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REVIEW

Application and development of bonnet polishing technology

Pengfei Zhang, Zhenzhong Wang,* Xuepeng Huang, and Hao Zhang
Xiamen University, Department of Mechanical and Electrical Engineering, Xiamen, China

ABSTRACT. Since the proposal of bonnet polishing technology, it has been widely used in the surface polishing of various high-precision curved components. Because of its unique polishing tools and polishing method, it has the characteristics of high polishing efficiency and high polishing accuracy. Therefore, bonnet polishing technology is particularly important in engineering applications. We mainly review the research progress of bonnet polishing technology in the past 10 years, including the introduction of bonnet polishing technology applied to important engineering projects such as the European Extremely Large Telescope, the main mirror of Japan's next-generation space telescope, the Shenguang-III mainframe unit, and the artificial skeleton. We summarize the key technologies of bonnet polishing technology such as removal mechanism, removal function, motion control, process control, and software development according to the typical applications of bonnet polishing technology. Finally, the current limitations are summarized according to the characteristics of bonnet polishing technology, and the development trend of bonnet polishing technology is also foreseen, hoping to provide a reference for the subsequent in-depth research of bonnet polishing technology.

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Keywords: bonnet polishing; removal mechanism; removal function; motion control; tool wear; medium-frequency error

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1 Introduction

High-precision surface components, particularly high-precision optical components with superior optical performance, are crucial basic components in many major projects within the aerospace and military defense fields. The demand for these components is significant, and they play a vital role in national security. Therefore, the development of ultra-precision batch processing for these components is highly important.

In recent years, significant progress has been made in the ultra-precision machining of high-precision optical components for major optical projects in the military and national defense fields, such as the Shen Guang project and large astronomical telescopes. This progress encompasses various machining methods, including ultra-precision grinding, computerized numerical control (CNC) small tool polishing (STP), magnetorheological polishing, ion beam polishing (IBP), and bonnet polishing. In addition, a "high-efficiency grinding + precision polishing + low defect manufacturing" batch processing technology chain[1] has been formulated. The precision polishing process represents the critical link in the entire process chain, where its efficiency significantly influences both the capacity and cost of producing high-precision optical components.

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*Address all correspondence to Zhenzhong Wang, wangzhenzhong@xmu.edu.cn

Following the grinding process, optical components exhibit numerous surface errors, particularly within the mid-frequency and high-frequency ranges. Efficient trimming during precision polishing is essential to mitigate these errors, thereby reducing the overall frequency band error of the optical components. In addition, the size of the optical component's aperture dictates the selection of an appropriate polishing spot size, necessitating the use of polishing tools of varying dimensions. Furthermore, due to the diverse geometry and curvature of optical components, polishing tools must possess a certain level of flexibility to adequately conform to variations in surface shape. Last, during the polishing of optical components, it is imperative to regulate the removal efficiency of the polishing tool in accordance with the principles of computer-controlled optical surfacing technology.

At a technical level, various polishing technologies for optical components have rapidly developed in recent years to meet processing needs. These include chemical mechanical polishing (CMP), STP,[2] magnetorheological finishing (MRF),[3] IBP,[4] and fluid jet polishing (FJP).[5] Furthermore, in terms of structural features, technologies such as chemical mechanical polishing, CNC STP, and robotic polishing use relatively simple equipment. However, the tool surface often cannot perfectly match the aspheric workpiece, which can affect the surface quality of the polished product. Consequently, bonnet flexible polishing technology has been proposed and implemented. This method uses a flexible bonnet as the polishing tool, allowing the polishing head to better match the surface of the workpiece. With adjustable bonnet inflation pressure and high spindle speed, this technology offers improved polishing efficiency and greater control over surface quality, making it a promising method for efficient polishing. The characteristics of various polishing technologies are shown in Table 1.

In the 1990s, bonnet polishing technology was jointly proposed and developed by the ZEEKO company and the University College London, led by Walker et al.,[6,7] to apply bonnet tools for polishing optical components. This equipment enables seven-axis control of the five-axis linkage, as evidenced by the reported experimental results in the literature. Subsequently, scholars from the University of Huddersfield, Chubu University in Japan, the Hong Kong Polytechnic University, Xiamen University, Harbin Institute of Technology, Zhejiang University of Technology, and other scientific research institutions continued to study and master the key technologies of bonnet polishing. Simultaneously, bonnet polishing technology has been applied to various fields and has reached an advanced stage of development. Bonnet polishing, as an efficient precision polishing technology, is gaining increasing attention due to its attributes of excellent flexibility, high removal efficiency, and controllable accuracy. It can be applied for uniform polishing with high-efficiency removal and corrective polishing for achieving desired surface shapes. However, the technology is still undergoing continuous improvement and requires further research by scholars.

This paper summarizes research on bonnet polishing technology over the past decade, focusing on its application areas, technical characteristics, key technologies, and current development limitations and presenting the summarized schematic diagram in Fig. 1. The paper outlines the

Table 1 Comparison of different polishing technologies.

Polishing technology	Advantages	Disadvantages
CMP	High surface planarity, high material removal precision	High cost, tool wear, high equipment costs
STP	Low cost, replaceable grinding head	Tool wear, SSD, edge effect, MSF errors
MRF	High polishing precision, no tool wear, no SSD, no edge effect	High equipment costs, low polishing efficiency, MSF errors
IBP	High accuracy of surface convergence, stable removal function, no SSD, no edge effect	High environmental requirements, high equipment costs, low polishing efficiency
FJP	High flexibility and wide range of processing materials	Poor polishing quality, low polishing efficiency, and unstable removal function
BP	Wide processing range, low cost, high flexibility, high polishing efficiency	Edge effect, MSF errors

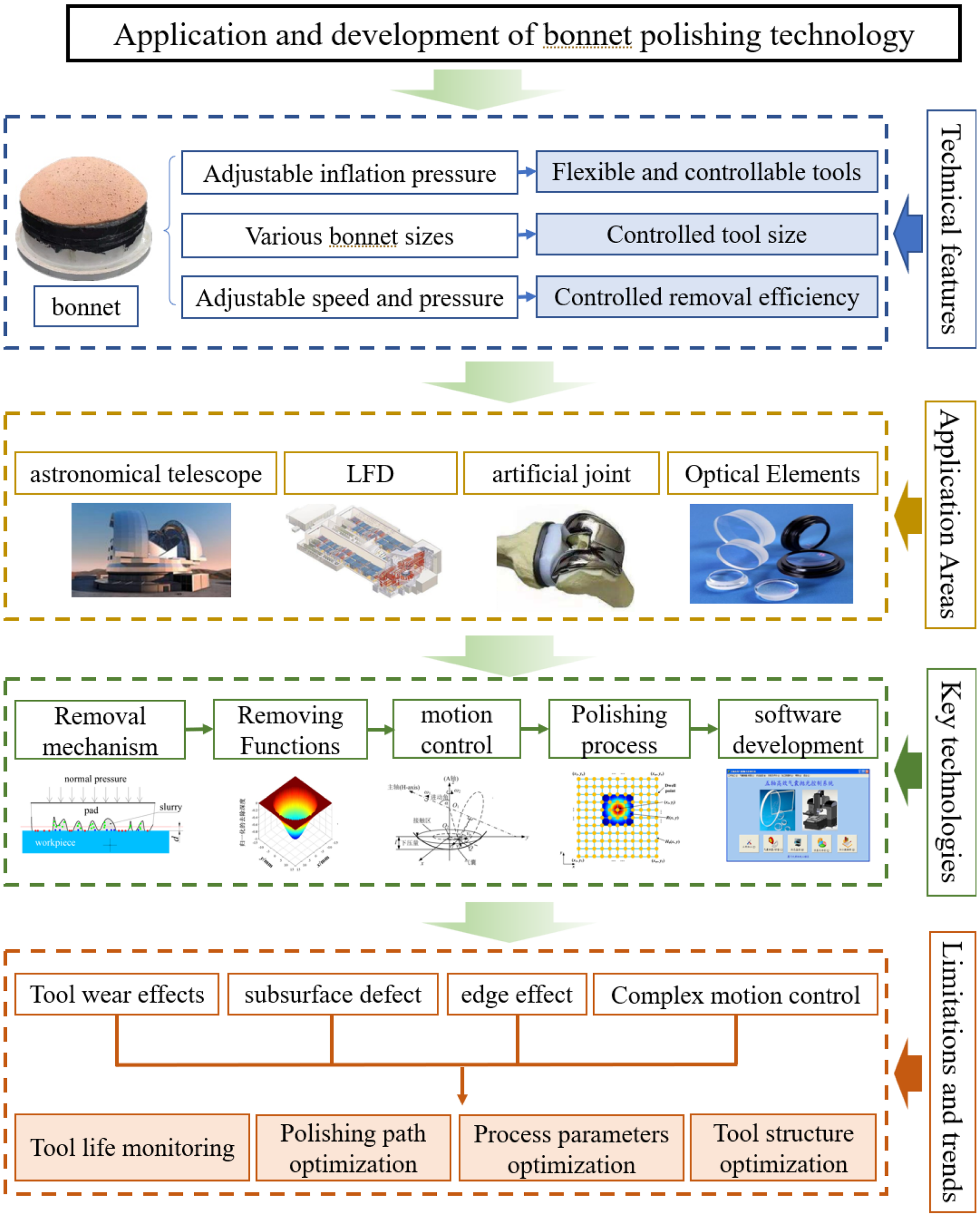

Fig. 1 Summary diagram of bonnet polishing technology.

future development direction of bonnet polishing technology, offering guidance for its advancement and serving as a reference for peers in the field.

2 Advantages and Application of Bonnet Polishing Technology

Bonnet polishing technology applied to aspheric workpieces is summarized as follows: Utilizing polishing equipment much smaller than the workpiece, the tool is employed for aspheric processing, based on quantitative surface shape detection data and a motion control model for polishing. Polishing is controlled by a computer along a specified path, speed, and pressure. The workpiece surface is illuminated, enabling precise control over material removal through the management of removal function residence time, improving the local surface shape to meet final accuracy requirements.

2.1 Advantages of Bonnet Polishing Technology

Bonnet polishing is a deterministic precision polishing technology suitable for the rapid and precise polishing of curved components. From Zhejiang University of Technology Timing, Ji Shiming et al.[8] reviewed the current status of research on deterministic polishing technology. Bonnet polishing, performed outside the confines of a polishing cloth package, serves as the polishing work surface. This approach ensures better contact between the bonnet and mold surfaces, resulting in a larger polishing area. In addition, the hollow structure of the bonnet polishing tool enables real-time control of contact flexibility between the tool and the contact surface. Thus, bonnet polishing technology offers strong controllability during the machining process, facilitating material removal homogenization and micritization. Jinwei et al.[9] from Beijing Institute of Technology designed and validated experiments for the existing bonnet polishing progressive motion control method. They ultimately achieved a workpiece surface of high quality, aligning with the requirements, thereby proving the feasibility and effectiveness of the existing motion control method. Zhenzhong et al.[10] from Xiamen University conducted a study on the controllability of the stiffness of the bonnet polishing tool. They analyzed the factors affecting the stiffness of the tool and its impact on the polishing process. Subsequently, they performed algorithmic design and simulation experiments, demonstrating that by presetting the standard value of stiffness according to requirements, the stiffness of the bonnet polishing tool can be controlled by adjusting the workpiece's reaction force on the tool.

Meanwhile, the flexible structure of the bonnet allows for better contact with the workpiece surface, and its shape adapts well. Fei et al.[11] from the Chinese Academy of Sciences achieved a processing data alignment accuracy of 0.30 to 0.70 mm by controlling the motion accuracy of the processing equipment and the bonnet position, thereby reducing the relative deviation of the bonnet's position with the workpiece to within 10 μm during processing. This method realizes the ultra-high precision face shape correction capability of bonnet polishing and achieves a surface shape correction capability of 0.8 nm [root-mean-square (RMS)] using the bonnet polishing equipment. The bonnet polishing equipment has achieved a surface shape correction result of 0.8 nm (RMS), providing an effective method for processing ultra-high-precision spherical and aspherical optical components.

Finally, the bonnet polishing technology can adjust polishing pressure and rotational speed to greatly enhance polishing efficiency. Xiamen University researchers, led by Tao et al.,[12] investigated the characteristics of bonnet polishing, analyzing spot size, shape, and material removal—the three primary aspects of the polishing process. Through fixed-point polishing experiments, they observed that the removal efficiency initially increased with inflatable pressure and then gradually decreased before rising again, correlating with the compression and bonnet speed.

2.2 Main Applications of Bonnet Polishing Technology

Due to its unique advantages, bonnet polishing technology is widely utilized in the polishing process of various components. Yu et al.[13,14] proposed a new bonnet polishing method based on power spectral density analysis and filtering theory. This method overcomes the challenge of eliminating mid-frequency errors in polishing and can address grinding errors in the spatial wavelength range of ∼1 to 50 mm. The technology is applicable to the European Extremely Large Telescope,[15,16] a next-generation ground-based telescope being developed by the European Southern Observatory (ESO), as illustrated in Fig. 2(a). The James Webb Space Telescope (JWST) features a primary mirror with a diagonal length of 6.5 m and is composed of 18 hexagonal submirrors, encompassing an area more than five times larger than that of the Hubble Space Telescope (HST),[17,18] as shown in Fig. 2(b). Namba et al.[19] from Kyoto University utilized sub-aperture jet and bonnet polishing technology, and with the aid of a seven-axis CNC polishing machine, they manufactured a chemically nickel-plated aspheric mandrel workpiece with a surface roughness of only 0.6 to 0.8 nm. This surface roughness meets the requirements for ultra-precision polishing technology, applicable from industrial machining to manufacturing the main mirror of the next-generation space telescope in Japan. Based on the Shenguang-III host project, major domestic enterprises have made a significant breakthrough in the development of large-scale polishing equipment. They have successfully addressed key technical challenges, including accurate motion control, high-precision design and assembly, and morphology control. As a result, they achieved the manufacture of Φ600-mm flat precision workpieces with a surface accuracy better than $\lambda/10$, thereby narrowing the gap between foreign countries and the domestic field.[20] Blunt and Racasan[21] utilized bonnet polishing technology to replace the traditional human bone machining process, as depicted in Fig. 2(c). They completed the manufacturing

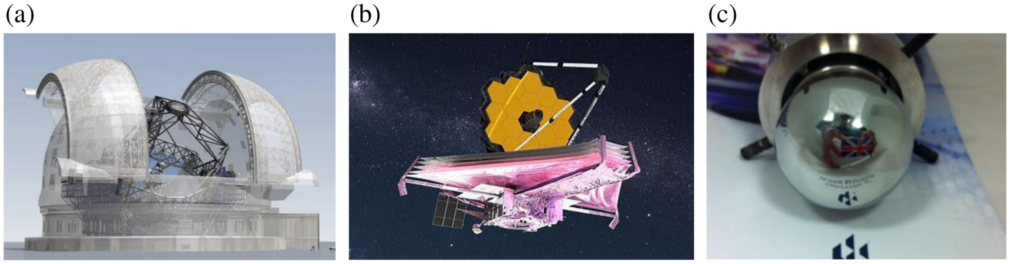

Fig. 2 Application examples of bonnet polishing technology. (a) European Extremely Large Telescope; (b) The James Webb Space Telescope; (c) Artificial joint.

of a new humeral head with multiple radii. The surface roughness of the new humeral head manufactured using bonnet polishing technology is only 16.1 nm. This method offers advantages, such as good surface quality, high precision, and significant enhancement of the lubrication performance of artificial bone, validating bonnet polishing technology as a feasible method for achieving high-precision machining of artificial bone arms. The feasibility of bonnet polishing technology in achieving high-precision processing of artificial bone has been verified. Zhi et al.[22] from the University of Electronic Science and Technology designed a bonnet polishing grinding head device based on the Princeton equation and Hertzian contact theory. They verified the accuracy of the mathematical model of the removal function by conducting single-point and multi-point polishing experiments on SiC components. Finally, they found that after seven cycles of rough and fine polishing processing experiments, the face shape convergence rate was 69.4% and 51.9%, and the face shape accuracy peak-to-veally (PV) was 570.1 nm, and RMS was 62.3 nm, respectively. Ath et al.[23] from Kyoto University applied bonnet polishing technology to EUV lithography photomask substrate calibration processing. They proposed a precision bonnet polishing process capable of achieving a PV of less than 50 nm while maintaining surface texture below 0.5 nm RMS, with a polishing time between 15 and 45 min. Ri et al.[24] from Xiamen University designed and manufactured a controllable bonnet polishing system for large-diameter aspherical components tailored to their specific processing requirements. Through processing experiments, they demonstrated that after 24 h of polishing, the system achieved a surface roughness of $0.068\,\lambda$ ($\lambda = 632.8$ nm) and a PV value of $0.905\,\lambda$ for the high-precision optical element.

3 Key Technology of Bonnet Polishing

The bonnet polishing technology, widely employed in various precision component polishing processes, has yielded high-quality polishing results and enhanced efficiency. Bonnet polishing technology can be extensively applied to polish various materials and types of precision components. Its essence lies in the ongoing exploration by numerous scholars into key aspects such as material removal mechanisms, removal characteristics, process control, intermediate frequency errors, and the development of motion control systems.

3.1 Bonnet Polishing Process Material Removal Mechanism

The polishing force is a crucial parameter influencing removal characteristics. Investigating the role of polishing force in the material removal process can directly characterize the effectiveness of bonnet polishing, reflecting the state of the tool system during polishing and quantifying processing stability, tool wear, and other processing state information.

The tool influence function (TIF) is commonly utilized to assess the removal characteristics of the polishing tool. Studying the relationship between the polishing force and the removal function is a key method for elucidating the material removal mechanism of the bonnet polishing process. This relationship is illustrated in Fig. 3.

3.1.1 *Relationship between polishing force and removal function*

Ri et al.[25] proposed a methodology to investigate the relationship between polishing force and material removal function. They measured the bonnet polishing force and computed the

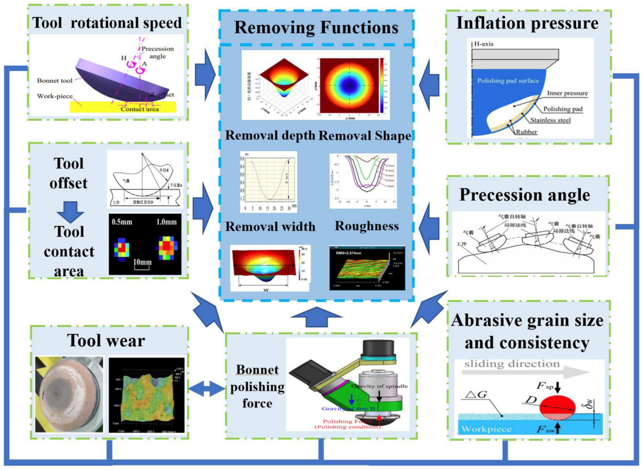

Fig. 3 Plot of polishing force and TIF.

coefficient of friction using a three-dimensional dynamometer. This approach aimed to analyze how four key parameters—spot size, tool rotation speed, internal pressure of the tool, and tool surface conditions—affect the removal of workpiece material in terms of force and friction, offering insights for optimizing the polishing process. Hongyu et al.[26] employed the finite element method (FEM) to elucidate the correlation between polishing force and material removal function, as illustrated in Fig. 3. They utilized FEM to derive the pressure distribution in the Preston equation and the velocity distribution based on the progressive motion geometry. This enabled the simulation of static and dynamic TIF for predicting TIF. In addition, they conducted direct force measurements to validate the finite element analysis results, obtaining a polishing force simulation error of 4.3%, which was experimentally verified. Both static and dynamic TIF residuals were found to be less than 5%.[27]

3.1.2 *Polishing force influencing factors and its effect on polishing effect*

In the current contact polishing technology, the polishing force directly influences its effectiveness. Therefore, many scholars have investigated the relationship between bonnet polishing force and polishing outcomes. Zeng and Blunt[28] applied bonnet polishing technology to process medical cobalt–chromium alloy, experimentally examining the impact of four process parameters: processing angle, tool head speed, tool offset, and tool pressure, on polishing force and material removal. They analyzed the correlation between polishing force and material removal rate, finding that both the normal and tangential components of the polishing force contribute to material removal, with tangential force showing a stronger correlation with the width of the influence function, and normal force exhibiting a stronger correlation with the maximum height of the influence function.

Tool wear directly influences force fluctuations. Bo et al.[29] determined the friction coefficient by measuring force signals with a three-component dynamometer. They concluded that the friction coefficient trends similarly to removal rates, suggesting that reduced friction coefficient due to tool wear is a significant factor in decreased removal efficiency. Bo et al.[30] compared the polishing force of bonnet tools using different polishing pads, investigating their correlation with tool removal characteristics. They found that polishing pad dressing improves bonnet contour error, increasing tool-workpiece friction while reducing cyclic polishing force amplitudes and enhancing TIF. Cao et al.[31] incorporated the strong time-varying factor of bonnet tool mechanical properties into the contact pressure calculation model, revealing significant time variations in pressure distribution influenced by polishing depth and rotational speed in the polishing zone. Yang et al.[32] developed an error model for progressive mechanism effects on polishing points, using finite element simulation to assess mechanism deformation due to gravity and polishing force. Their MATLAB simulation analyzed its impact on polish quality, offering a basis for optimizing polishing mechanisms.

Li et al.[33] proposed a new bonnet polishing technology based on the concept of flexible polishing to enhance the efficiency and quality of mold free-form surface polishing. They studied the movement trajectory, pressure distribution, and polishing force distribution of abrasive grains in the bonnet polishing contact area. They established a movement model and a pressure model for abrasive grains in the bonnet polishing contact area, revealing the influence of abrasive grain diameter on polishing force and shear stress within the workpiece. They investigated shear stress distribution within the workpiece during polishing and clarified the fatigue removal mechanism, providing a theoretical foundation for bonnet polishing application.

3.1.3 *Polishing force control method*

To achieve a stable polishing force, effective prediction and control methods are essential. Pan et al.[34] developed a semi-quantitative prediction model for TIF efficiency based on polishing force, which was validated through experimentation and successfully forecasted TIF efficiency trends. Subsequently, online collected polishing force data were utilized to predict TIF spot shape and efficiency, aiming to enhance bonnet productivity by minimizing offline measurement time. Sha, Shi et al.[35–37] proposed a bonnet polishing method utilizing magnetorheological torque servoing (MRT) for polishing force control. They established the relationship between load torque and polishing force, leading to the development of a theoretical model for removal rate determination. By utilizing real-time output from the magnetorheological torque servo device and indirectly detecting torque, they obtained polishing force data, compared them with theoretical torque, and controlled MRT output torque for polishing force detection and control, simplifying the bonnet polishing system's control mechanism. Schneckenburger et al.[38,39] proposed a method utilizing MRT for polishing force control. They suggested installing speed and torque sensors on the polishing head, alongside tilt and force sensors, to measure polishing pressure correlation for processing evaluation. Using these data, machine learning algorithms were applied to predict machined part surface quality, reducing polishing iterations and shortening production time. Yuhai et al.[40] proposed a dual-head flexible constant-force blade polishing process called the "three-axis, two-linkage line polishing method" for turbine blades. They analyzed and explored principles behind generating polishing paths, controlling polishing speed and force, and developed a turbine blade polishing machine utilizing a bonnet as a tool head. This method enables two flexible polishing heads to simultaneously conduct constant-force flexible polishing on the blade's leaf basin and back, effectively ensuring polishing quality and improving production efficiency.

3.2 Process-Oriented Precise Regulation of Removal Characteristics

The bonnet polishing force mentioned above represents a crucial process parameter, significantly influencing the material removal mechanism. Understanding this force is vital for studying material removal mechanisms. Furthermore, deterministic polishing should not only investigate the polishing force in the bonnet polishing process but also concentrate on modeling the fixed-point removal characteristics of the bonnet tool. Refer to Fig. 4 for specific details.

3.2.1 *Microscopic abrasive removal effect*

In the realm of ultra-precision polishing, primary processing methods encompass CMP, bonnet polishing (BP), FJP, and IBP. Among these, CMP and BP share commonalities in material removal mechanisms, as illustrated in Fig. 5.

The CMP method is commonly employed for flat-plane polishing. The polishing contact area is divided into sub-aperture and full-aperture regions. Throughout the polishing process, a chemical reaction occurs between the polishing liquid and the workpiece surface material, altering the material properties to facilitate material removal. Mechanically, the polishing head engages in relative motion with the workpiece, enabling abrasive particles in the polishing liquid to remove surface material, thereby achieving high polishing efficiency. Due to its material removal mechanism, it is imperative to select an appropriate polishing solution based on the workpiece material before processing. In addition, the polishing pad and abrasive particles in the polishing solution must not chemically react.[41–43,44] The BP method uses a special polishing tool structure consisting of a metal base, rubber layer, and polishing pad. The polishing pad is

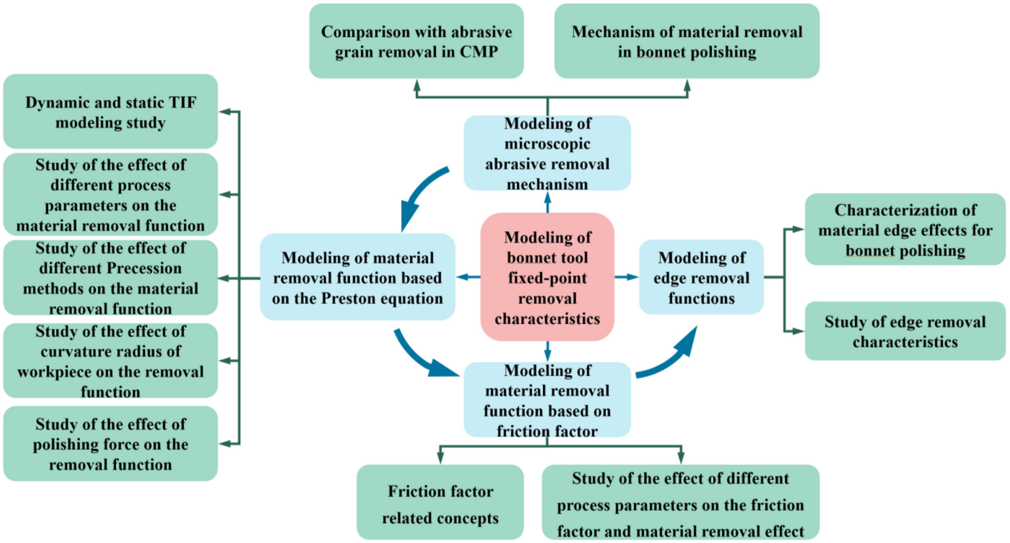

Fig. 4 Modeling of fixed-point removal characteristics of bonnet tools.

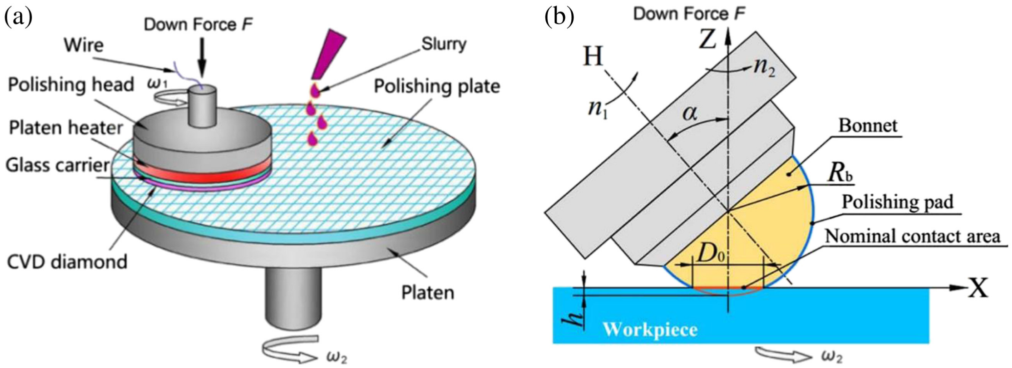

Fig. 5 Schematic diagram of CMP and bonnet polishing. (a) CMP and (b) Bonnet polishing.

affixed on top of the rubber layer, and the polishing tool is inflated with a certain pressure gas. As shown in Fig. 2(b), during precession polishing, the tool spindle consistently rotates and always holds a posture with a fixed angle to the local normal of the workpiece, which is referred to as the precession angle. The removal principle involves introducing polishing materials into the pores of the polishing fluid layer within the abrasive. The rotation of the bonnet tool head, combined with downward pressure, facilitates the extrusion process, leading to the removal of the workpiece material through friction and scraping by the abrasive particles. Unlike CMP, bonnet polishing is better suited for polishing curved workpieces. As bonnet polishing technology advances, it ensures the certainty and stability of material removal, garnering increasing attention.

Cao et al.[31,45] experimentally determined the removal mechanism of bonnet polishing on the workpiece. Their findings suggested that abrasive particles in the polishing solution predominantly contributed to workpiece removal. They observed a linear relationship between residence time and material removal rate, proposing the alleviation of material removal by the polishing pad to achieve better surface quality. In addition, they developed a multiscale prediction model for the material removal characteristics of bonnet polishing, which was validated through experiments. Their analysis identified tool offset, precession angle, and spindle speed as key factors influencing the material removal rate.

Shi et al.[46,47] elucidated the material removal mechanism of the bonnet polishing process at the microscopic scale, utilizing the microscopic contact theory and friction theory. They considered the abrasion effect of polishing pads and developed a model for the removal of abrasive particles in the polishing solution and micro-convex bodies on the surface of polishing pads.

This model was compared with the traditional Preston equation through experiments, revealing a nonlinear relationship between the process parameters and material removal. Comparing with the traditional Preston equation through experiments better illustrated the nonlinear relationship between process parameters and material removal.

Lin et al.[48] proposed a method for predicting bonnet surface morphology, which is based on the micro-contact behavior between the polishing pad and the workpiece surface, as well as the material removal characteristics. They established a prediction model for material removal and validated its correctness through experiments with various polishing parameters. Building upon this, they suggest, based on simulation results, that the average radius and distribution of micro-bumps on the polishing pad surface affect the material removal rate. Controlling these factors effectively enhances polishing efficiency.

Building on the aforementioned research, this study clarifies the material removal mechanism in the bonnet polishing process. It demonstrates that abrasive particles in the polishing liquid primarily remove material from the workpiece surface. In addition, process parameters such as bonnet offset, precession angle, and spindle rotation speed significantly impact the removal effect. To elucidate the influence of these parameters on material removal, several scholars have investigated material removal function modeling based on the Preston equation.

3.2.2 *Modeling of material removal function based on the Preston equation*

The Preston equation, introduced by F. W. Preston in 1927 and represented by Eq. (1), serves as the foundation. Li et al.[49] conducted pressure simulations of a single-point polishing spot using finite element simulation software. They validated the simulation model's accuracy through experiments measuring single-point forces. Building on the inlet polishing process and the Preston equation, they established both dynamic and static TIF models, which were subsequently validated through experiments.

$$\Delta h(x,y) = k \cdot p(x,y) \cdot \nu(x,y), \tag{1}$$

where Δh is the amount of material removed per unit time, k is the Preston coefficient, $p(x,y)$ is the pressure in the contact area of the polishing spot, which is related to the bonnet inflation pressure and the tool offset, and $\nu(x,y)$ is the instantaneous velocity of the polishing contact point, which is related to the spindle speed and precession angle.

Chunjin et al.[50] employed finite element simulation to analyze the dynamic and static contact areas as well as stress distribution during bonnet polishing. The simulation results reveal that both contact areas exhibit a circular shape, with the stress distribution in the dynamic contact area exhibiting a certain offset in the advancing direction. Based on the stress distribution function of the static contact area, the stress distribution function in the dynamic contact area was derived using a fitting method. In addition, they designed a new bonnet polishing head in the same year and evaluated it using finite element simulation software. The findings indicate that a stainless steel metal layer is more suitable for constructing the bonnet head compared with a metal plate. Furthermore, the bonnet head demonstrates maintained flexibility and higher stiffness. Experimental validation confirms the stability and material removal efficiency of the newly designed bonnet head.[51] Pan et al.[52] developed a theoretical model for material removal and progressive rate to achieve deterministic material removal prediction in dynamic bonnet polishing. The prediction results align closely with experimental outcomes, demonstrating a high degree of consistency.

Zeng et al.[53] conducted a comparative analysis of the impact of precession angle, spindle speed, tool offset, and bonnet inflation pressure on the width, depth, and removal rate of the material removal function through experiments. They proposed a modified Preston equation based on the experimental findings, considering diamond abrasive and urethane polishing pads as factors affecting material removal. Lin et al.[54] explored the effect of various inflation pressures on the removal function, observing the generation of three types of removal functions: M-type, trapezoidal, and Gaussian. Experimental validation indicated that the Gaussian removal function resulted in a lower high-frequency error on the surface of the optical element.

Wang et al.[55] investigated the impact of various progressive modes on the material removal function using the Preston equation and finite element analysis software. They found that under continuous progressive mode, the removal function exhibits asymmetry and a shifted peak. Yunpeng et al.[56] developed a material removal model based on Preston's method. They derived the relative velocity distribution between the polisher and the workpiece, calculated the pressure distribution using Hertzian contact theory, and simulated the removal function under tilting, progressive, and vertical modes. Subsequently, they established a finite element analytical model to assess stress distribution between the tool and optics during polishing, validating the model's accuracy through experiments.

Jianfeng and Yingxue[57] investigated the impact of workpiece curvature on the removal function by focusing on convex workpieces. They examined how different radii of curvature affect the material removal process and developed a material removal model using the Preston equation. The model's accuracy was confirmed by comparing simulated material removal depth with experimental results.

Pan et al.[34] investigated the influence of polishing force on the removal function. They employed online force detection technology to predict the TIF shape, integrated Hertzian elastic contact theory with an enhanced version of Preston's law, and derived a predictive model for TIF efficiency based on polishing force. Experimental results demonstrated that when the spindle speed was $\leq$1000 rpm, the maximum removal depth predicted by the model matched the experimental value.

The literature review above has enhanced the depth of modeling the material removal function based on the Preston equation, elucidating the impact of various factors on the removal function during polishing. In addition, some scholars have proposed a method for modeling the material removal function based on the friction factor.

Previous studies on the material removal function based on the Preston equation focused solely on the central region of the workpiece. However, during actual polishing, the removal effect of polishing tools at the workpiece's edge will exhibit an edge effect.

3.2.3 *Modeling of edge removal functions*

Exposing the edge with the polishing head leads to a dramatic increase in pressure in the contact area and edge removal, resulting in uncontrolled outcomes that significantly degrade the workpiece surface finish quality. In response, experts and scholars have investigated the edge removal characteristics during bonnet polishing. Li Hongyu et al.[58] examined the edge removal characteristics of bonnet polishing at the workpiece's edge, employing empirical predictions to establish a model for material edge removal. This model divides the edge removal effect into hexagonal workpiece areas. In various zones, the "Tool-Lift" method is utilized to regulate the polishing spot, thereby managing the edge removal effect and spot size for controlled material edge removal. To enhance processing quality, the study analyzed the material removal rates at the hexagonal workpiece's top corners and edges. In addition, different-sized bonnets were used on the workpiece's center and edge regions to mitigate the edge effect's impact on processing quality.[59] Through comprehensive research, the study established an edge removal function model and analyzed the impact of various extension amounts on this function through simulations and experimental validation. This approach enabled a more accurate prediction of the workpiece edge's height distribution.[60] Building upon this foundation, optimization and control of process parameters during polishing were undertaken, leading to significant enhancements in the workpiece edge's quality.[61] Beaucamp et al.,[62,63] also utilizing the "Tool-Lift" method, aimed to enhance workpiece machining quality by investigating the impact of spindle speed, inflation pressure, and precession angle on machining quality. Ke et al.[64] conducted a preliminary study on edge effects, investigating the optimal combination of process parameters and the ratio of the outreach to the diameter of the polished spot to address the complex control problem of "Tool-Lift."

Consequently, scholars have proposed various effective solutions to mitigate the edge effect on the workpiece, such as the "Tool-Lift" method, optimization of process parameters, and adjusting the reach-to-diameter ratio of the polished spot. Researchers have explored the fixed-point removal function across the entire workpiece surface to enhance polishing and processing quality. This investigation integrates bonnet polishing features, motion control, and processing path planning, as illustrated comprehensively in Fig. 6.

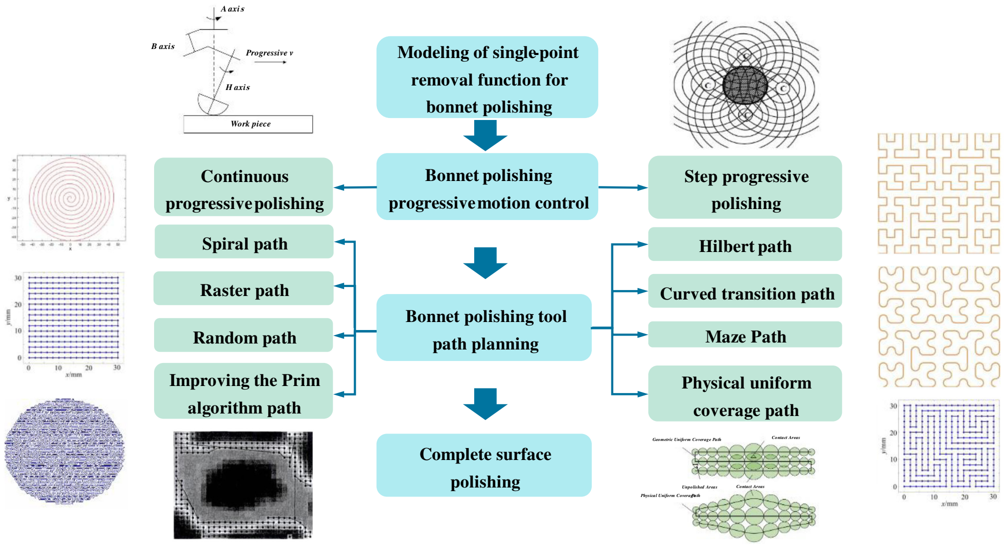

Fig. 6 Motion control of bonnet polishing process.

3.3 Bonnet Polishing Process Control

The investigation of fixed-point removal characteristics in bonnet polishing technology primarily focuses on the deterministic analysis of static fixed points on the bonnet. However, during the actual bonnet polishing process, the utilization of sub-aperture polishing necessitates the design of progressive motion control and tool path planning to fulfill the requirements for polishing large-diameter optical components with the bonnet.

3.3.1 *Progressive motion control*

There are two primary methods for bonnet progressive polishing optics: step-by-step progressive polishing and continuous progressive polishing, as illustrated in Fig. 7. During the entire workpiece processing, the bonnet tool spindle consistently rotates around the normal to the polishing point. Continuous progressive polishing involves simultaneous rotation of the bonnet tool spindle and its rotation around the polishing point. Step-by-step progressive polishing divides the continuous progression of the bonnet tool spindle into several directions, superimposing only the rotational motion of the bonnet tool spindle to achieve or approximate continuous progress.

David et al.[65,66] proposed a continuous progressive motion control strategy. Due to the complexity of the control algorithm arising from the increased number of linkage axes, they

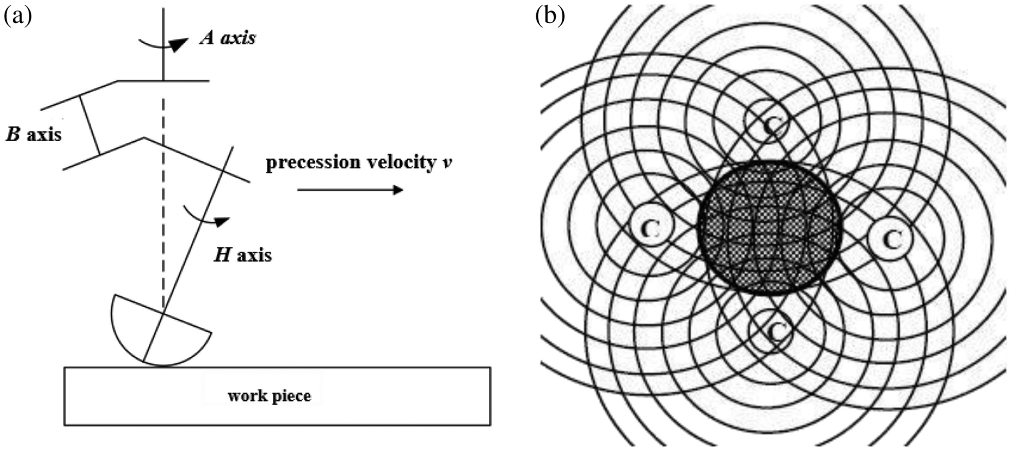

Fig. 7 Precession mode of bonnet polishing. (a) Continuous precession polishing and (b) step precession polishing.

introduced a step-by-step polishing method to approximate the polishing texture produced by continuous progressive motion. They experimentally verified the feasibility of modifying the method. Ri et al.[67] analyzed the motion relationship of the five-axis bonnet polishing mechanism. They considered the intersection point of the bonnet spindle and bonnet as the research focus and established an axisymmetric aspheric workpiece bonnet progressive motion model. Using the highest efficiency as the control strategy, they developed a control algorithm for the bonnet polishing mechanism and validated the motion model and control algorithm through simulation experiments. Subsequently, the control of machine progressive motion for free-form surface machining was achieved.[68] A motion control modeling method for four-axis machining of aspheric workpieces was then proposed on a five-axis linked machine.[69] In addition, a static stiffness model of the machine tool was established. A machine attitude optimization algorithm was also proposed, with the minimum displacement of the polishing tool as the objective to achieve machine attitude optimization and control.[70] Based on the characteristics of continuous progressive polishing, an optimization model of the normal rotation rate of the tool around the surface of the workpiece and the progressive rate was established. Simulation results demonstrated that a ratio greater than 20 provides a better parameter combination, verified through experiments.[71] Cao et al.[72] proposed a rocking bonnet polishing method, which varies the progressive angle during the polishing process. This affects the speed change of various regions of the polished spot, allowing for the generation of special three-dimensional surfaces using this motion control method.

The motion control of the bonnet during the polishing process is determined by different types of machine tools and workpiece surface functions; similarly, tool path planning in whole surface polishing needs to be determined based on the workpiece surface function.

3.3.2 *Bonnet polishing process control*

The continuous development of bonnet polishing technology has led to higher precision and efficiency requirements in its application across various fields. Process control is a critical research area in bonnet polishing technology, encompassing optimization of progressive and movement modes, residence time calculation, and other aspects. Many scholars have conducted extensive research on these topics.

The progressive mode significantly impacts the removal effect and efficiency of bonnet polishing. Therefore, optimizing the progressive mode plays a crucial role in advancing bonnet polishing process technology. David et al.[73,74] proposed a step-by-step progressive mode to address the complexity of control algorithms and the numerous linkage axes in continuous progressive mode. They demonstrated the feasibility of this optimization mode through experimental results using a four-step progressive process. In addition, Ri et al.[69] suggested incorporating constraints, the most effective control algorithm, into the continuous progressive polishing process to shorten progressive time and enhance polishing efficiency. Through the establishment of a continuous progressive polishing motion model combined with control algorithm simulation testing, they confirmed its correctness and stability, indicating further enhancement of continuous progressive polishing efficiency.

Optimizing the motion mode in the bonnet polishing process significantly enhances the overall efficiency of the system, providing numerous opportunities to optimize multiple aspects simultaneously. Mingsheng et al.[75] and Li et al.[76] aimed to achieve rapid and uniform material removal. They established a material removal model for simulation and analyzed the influence of progressive rate, stacking frequency, and row spacing on the efficiency and effectiveness of continuous progressive bonnet polishing. By optimizing progressive speed, stacking frequency, and row spacing, they successfully improved polishing efficiency and effectiveness. Experimental verification confirmed the alignment between the obtained results and simulation outcomes, thus fulfilling the goal of enhancing polishing efficiency and effectiveness through motion optimization.

Residence time calculation stands as a core technology in the precision polishing of large-diameter optics. Despite existing research, developing a computational algorithm with absolute stability, high convergence rate, and rapid solution speed remains challenging. Wang et al.[77] proposed an adaptive iterative algorithm for computing dwell time. Simulations conducted during bonnet polishing demonstrated the method's stability, high convergence rate, and fast solution speed, even on standard computers. Lipeng et al.[78] proposed a new method, the "layered threshold removal method," for calculating residency in incoming bonnet polishing. They validated the algorithm's rationality through simulations and experiments, offering a theoretical foundation for future bonnet polishing of free-form surface workpieces. Pan et al.[79] established a theoretical framework for optical optimization in calculating residence time for trimming shape. They proposed and experimentally validated an improved algorithm. Despite the removal function's instability during polishing and the initial surface gradient, the experimental results indicated an acceptable convergence rate, affirming the algorithm's accuracy and practicality.

3.4 Mid-spatial Frequency Error Suppression

During the bonnet polishing process, a small ripple error is generated on the element's surface, categorized as a mid-spatial frequency (MSF) error. The MSF error significantly influences the element's performance, making its size a critical indicator of surface quality. The MSF error comprises residual errors from the previous grinding process and new errors introduced during gadget polishing, leading to filamentary damage to optical components and decreased beam power, thus impacting the stable operation of strong laser systems. This issue is urgent and prevalent in current gadget polishing technology. Currently, the mid-frequency error resulting from the bonnet polishing path is primarily mitigated by adjusting the polishing path.

Due to its soft material, the bonnet polishing tool tends to sink into the corrugated wave valleys during workpiece grinding, which prevents the removal of residual mid-frequency errors. Hence, enhancing the stiffness of the bonnet tool is essential to suppress workpiece mid-frequency errors.

3.4.1 *Path suppression of MSF error*

The polishing process path significantly impacts the polishing outcome, particularly the MSF error, motivating numerous scholars to investigate bonnet polishing paths. David et al.[73,74] delineated various polishing paths, comprising helical, grating, and random paths. Their shared feature is non-crossing paths. Grating and random paths were employed to polish the glass. The experimental results demonstrate that the grating path yields noticeable periodic streaks. Power spectral density analysis reveals that the period correlates with the grating spacing. Moreover, the surface quality of workpieces polished via the random path surpasses that of the grating path. To assess the impact of adjacent processing path spacing in the grating path and adjacent processing point spacing within the same path on processing quality, Mingsheng et al.[75] evaluated material removal efficiency and processing quality, employing dichotomy principles to determine optimal adjacent path spacing. Wang et al.[80] analyzed the influence of step lengths at various polishing points on the PV and RMS of the workpiece surface. They concluded that as step length increases, both PV and RMS of the workpiece surface increase. They also observed an overall inverted L-type relationship between step length and PV/RMS of the workpiece surface. Furthermore, various scholars have proposed diverse machining paths to enhance workpiece quality. Guidan et al.[81] experimentally analyzed the impact of different machining paths on the optical component surface's MSF error. The results indicate that the improved Prim algorithm path can significantly reduce the MSF error on the optical specimen surface following Z-word grating path processing. Wang et al.[82] introduced a generation algorithm for the labyrinth path and compared it with the grating path, Hilbert path, and labyrinth path regarding workpiece surface topography through experiments. The experimental results demonstrate that the labyrinth path ensures uniform polishing, preventing periodic topographic features on the workpiece surface. Moreover, compared with the Hilbert path, it effectively suppresses MSF error generation. Takizawa and Beaucamp[83] considered that the angularity of the polishing path leads to significant speed changes at polishing tool corners, especially under high feed rates, resulting in surface ripples on the workpiece. Therefore, the article proposes a curved over-polishing path to mitigate speed changes along the polishing path, thereby enhancing workpiece surface quality. Peng et al.[84] optimized the Hilbert path by incorporating semi-circular over-polishing into the polishing path and verified the optimization's effectiveness through experiments. Jiang[85] proposed an adaptive partition grating polishing path based on the initial surface shape of optical components to adjust the grating spacing. Qizhi et al.[86] and Yanjun et al.[87] proposed a physically uniform coverage spiral polishing path, circumventing the traditional Archimedes helix polishing path in overcut and undercut areas. They experimentally confirmed that this approach yields superior polishing results compared with the traditional method.

Through the literature review above, scholars have proposed numerous polishing paths, characterized by their non-intersecting nature. To mitigate corner issues within these paths, the method of curve excess has been suggested. In addition, some scholars advocated for physically uniform coverage of the polishing path to prevent overcutting and undercutting areas on the machined surface.

3.4.2 *Process Parameter Suppression of MSF Error*

In addition to controlling the polishing path as discussed earlier, Huang et al.[88] studied the impact of polishing process parameters on the distribution of MSF error and observed that the error distribution was particularly influenced by spindle speed and feed speed. They succeeded in reducing the MSF error and obtained a surface with an RMS of 1.6 nm. Rao et al.[89] incorporated the Bessel function to isolate the bonnet radius, precession angle, and contact radius characteristics in the bonnet polishing process. They found that the degree of scratch ripple bending in TIF is primarily related to optimizing the precession angle of the bonnet tool. By preventing the concentration of scratch direction, it is possible to alleviate the surface texture across a broad range of applications.

3.4.3 *Tool suppression of MSF error*

In addition, scholars have enhanced bonnet tools to mitigate MSF errors on the workpiece surface. For instance, Walker et al.[90] introduced the “Grolishing” process, which involves affixing metal rings, diamond pellets, and other hard materials onto the bonnet surface to enhance tool rigidity, as depicted in Figs. 8(a) and 8(b). This approach can effectively eliminate residual surface MSF errors from the grinding process, leading to improved engineering application outcomes.

Yu et al.[91] affixed a round brass block with an 80-mm radius onto the surface of a bonnet, as depicted in Fig. 8(c). They used aluminum oxide polishing powder with a particle size of 9-μm to polish components of the European Extremely Large Telescope. After five subsequent polishing sessions, the PV and RMS values of the workpieces reached 56 and 12 nm, respectively.

3.5 Machining Process and Motion Control Integration Software System Development

Processing control software optimizes the performance of machine tools and equipment by efficiently utilizing core technology. It integrates key process technology into the machining process, bridging the gap between machining processes and equipment. Given the non-intuitive movement and complex workspace of bonnet polishing machine tools, traditional CNC system process software struggles to meet control requirements. Therefore, developing integrated process software for bonnet polishing is crucial for future automation, with intelligence playing a significant role.

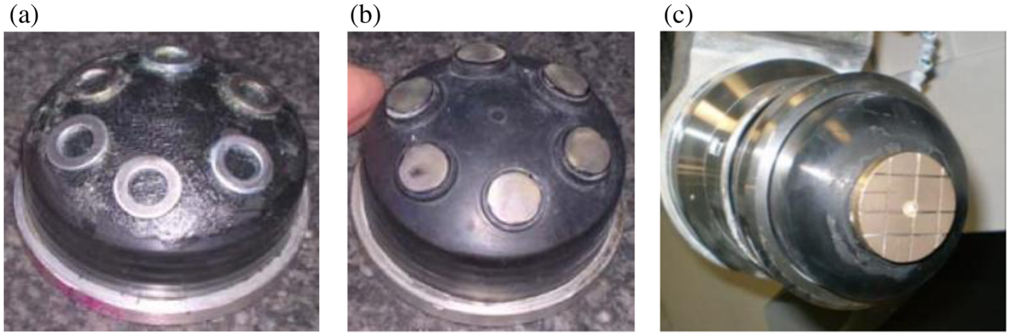

Fig. 8 “Grolishing” tool. (a) Stainless steel ring. (b) Diamond pill tablets. (c) Brass ingot.

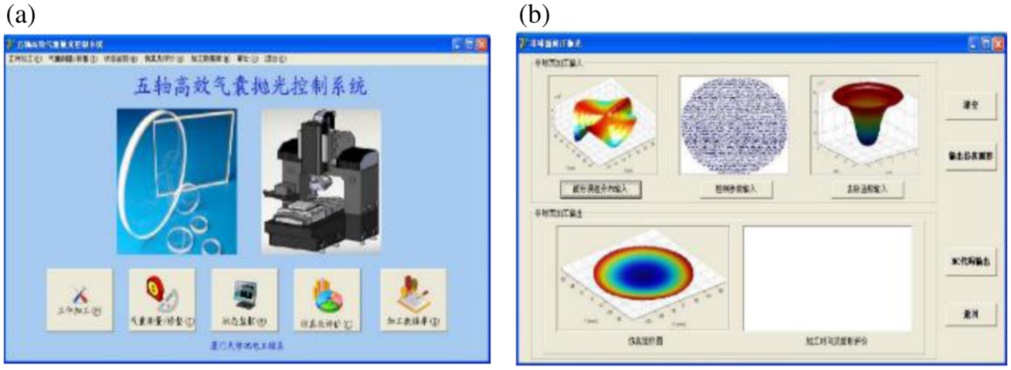

Fig. 9 Control software of five-axis high-efficiency bonnet polishing system. (a) Main interface and (b) software interface.

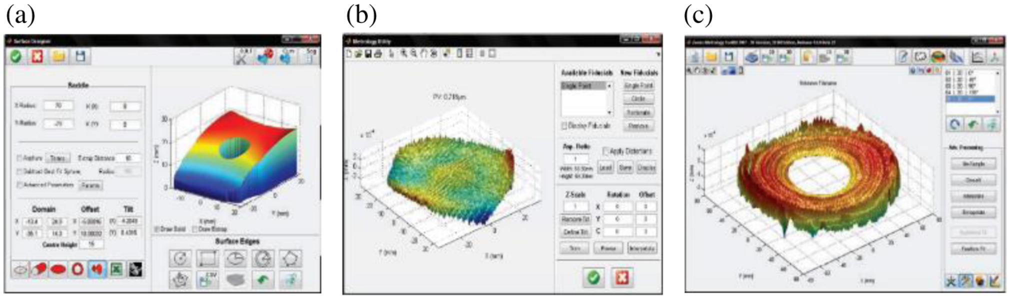

Fig. 10 ZEEKO's process software interface. (a) TPG software. (b) Precession software. (c) Metrology Toolkit software.

Pan[92] addressed the requirements for polishing and measuring the large aperture axisymmetric aspheric surface of the bonnet. They selected Delphi 6.0 and Matlab 7.0 as development tools to integrate functions such as bonnet tool measurement and trimming, conformal polishing, monitoring process status, and machine tool communication. This integration led to the development of a five-axis high-efficiency bonnet polishing system control software, depicted in Fig. 9. This software achieves progressive motion control for bonnet polishing optics, enhancing automation and efficiency in the machining process.

The ZEEKO company has effectively utilized three series of software—TPG, Precessions, and Metrology Toolkit—in the field of bonnet polishing, as depicted in Fig. 10. Specifically, the TPG software generates both simple and complex tool paths for ZEEKO IRP series polishing machines, compatible with Precession and third-party tools and machines. The Precession software includes modules for measurement, influence function library, optimization, and parallel processing, enabling real-time error correction during bonnet polishing and optimizing tool path planning, significantly reducing polishing time and improving surface deviation convergence. Meanwhile, the Metrology Toolkit software reads and analyzes data from various metrology instruments, offering functions such as workpiece surface measurement, geometry manipulation, point cloud processing, machining compensation, and data visualization.

4 Summary and Prospect

This paper summarizes the bonnet polishing technology from the aspects of application fields, advantages, key technology, and development status. Compared with traditional polishing methods, bonnet polishing has the advantages of high machining accuracy and high removal efficiency. Bonnet polishing technology has good adaptability to polish surfaces and is suitable for polishing aspherical and free-form surfaces. However, the efficiency comes with the challenge of polishing pad wear. The surface morphology of these pads significantly influences their removal function, and rapid wear can lead to removal function instability, affecting overall surface quality.

Moreover, bonnet polishing operates by applying pressure from the bonnet onto free polishing powder particles to abrade the workpiece surface for material removal. Excessive pressure can result in sub-surface defects. Many current super-large aperture telescopes utilize primary mirrors composed of spliced high-precision sub-mirrors. However, practical applications of bonnet polishing still encounter edge effects that demand a more cost-effective and precise solution.

In summarizing and reviewing the current bonnet polishing technology, there are some problems and shortcomings mainly in the following aspects:

1. Bonnet polishing technology inherently introduces MSF errors and edge effects. The current research focuses mainly on experimental approaches to mitigate these issues, lacking theoretical models, which hinders practical engineering applications.
2. Various types of abrasives and polishing pads significantly influence polishing efficiency and results. Currently, research on these variables is scarce and requires further investigation.
3. The current research on bonnet polishing is mainly based on experimental data, lacking systematic theoretical models to describe the material removal mechanisms and surface morphology changes during the polishing process.
4. Different polishing fluids have a significant impact on surface quality, polishing rate, and final results, but systematic studies on different fluid and material combinations are currently limited.

To further improve bonnet polishing technology and broaden the application fields of bonnet polishing technology, the subsequent research direction includes the following aspects:

1. Establishing a library of the relationship between bonnet polishing wear and removal function to reduce uncertainty caused by pad wear.
2. Improving bonnet polishing paths and process parameters to minimize sub-surface damage and full-band errors.
3. Optimizing polishing processes to suppress edge effects.
4. Exploring the combination of different polishing tool structures and optimizing bonnet tools to broaden the application scope of bonnet polishing technology.

After nearly two decades of development, bonnet polishing technology has emerged as the primary method for polishing optical components and is extensively applied to various curved surface workpieces. This paper primarily discusses the application and technical characteristics of bonnet polishing technology, the removal mechanism, fixed-point removal characteristic modeling, polishing process motion control, and integrated software development based on extensive research findings by scholars. It summarizes the current limitations and development trends of bonnet polishing technology, aiming to assist scholars studying this field and foster its further advancement.

Code and Data Availability

The datasets generated and analyzed in this study are available directly from the article. There are no codes or other materials.

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Pengfei Zhang is currently pursuing a master's degree at Xiamen University (XMU), China. His research interests focus on robot-assisted machining technology and bonnet polishing.

Zhenzhong Wang received his PhD in mechanical engineering from Xiamen University in 2009. He is a professor of mechanical engineering at Xiamen University. His current research interests include intelligent manufacturing, ultrasonic vibration-assisted machining, and robot-assisted machining technology.

Xuepeng Huang is currently a postgraduate student pursuing his PhD in Xiamen University (XMU), China. His research interest is mainly focused on robot assisted machining technology and precessions polishing.

Hao Zhang: Biography is not available.