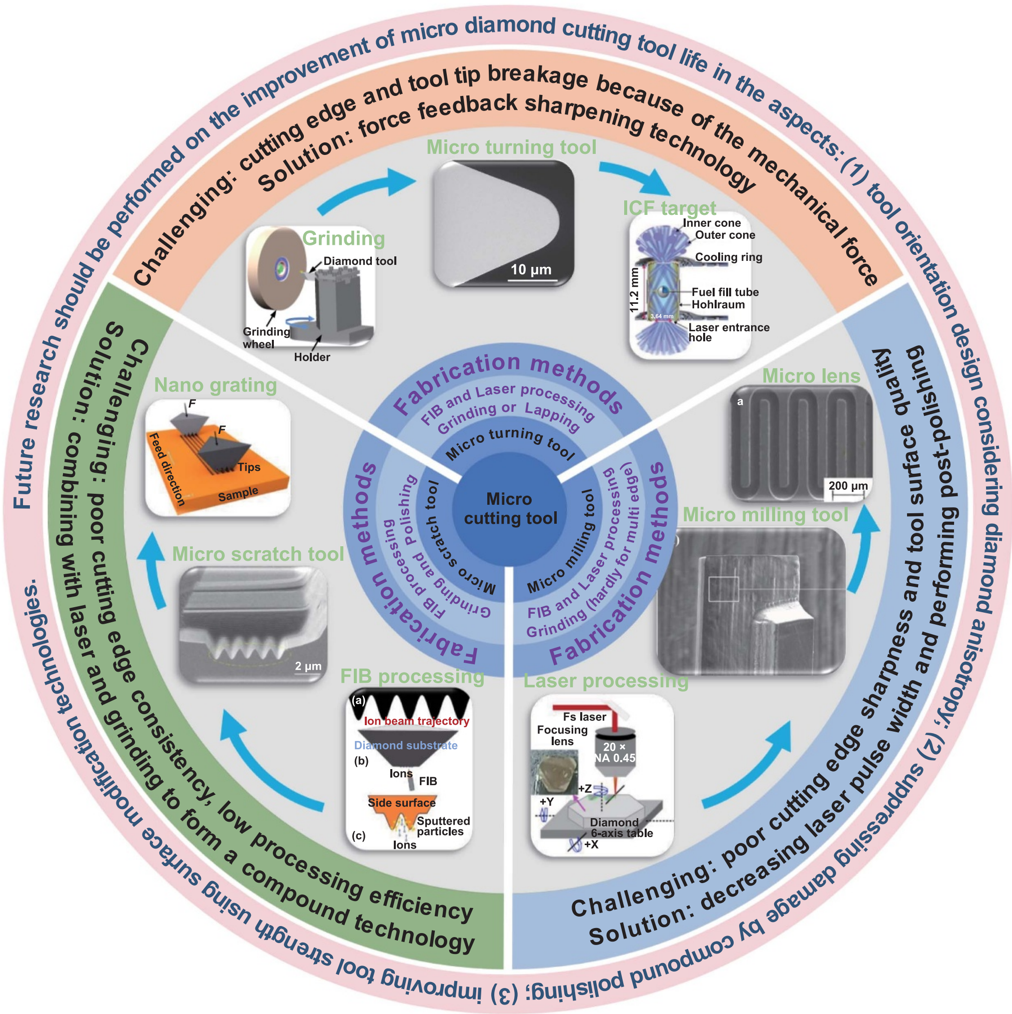

Figure 14. Summary and future development directions for the design and manufacturing of micro diamond cutting tools. Reprinted from [147], © 2021 Elsevier Ltd All rights reserved. Reproduced from [214]. CC BY 4.0. Reprinted from [215], © 2020 The Society of Manufacturing Engineers. Published by Elsevier Ltd All rights reserved. Reprinted from [216], © 2016 Elsevier Inc. All rights reserved. Reproduced with permission from [217].© IMechE 2022. Reprinted from [218], © 2021 The Society of Manufacturing Engineers. Published by Elsevier Ltd All rights reserved.

numerous theoretical calculations are required for general crystal orientations to search for the global optimal solution. In such a way, the purpose of both good machinability and wear resistance may be achieved.

(b) ***Suppression of damage.*** Damages and defects are inevitably generated in the tool subsurface due to the mechanical force of diamond grit in the lapping process, which should be suppressed as much as possible. Compound polishing may be an effective solution, such as chemical assisted polishing, thermo-chemical assisted polishing, plasma assisted polishing, and oxidative assisted polishing, in order to remove damages and defects.

(c) ***Tool strengthening treatment.*** The damages and defects in the tool subsurface that formed in the lapping process can be repaired with some post processing technologies, such as thermo-chemical refinement, by providing an environment for weak oxidation and physical annealing of damaged diamond carbons. Tool surface modification with ion implantation technology, through which the atomic density of the lattice can be increased to improve the surface strength and reduce the surface energy and friction, is another effective approach to strengthening micro diamond tools.

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Conflict of 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.

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