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Research progress of magnetorheological polishing technology: a review

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Abstract As an essential link in ultra-precision machining technology, various new surface polishing technologies and processes have always attracted continuous in-depth research and exploration by researchers. As a new research direction of ultra-precision machining technology, magnetorheological polishing technology has become an important part. The polishing materials and magnetorheological fluids involved in the process of magnetorheological polishing are reviewed. The polishing principle, equipment development, theoretical research and process research of magnetorheological polishing technologies, such as the wheel-type, cluster-type, ball-type, disc-type and other types, derived from the magnetorheological polishing process, are reviewed. The above magnetorheological polishing technologies are analyzed and compared from the perspective of processing accuracy, processing efficiency and application range. The curvature adaptive magnetorheological polishing technology with a circulatory system is proposed to achieve high efficiency and high-quality polishing.

Keywords Ultra-precision machining · Magnetorheological polishing · Research progress · Curvature adaptive · Development trend

1 Introduction

A new round of scientific and technological revolution and industrial change is breeding and emerging, and global scientific and technological innovation is showing new developments. The manufacturing sector is brewing a breakthrough in traditional processing methods to enhance the development of modern science and technology [1]. The significant instruments supported by ultra-precision machining technology, such as C919 aircraft, Jiao long aircraft and horizontal dual five-axis mirror milling machine, have played a decisive role in promoting the process of high-quality development of the equipment manufacturing industry [2]. The new functional materials supported by ultra-precision processing technology, such as semiconductor, optical and ceramic materials, have laid a solid foundation for developing aerospace, electronic information and civil industries. As an important supporting technology for the technological revolution and industrial change, ultra-precision machining technology has become an important development direction of modern manufacturing science. At present, ultra-precision machining technologies mainly include ultra-precision cutting technology [3], ultra-precision grinding technology [4], and ultra-precision polishing technology [5]. However, the ultra-precision polishing technology is based on keeping the physical properties of the processed materials to achieve the ultimate surface quality, shape accuracy and dimension accuracy. It is one of the most effective processing methods to obtain high-quality workpiece surfaces efficiently [6–8].

Due to the unique advantages of ultra-precision polishing technology in processing, it has attracted the attention of scientific research institutions worldwide. So far, many new ultra-precision polishing methods have been proposed, including small grinding head polishing [9], laser polishing [10],

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consolidated abrasive polishing [11], chemical-mechanical polishing [12], abrasive water jet polishing [13], ion beam polishing [14], and magnetorheological polishing [15]. Among them, magnetorheological polishing technology is an emerging ultra-precision polishing technology with high precision of processed surface shape, wide machining range and small depth of subsurface damage, which is a hot topic in current research [16–20]. This technology is mainly used in ultra-precision machining, with high processing accuracy. The research content of magnetorheological polishing technology (various factors affecting the accuracy of magnetorheological polishing) includes the development process, polishing mechanism, processed materials, magnetic processing equipment, process methods, etc. Scholars at home and abroad have carried out systematic research on these contents. However, there are very few literature reviews on the research content of magnetorheological polishing technology. This also hinders the in-depth development of magnetorheological polishing technology. Therefore, an overview of the research content of magnetorheological polishing technology is a key basis for the further development of this technology in the future.

In this paper, the research progress of magnetorheological polishing technology is reviewed. Section 1 introduces the proposal and development of magnetorheological polishing technology. Section 2 summarizes the materials processed by magnetorheological polishing technology, focusing on their application and the processing accuracy that can be achieved. Section 3 introduces the research progress of magnetorheological fluid (MRF), mainly on the sedimentation stability and shear yield stress of MRF and the research progress of magnetorheological polishing fluid (MPF). Section 4 divides magnetorheological polishing techniques into wheel-type, cluster-type, ball-type, disc-type, etc. It mainly introduces its polishing principle, equipment research and development, theoretical analysis and processing technology. Section 5 compares the above types of magnetorheological polishing techniques from the perspective of material removal rate, surface roughness, surface uniformity, and range of application. In addition, the curvature-adaptive magnetorheological polishing technology with a circulation system is introduced. Section 6 presents the future development trend of magnetorheological polishing technology prospects.

2 Proposal and development of magnetorheological polishing technology

The development history of magnetorheological polishing technology is shown in Fig. 1, which goes through the following three stages.

2.1 Period from the 1940s to 1970s being the beginning of technology

As early as 1948, researcher Rabinow [21] first discovered the phenomenon of the rheology of magnetic fluids in the presence of magnetic fields. The phenomenon is that a magnetic fluid behaves as a liquid with good fluidity under a zero magnetic field, and a magnetic fluid behaves as a solid-like characteristic under a strong magnetic field. After research, it was found that the phenomenon changed continuously and controllably, and the magnetic fluid was subsequently referred to as magnetorheological fluid. However, its development was prolonged in the following three decades because the rheological properties of magnetorheological fluids have yet to be recognized.

2.2 Period from the 1970s to the early twenty-first century being the development of technology

In 1986, Professor Kordonski pioneered the research on magnetorheological polishing technology, and confirmed that a rationally formulated magnetorheological fluid in a magnetic field could polish optical materials. Since then, magnetorheological polishing techniques have emerged [22, 23]. Since 1990, due to the booming development of medical devices, optoelectronics, and communications industries, people have had higher product quality, reliability, and performance pursuit. This forced the further development of magnetorheological polishing technology. In 1992, Prof. Kordonski designed the world's first prototype of magnetorheological polishing technology [24]. However, the prototype does not have the basic idea of computer-controlled optical surfacing (CCOS), which can only process aspherical surfaces now. It is difficult to trim the surface shape with high precision [24]. Subsequently, Professor Kordonski collaborated with the Center for Optics Manufacturing (COM) at the University of Rochester to develop magnetorheological polishing equipment [25]. In 1993, this team developed a new generation of magnetorheological polishing prototype. Through many experimental studies, it verified the high efficiency and low damage polishing advantage of magnetorheological polishing technology for optical materials [26]. In 1995, for developing cutting-edge technologies such as aerospace and defense, the COM was the first to develop orthorhombic magnetorheological polishing equipment. Moreover, a batch of optical components with a diameter of less than 50 mm was processed by it. A high-quality surface with a surface roughness R_a of 1 nm was obtained, thus starting the innovation of magnetorheological polishing technology [27]. In 1996, the COM added the idea of CCOS to the original orthotropic wheel magnetorheological polishing equipment, which brought it into the era of intelligent computer numerical control (CNC)

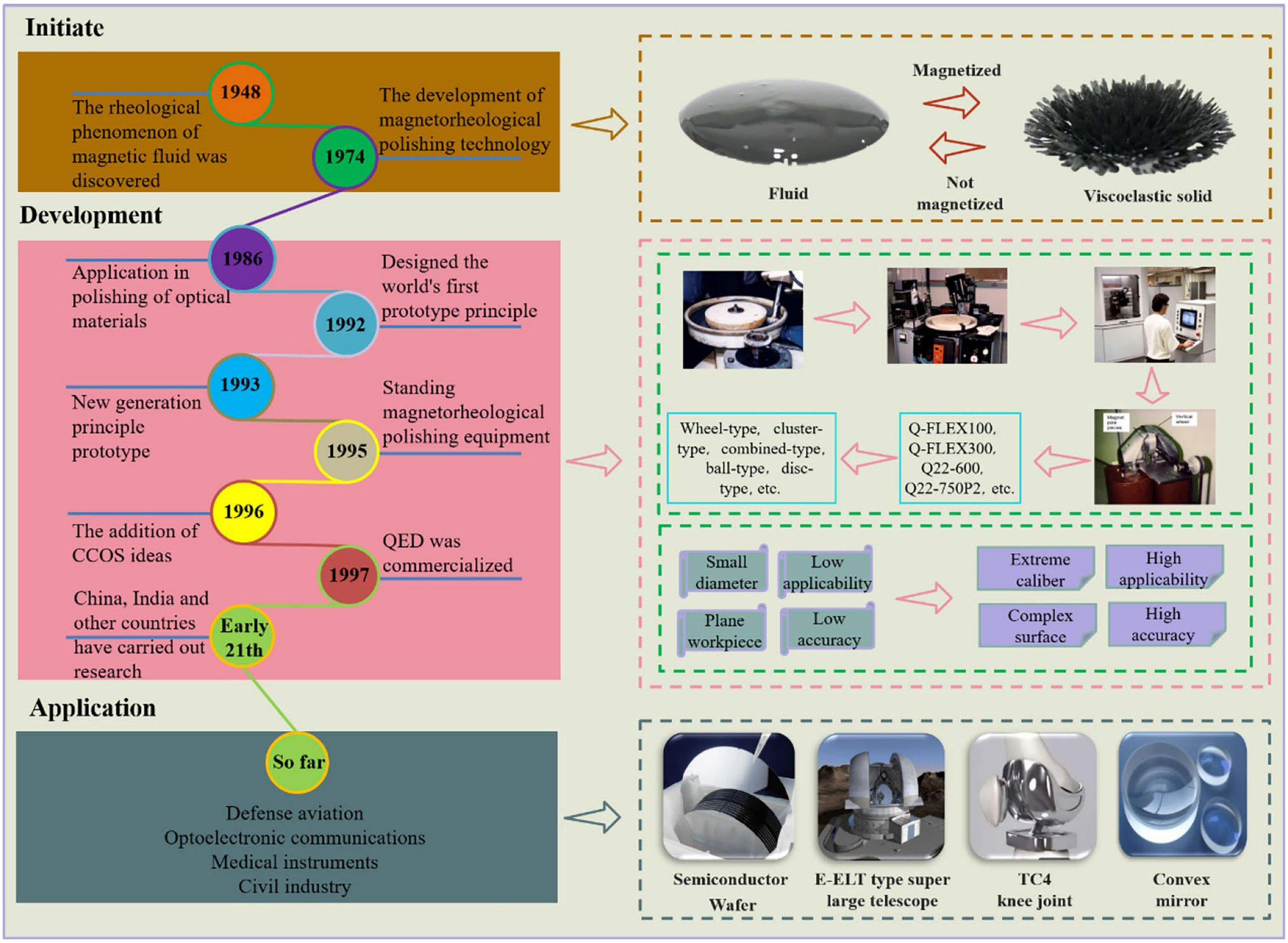


Fig. 1 Development history of magnetorheological polishing technology

[28]. In 1997, the COM started commercializing magnetorheological polishing equipment by establishing QED. However, at this time, the application of magnetorheological polishing equipment has certain limitations, mainly in the form of special machines to order [29]. Since the beginning of the twenty-first century, research on magnetorheological polishing technology has blossomed everywhere. Many kinds of magnetorheological polishing techniques exist, such as wheel-type, cluster-type, ball-type, disc-type, etc. The typical teamson wheel-type magnetorheological polishing technology include the QED in the United States [30], Zhang's team at Changchun Institute of Optics, Fine Mechanics and Physics (CIOMP) [31–33], Feng's team at Tsinghua University [34], Peng's team at National University of Defense Technology [35–37], Schinhaerl's team at the University of Applied Sciences Deggendorf [38, 39], Cho's team at Inha University [40], Zhang's team at China Academy of Engineering Physics [41], etc. It is worth mentioning that the QED has quickly become the world's leader in magnetorheological polishing and related technologies. The typical teams on cluster-type magnetorheological polishing technology include Yan's team at Guangdong University of Technology, China [42]. The typical teams on ball-type magnetorheological polishing technology include Anant's team at the Indian Institute of Technology [42–45] and Chen's team at the Harbin Institute of Technology [46]. The typical teams on disc-type magnetorheological polishing technology include Yin's team at Hunan University [47].

2.3 Period from the early twenty-first century to the present being the application of technology

Since the early twenty-first century, a new global scientific and technological revolution and industrial change have developed. New technologies have been accelerating the integration with ultra-precision machining technology. As a new research direction of ultra-precision machining technology, magnetorheological polishing technology plays an important role in the fields of national defense aviation, optoelectronic communications, medical instruments and civil industry due to its unique polishing advantages. The followings are the main applications of magnetorheological polishing technology.

2.3.1 *Defense and aviation, optoelectronic communication field*

The development of modern warfare, defense and aviation technology depends on advanced optoelectronic communication, control and weapon equipment technology. However, advanced optoelectronic communication, control and weapon processing are inseparable from applying magnetorheological polishing technology. For example, using magnetorheological polishing for the convex spherical (BK7) mirror used in the nuclear fusion device can converge the root-mean-square (RMS) of the mirror from 22 nm to 6 nm, improving the performance of the mirror [48]. Using magnetorheological polishing for the hemispherical resonant gyroscope used in the Jetlink inertial guidance system allows obtaining a surface roughness of R_a 3.2 nm, which improves the accuracy of the hemispherical resonant gyroscope in use [49]. Using magnetorheological polishing for the surface damage of fused silica optics used in high-power lasers, a 90% surface damage repair rate can be obtained, effectively reducing the waste of fused silica material [50].

2.3.2 *Medical instruments field*

The application of biomedical materials has greatly contributed to the development of medical standards and has the enormous market potential [51]. However, for biomedical materials, ultra-smooth surface quality and ultra-low surface roughness are important constraints to their development. Therefore, applying magnetorheological polishing technology is indispensable to obtain a high-quality machined surface. For example, the use of magnetorheological polishing for ultra-high molecular weight polyethylene (UHMWPE) is used in the artificial acetabulum, which increases its microhardness and improves its service life accordingly [52]. Using magnetorheological polishing for the titanium alloy used in artificial joints, ultra-smooth surface quality with a surface roughness R_a of 2.87 nm can be obtained, improving its service performance [53]. Using magnetorheological polishing for the cobalt-chromium-molybdenum alloy used in the artificial hip joint allowed obtaining a high-quality surface of 5 nm, improving its accuracy [54].

2.3.3 *Civil industry field*

With the progress of science and technology, pursuing high-quality, high-performance, and high-reliability products has greatly promoted the application of magnetorheological polishing technology in the civil industry. For example, magnetorheological polishing for stainless steel parts formed by selective laser melting (SLM) can effectively reduce the residual stresses on their surfaces [55]. Using magnetorheological polishing for the inner wall of a hydraulic cylinder used by heavy machinery can effectively improve its surface accuracy and increase its service life [56]. Using magnetorheological polishing for the cylindrical copper rod in the printing press can reduce its surface roughness and enhance its surface characteristics [57].

3 Magnetorheological polishing materials

Once the magnetorheological polishing technology was proposed, it attracted the attention of domestic and foreign researchers because of its unique advantages and ability to achieve low-loss processing. Numerous studies have shown that researchers are keen to conduct relevant research on new functional materials. At present, from the level of ultra-precision machining, the new functional materials in the existing research are divided into the following categories: soft and brittle artificial crystal materials, hard and brittle optical crystal materials, hard and brittle semiconductor materials, hard and brittle ceramic materials, and alloy materials [58, 59]. Table 1 lists the applications and precision of some novel functional materials in existing research [11, 53, 54, 60–69].

The physical properties of some new functional materials in existing research are listed in Table 2. Due to its superior physical and chemical properties, new functional materials are widely used in aerospace, medical devices, optoelectronic communications and the civil industry [62, 70]. However, these new functional materials have the same characteristics: high brittleness, high hardness and easy-to-produce sub-surface damage, which have an extremely adverse effect on the device's performance and working life. Meanwhile, it also challenges ultra-precision machining greatly [71, 72]. Therefore, to meet the application requirements of the novel functional materials, it is necessary to ensure their external dimensions, surface shape accuracy, surface roughness, and other precision requirements.

4 Research progress of magnetorheological fluid

4.1 Research on properties of magnetorheological fluid

MRF is a liquid with rheological properties. When the liquid is in the magnetic field, it will have rheological behavior due to the guidance of magnetic particles. It is mainly composed of magnetic-sensitive particles, base carriers and additives. At present, the research on MRF in magnetorheological

Table 1 Applications and precision of some of the novel functional materials in existing researches

Classification	Example	Application	Precision/nm
Soft and brittle artificial crystal materials	CaF_2	Extreme ultraviolet lithography	1.74 [11]
	ZnSe	Infrared optical instrument	1.57 [60]
	KDP	Electro-optical modulators, Q-switches	1.2 [61]
Hard and brittle optical crystal materials	K9	Lasers, LCD TVs	1.4 [62]
	SiO_2	Astronomical telescopes, Lasers	0.165 [63]
	Al_2O_3	Infrared alert system, Missile fairing	0.27 [64]
Hard and brittle semiconductor materials	Si	Rectifiers, diodes	0.5 [65]
	InP	Integrated circuits	0.35 [66]
	SiC	Transistors, radar	0.49 [67]
Hard and brittle ceramic materials	ZrO_2	Ceramic armor	0.7 [68]
	Si_3N_4	Precision bearings, wear-resistant tools	4.35 [69]
Alloy materials	TC4	Heat shields, engine blades	2.87 [53]
	CoCrMo	Artificial bones	5.0 [54]

Table 2 Physical properties of some new functional materials in existing research

	Al_2O_3	SiC	Si_3N_4	SiO_2
Density, $\rho/(kg \cdot m^{-3})$	3 950	3 200	3 500	2 200
Modulus of elasticity, E/GPa	350	410	310	77
Mohs hardness	9.2	9.5	9.0	6.5
Compressive strength, σ_{bc}/GPa	2–2.7	2–2.5	3.5	1.15
Bending strength, σ_b/GPa	0.3–0.5	0.45	0.6	0.089
Fracture toughness, $K_{IC}/(MPa \cdot m^{1/2})$	3.00	3.50	5.30	2.12
Corrosion resistance	Strong	Strong	Strong	Ordinary

polishing technology mainly includes sedimentation stability, shear yield stress, etc.

4.1.1 Sedimentation stability

The magnetic-sensitive particles, base carrier and additives are mixed in a certain proportion, and the mixed liquid formed after a long period of dispersion is MRF. However, the magnetic particles in the free state of the MRF will condense due to the interaction force between molecules. When more and more magnetic particles are condensed, sedimentation occurs. However, the amount of magnetic particle sedimentation determines the stability of the MRF. It also determines the effective use time of the MRF. This is ultimately reflected in the processing efficiency and quality of polishing.

Xiong et al. [73] prepared MRF using oleic acid, polyethylene glycol and sodium dodecyl benzene sulfonate (SDBS) as surfactants. A new evaluation method for the anti-sedimentation stability of MRF was explored by measuring the influence of dispersed particles on the wettability of MRF. It is concluded that the smaller the HLB value of the surfactant, the better the anti-sedimentation performance of MRF. The contact angles of the three surfactants are shown in Fig. 2.

Shu et al. [74] modified hydroxy iron powder with nonionic surfactant polyethylene glycol (PEG) and obtained a water-based MRF after modification. The lowest sedimentation ratio is only 8.56%, and the initial performance is restored after re-stirring. The volume removal rate of K9 glass was higher than 1.4 mm^3/min by using the prepared MRF. The SEM photos of hydroxyl iron powder before and after modification are shown in Fig. 3.

Yang et al. [75] used dimeric acid as a surfactant to prepare MRF and believed that the MRF containing dimeric acid formed loose flocculation and enhanced sedimentation stability. Niu et al. [76] prepared MRF using oleic acid and polymethyl methacrylate as surfactants. It is concluded that oleic acid and polymethyl methacrylate can improve the settling stability of MRF. This is because both can provide a stronger steric hindrance effect, as illustrated in Fig. 4.

Song et al. [77] used nano-carbonyl iron particles to partially replace micron-carbonyl iron in dispersing. It is concluded that the sedimentation stability can be improved by adding the proper amount of nanoparticles. Piao et al. [78] synthesized magnetic Fe_3O_4/SiO_2 nanoparticles by sol-gel method. When added to MRF, the rheological properties and dispersion stability of MRF were higher than those of pure MRF, and the sedimentation rate was reduced by 28.3%. Guo et al. [79] prepared MRF with three kinds of nano-SiO_2 with different specific surface areas (150 m^2/g, 200 m^2/g, 380 m^2/g) and carbonyl iron powder. It is concluded that SiO_2 will gelate after entering MRF, which will increase the viscosity of MRF. To a certain extent, the fluidity of the MRF

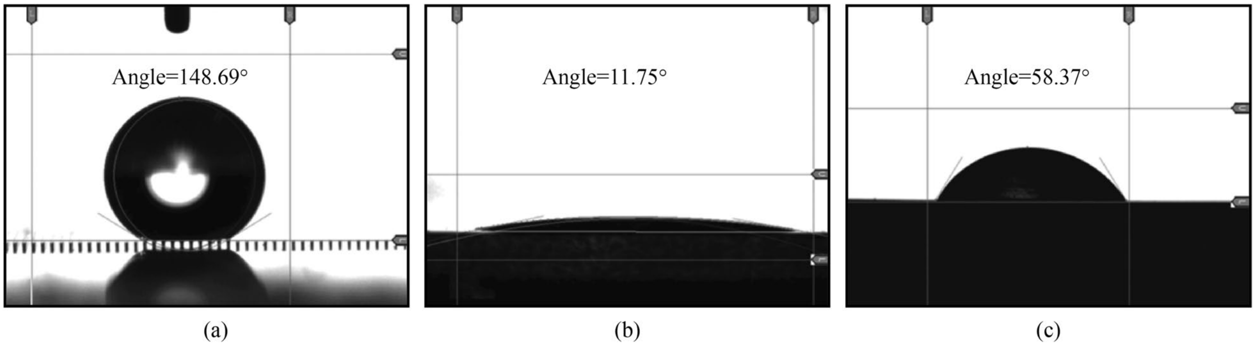


Fig. 2 Contact angles of the three surfactants [73] **a** polyethylene glycol, **b** oleic acid, **c** SDBS

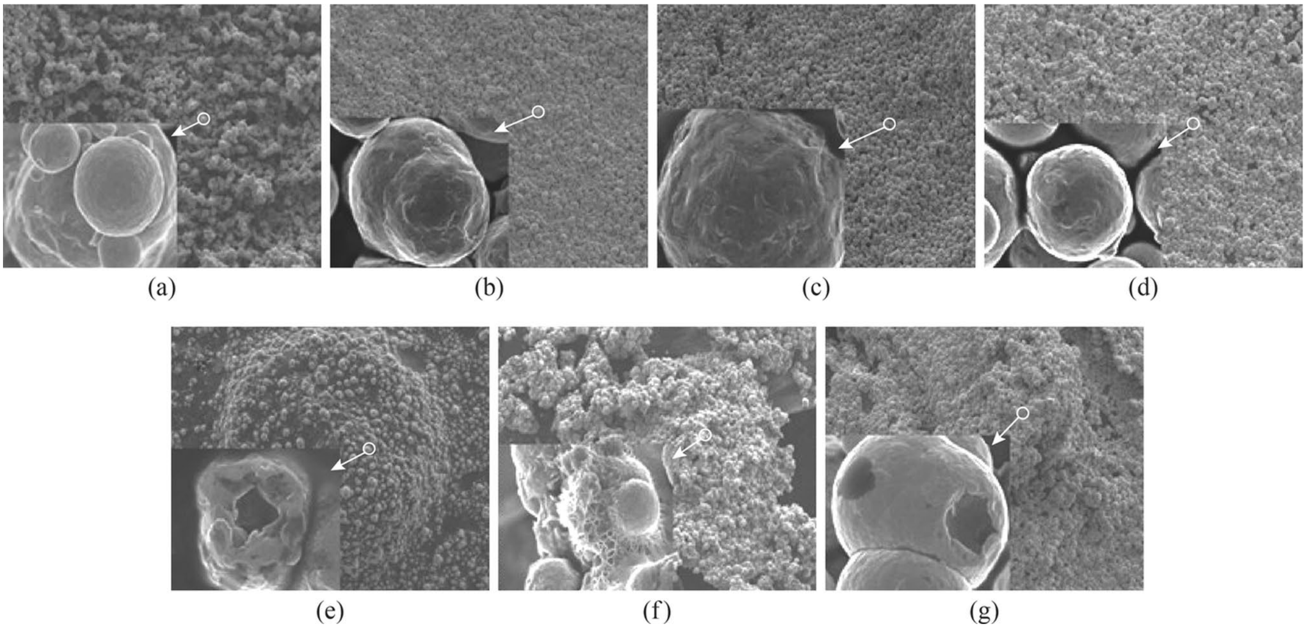


Fig. 3 SEM photos of hydroxyl iron powder before and after modification [74] **a** hydroxy iron powder, **b** PEG-200, **c** PEG-400, **d** PEG-600, **e** PEG-800, **f** PEG-1000, **g** oleic acid

is reduced, thus slowing down the settlement. The results obtained after the static experiment are shown in Fig. 5.

In summary, to improve the settling stability of MRF, it is necessary to add different kinds of additives to MRF. The additives added to MRF in existing studies are represented by oleic acid and SiO_2, but the principles of action of the two are also very different [80]. Oleic acid, by coating the magnetically sensitive particles to form a wrapping structure, blocks the interaction between the iron powders, slowing the settlement. SiO_2, the gelation of SiO_2 will form a stable three-dimensional structure, which plays a certain buffer role in the aggregation of magnetic particles, thereby slowing down the sedimentation rate.

4.1.2 Shear yield stress

The shear yield stress of MRF refers to the minimum stress value required for MRF to change from a flow state to a solid state under the action of the magnetic field. Shear yield stress is an important property index of MRF and one of the important parameters for measuring the rheological properties of MRF.

Zhu et al. [81] prepared four kinds of MRFs with different volume fractions (10%, 20%, 30%, and 40%) to study their shear properties. The shear stress of these four MRFs at different shear rates was measured by the rheometer, as shown in Fig. 6. It is considered that the larger the volume

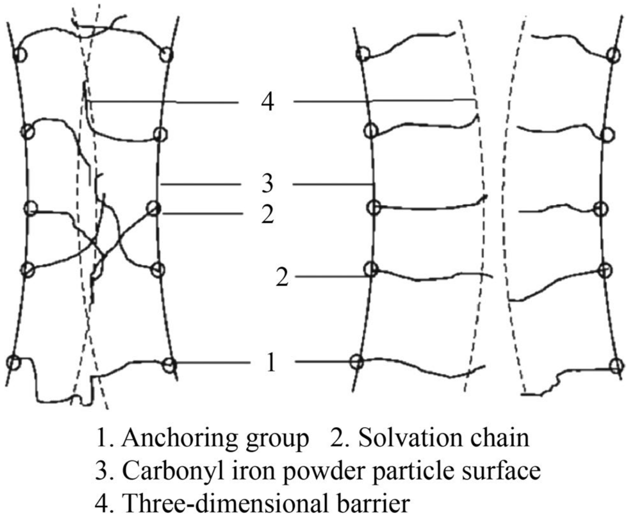


Fig. 4 Diagram of steric hindrance effect of oleic acid and polymethyl methacrylate [76]

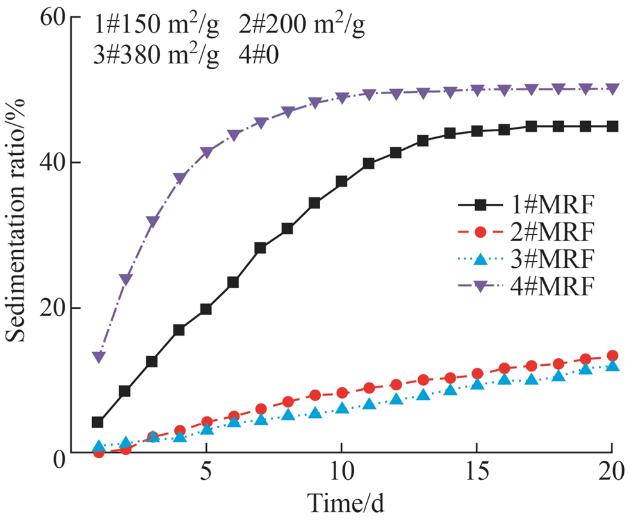


Fig. 5 Results obtained after static experiment [79]

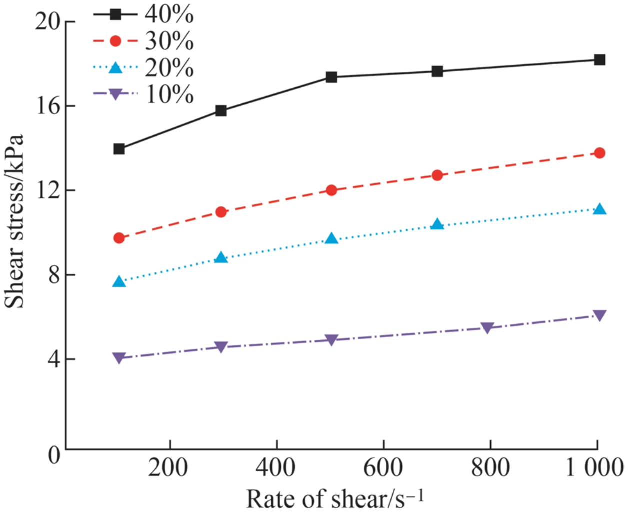


Fig. 6 Effect of shear rate on shear stress of MRFs [81]

fraction, the better the shear performance of MRF. Xiao et al. [82] discussed the microscopic changes of silicone oil-based MRF under the action of a magnetic field (see Fig. 7) and the corresponding shear mechanical properties. It is concluded that the shear stress of MRF depends on the strength of the applied magnetic field, and there is a certain relationship between them. When the current is small, the shear stress increases exponentially, and the index value is about 1.5. When the impressed current increases, the shear stress increases linearly and finally reaches a stable value.

Ginder and Davis [83] explored the relationship between the diameter of magnetically sensitive particles and shear stress. It is concluded that the shear yield stress of MRF increases significantly with the increase in particle size. However, when the particle size exceeds a certain range, the shear yield stress of MRF is independent of the particle size. Zhao et al. [84] studied the microstructure and shear properties of the interface between carbonyl iron particles (CIPs) and dimethylsilicone oil (DSO) by molecular dynamics simulation method. It is concluded that strong bonding strength exists between the Fe atom on the CIPs surface and DSO molecular chain during the shearing process. MRFs with different viscosity DSOs were prepared. It was found that high interfacial shear strength could improve the rheological properties of MRFs. Zhu et al. [85] established a multi-chain calculation model of MRF based on the magnetic interaction energy between particles. The magnetic shear stress-strain relationship is obtained using the magnetic energy density variation. Li [86] obtained the relationship between the shear yield strength and magnetic field strength of IL-MRF and SO-MRF based on Bingham plastic model fitting, as shown in Fig. 8. It can be seen from Fig. 8 that the shear yield strength of IL-MRF is greater than that of SO-MRF under a larger external magnetic field. It is worth noting that when the applied magnetic field reaches 436 kA/m, the shear yield strength of IL-MRF is 29% higher than that of SO-MRF. That is, IL-MRF exhibits a better magnetorheological effect.

In summary, the microstructure of shear stress in MRF is as follows: under the action of a magnetic field, the magnetically sensitive particles gradually form a chain structure and are in a condensed state. When the magnetization of the magnetically sensitive particles continues to increase, the shear stress also changes, showing a trend of obvious increase. In addition, the particle size and magnetic field strength of magnetically sensitive particles greatly influence the shear stress.

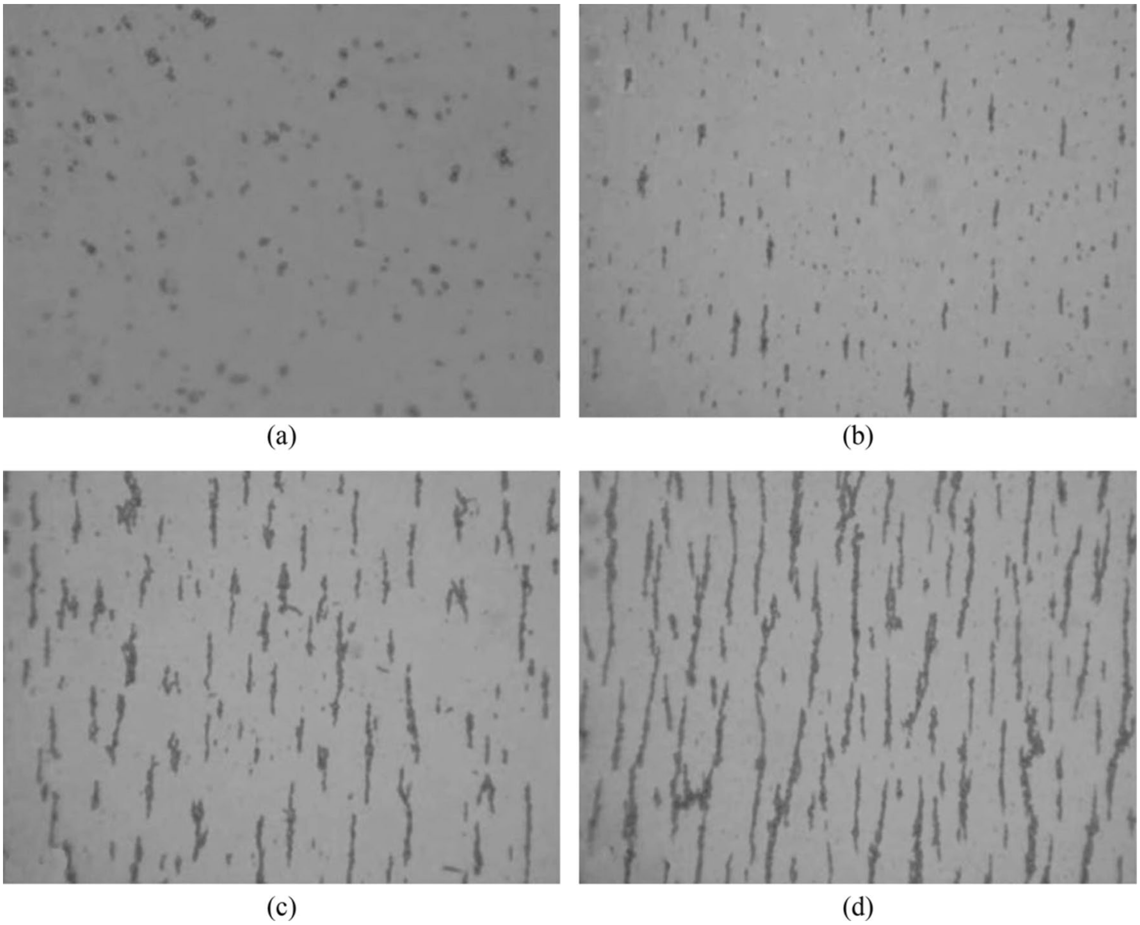


Fig. 7 Microscopic changes of MRFs with different magnetic field intensities [82] **a** 0 mT, **b** 15 mT, **c** 75 mT, **d** 150 mT

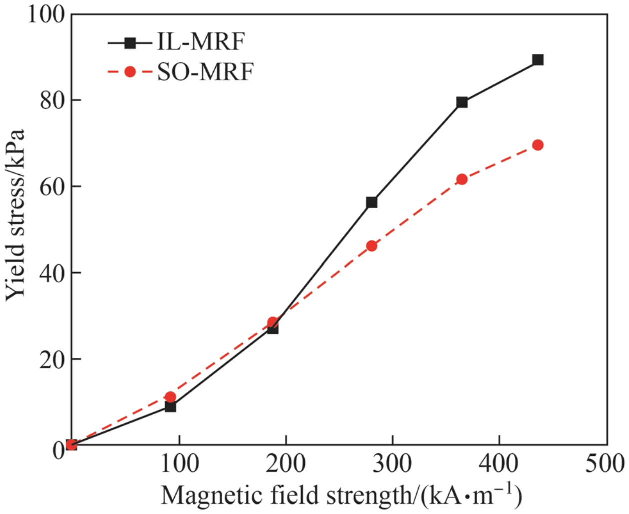


Fig. 8 Relationship between the shear yield strength of IL-MRF and SO-MRF and the magnetic field strength [86]

4.2 Research status of magnetorheological polishing fluid

The main components of MPF are similar to those of MRF. It is mainly composed of base carrier fluid, magnetic particles, abrasive particles and surfactants. Currently, MPF can be divided into two types according to the different base carrier fluids. The first is a water-based MPF using water as the base carrier fluid. It can be used to process the polishing of most materials. However, it is not able to process water-soluble materials. The second is the oil-based MPF using oil (mineral oil, silicone oil, etc.) as the base carrier fluid. It is suitable for the processing of water-soluble materials. As an important part of magnetorheological polishing technology, the properties of MPF directly affect the processing quality of optical materials. Scholars at home and abroad have conducted extensive research on it.

Bai [87] used zirconia to modify the surface of carbonyl iron powder to study the properties of MPF prepared by this composite particle. It is concluded that the modified carbonyl iron powder with MPF has better stability and a higher material removal rate for polishing glass and ceramic crystals. Mahender et al. [63] investigated the influence of temperature on the properties (shear force and viscosity) of water-based MPF. It is believed that the higher the temperature, the smaller the shear force and viscosity of the MPF. Subsequently, a water-based MPF with cerium oxide as abrasive was prepared at 25 °C, and a high-quality surface of 0.165 nm was obtained by polishing the fused quartz glass. Bai et al. [88] from Changchun Institute of Optical Machinery configured a water-based MPF suitable for optical processing. K9 and Si were polished with the prepared polishing fluid, and the material removal rates of 4.83 μm/min and 1.376 μm/min were obtained, respectively. The stability and high removal efficiency of the prepared polishing fluid were verified. Peng et al. [61] from the National University of Defense Technology developed an oil-based MPF. The removal function experiment of KDP crystal is carried out, and the stable removal function is obtained through optimization.

With the in-depth study of the performance of MPFs, MPFs are gradually commercialized. QED Company in the United States has developed a variety of commercial MPFs, such as QED-C11, QED-D10, QED-D20, QED-C30, etc. These MPFs have low zero-field viscosity, high material removal efficiency, and stable composition under the control of a recirculation system. They are now used in practical engineering processes. According to available data [89], the PRR (peak removal efficiency) for polishing BK7 by QED-C10 can reach 4.47 μm/min, and the PRR for polishing single crystal Si by QED-D20 can reach 5 μm/min. However, QED is absolutely secretive about the polishing fluid's composition, content, and formulation process, and the product is expensive. There are also many institutions in China to develop a series of MPFs. For example, ZJY-C-A/B water-based MPF developed by Hunan Norbest Technology Co., LTD. It is mainly used for the magnetorheological polishing of quartz, microcrystal, K9, metal mirror and other materials. ZJY-D-A/B water-based MPF is mainly used for the magnetorheological polishing of crystals, hard and brittle materials, ceramics and sapphire. However, the domestic research on the preparation process and additive composition of MPF is not deep enough. The stability of fluid and material removal efficiency still have increased gaps with foreign countries.

5 Research status of magnetorheological polishing technology

5.1 Wheel-type magnetorheological polishing technology

5.1.1 Principle introduction

The wheel-type magnetorheological polishing technology uses the "point contact" processing method to process the workpiece. It is mainly used in the high-efficiency and high-quality processing of aspherical surfaces, spherical surfaces, complex surfaces, large-size prism, and other components. It can obtain sub-nano-level polishing quality. Depending on the different structures of polishing equipment can be divided into upright type and inverted type. Take the inverted magnetorheological polishing equipment as an example, its principle is shown in Fig. 9a [90]. The magnetic poles are located inside the polishing wheel. When the electromagnet is energized, a high-gradient magnetic field is generated between the magnetic poles and the workpiece to be processed. A cycle system transports the magnetorheological fluid to the surface of the polishing wheel. When the magnetorheological fluid passes through the high-gradient magnetic field, it forms a flexible ribbon on the surface of the polishing wheel. When the flexible ribbon comes in contact with the workpiece and creates mutual motion, a tremendous shear force is generated between the two. Thus, the surface of the workpiece is micro-removed. The material removal function is shown in Fig. 9b [91].

5.1.2 Equipment research and development

QED is a leader in the development of wheel-type magnetorheological polishing equipment. It has already produced many more mature magnetorheological polishing equipment and realized the commercialization of wheel-type magnetorheological polishing equipment. Among them, the

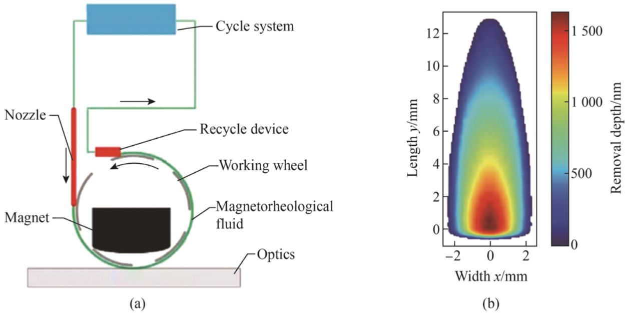


Fig. 9 Principle of wheel-type magnetorheological polishing and material removal function **a** working principle [90], **b** material removal function [91]

smallest polishing wheel has been developed with a diameter of 10 mm, which can effectively process small complex parts. The largest wheel developed has a diameter of 370 mm, which can process concave lenses with the maximum size of 2.3 m and convex lenses of 1.7 m. Some of the latest magnetorheological polishing equipment produced by the company is shown in Fig. 10. In order to increase the applicability of the equipment, Peng's team [92] from the National University of Defense Technology designed aninverted magnetorheological polishing machine based on the traditional wheel polishing equipment. Its four-axis linkage and spindle control can realize the correction of the surface profile of many optical parts. The equipment was used to process optical glass, and its Peak-to-Valley (PV) value was successfully reduced from 261.7 nm to 55.3 nm, RMS value from 46.8 nm to 5.5 nm, and surface roughness R_a value from 1.58 nm to 0.57 nm. The equipment is shown in Fig. 11a. Further, Li et al. [90] at Changchun Optical Machinery Institute increased the flexibility of the polishing equipment by integrating the polishing equipment into a five-axis CNC machining center. A hardware basis is provided for the processing of large-aperture aspherical optical components. The equipment is used to process a large diameter SiC with a size of 2 m, and its RMS value successfully converges from 0.098λ to 0.019λ, which verifies the practicability of the equipment. The equipment is shown in Fig. 11b. Wang et al. [93] of Tsinghua University proposed a new wheel-type magnetorheological polishing equipment with the form of revolution and rotation motion, which realized the renewal of magnetorheological fluid by alternating the strength and weakness of the magnetic field area. The reliability of the equipment was also verified by polishing experiments on optically aspherical surfaces. The equipment is shown in Fig. 11c. In order to further reduce the production cost, Shu [94] of Southwest University of Science and Technology integrated the wheel-type magnetorheological polishing equipment into the robotic arm. It can not only increase the size of the workpiece but also reduce the cost and, at the same time, has a high processing accuracy and efficiency. The equipment is shown in Fig. 11d. Huang et al. [41] of China Academy of Engineering Physics, configured two magnetorheological polishing heads with a diameter of 50 mm and 430 mm, respectively, on the same 8-axis CNC machine tool. A series of process tests were carried out with the equipment; the material removal characteristics and surface shape correction ability of large and small grinding heads were investigated; and a good polishing effect was obtained. Its equipment is shown in Fig. 11e. In addition, the commercialization of wheel-type magnetorheological polishing equipment has also made certain progress in China.


Q22-1200

Q22-600

Q22-750P2

Q-flex-100

Q-flex-300

Fig. 10 Some of the latest magnetorheological polishing equipment

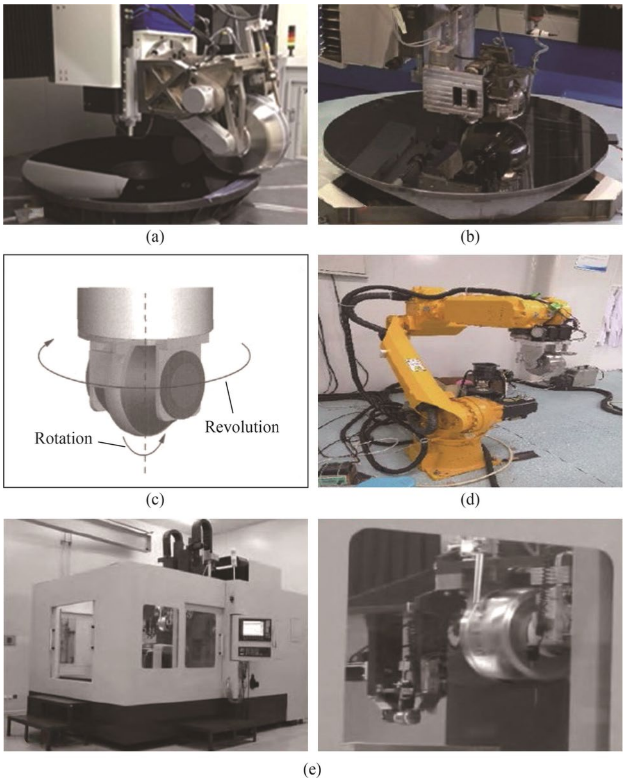


Fig. 11 Wheel-type magnetorheological polishing equipment developed by some domestic research institutes **a** National University of Defense Technology [92], **b** Changchun Optical Machinery Institute [90], **c** Tsinghua University [93], **d** Southwest University of Science and Technology [94], **e** China Academy of Engineering Physics [41]

So far, many companies have produced commercial magnetorheological polishing equipments. For example, the DQ series produced by Changguang Daqi Technology Co., Ltd.; MRP series produced by Suzhou Langxin Precision Optics Co., Ltd.; ZJY-NCM series produced by Hunan Norbest Technology Co., Ltd. Table 3 describes the parameters of some commercial magnetorheological polishing equipment. Among them are 12 kinds of polishing heads for wheel-type magnetorheological polishing equipment, with the smallest size of 10 mm and the largest size of 370 mm. At present, the wheel-type magnetorheological polishing equipment primarily uses electromagnets as the magnetic field source. The above commercial wheel-type magnetorheological polishing equipment provides a solid hardware foundation for developing magnetorheological polishing technology.

5.1.3 Theoretical research

5.1.3.1 Material removal model research In order to better understand the material removal mechanism of wheel-type magnetorheological polishing, the theoretical model of the magnetorheological polishing process was established. Miao et al. [95, 96] proposed the Preston equation for material removal by combining the shear force on the workpiece surface with the material's mechanical properties. They verified through experiments that the material volume removal rate in the polishing process had a linear relationship with the shear force. Sidpara and Jain [97] established a theoretical model of the shear force of magnetorheological fluid to study the influence of process parameters (rotation speed, working clearance, etc.) on the tangential force of the workpiece during polishing. The accuracy of the theoretical

Table 3 Some parameters of commercial magnetorheological polishing equipment

Partial company	Type	Polishing head specification	Applicable material	Applicable surface	Processing precision
QED	Q-FLEX-100	10/20/50/150 mm	Optical glass, silicon carbide, sapphire, etc.	Lane, sphere, aspherical surface, part shape, etc.	① RMS < 1 nm ② RMS < 0.5 nm
	Q-FLEX-300				
	Q22-600	50/370 mm			
	Q22-1200				
	Q22-750P2				
Suzhou Langxin Precision Optics Co., Ltd	MRP-300	70/200 mm	Microcrystal, ULE, BK7, monocrystalline silicon, SiC, etc.	Plane, sphere, higher order aspherical surface, etc.	① RMS < 10 nm ② RMS < 0.6 nm
	MRP-600	70/200/340 mm			
	MRP-1000	200/340 mm			
Changguang Daqi Technology Co., Ltd	DQ-8	50/80/160/360 mm	K9, fused quartz, ULE, silicon carbide, etc.	Plane, sphere, quadric surface, etc.	RMS ≤ 5 nm
	DQ-5				
	DQ-Flip-300	50/80/160 mm			
	DQ-RM-150				
Hunan Norbest Technology Co., Ltd	ZJY-NCM-600	50/100/200 mm	Quartz, microcrystal, ULE, sapphire, etc.	Plane, sphere, higher order aspherical surface, etc.	① RMS < 10 nm ② RMS < 0.6 nm
	ZJY-NCM-800	100/200/340 mm			
	ZJY-NCM-1000	200/340 mm			

① is the case of batch processing; ② is the situation of laboratory processing.

model was verified by polishing experiments on monocrystalline silicon. Liu et al. [98] proposed a material removal rate model involving pressure and shear stress, verifying the model's effectiveness through experiments. Bai et al. [88] investigated the effect of variation of each removal function shape and removal amount on the material removal stability by making removal function spots. It was concluded that the volumetric material removal efficiency variation was better than 1% when processing K9 glass and Si. Further, Liu et al. [99] proposed an interactive regionalized modeling method for the impact function of aspheric optics, which was considered effective in obtaining the impact function of aspheric tools. The computational flow of their regionalized modeling method is shown in Fig. 12. Bai et al. [100] established the normal pressure and effective friction equations of the polishing region based on the continuum and dense particle flow theories. On this basis, a new magnetorheological material removal model was established. The new model reveals the generation mechanism of the shear force of the polished workpiece, and realizes the effective decoupling of the main process parameters that affect the material removal of MPF. In addition, the material removal mechanism of wheel-type magnetorheological polishing has also been investigated by the team of Schinhaerl et al. [101] at the University of Daigendorf, Germany, and the team of Guo et al. [102] Akita Prefectural University, Japan.

5.1.3.2 Trajectory planning and dwell time algorithm research Chen et al. [103] proposed a new method for measuring normal profile errors when polishing complex surfaces on machining trajectories. The workpiece's clamping accuracy, the multi-axis machining numerical control program, and the magnetorheological polishing equipment's dynamic performances are obtained by dynamic measurement of normal contour error. It provides a basis for the validation and safety check of the magnetorheological polishing process.

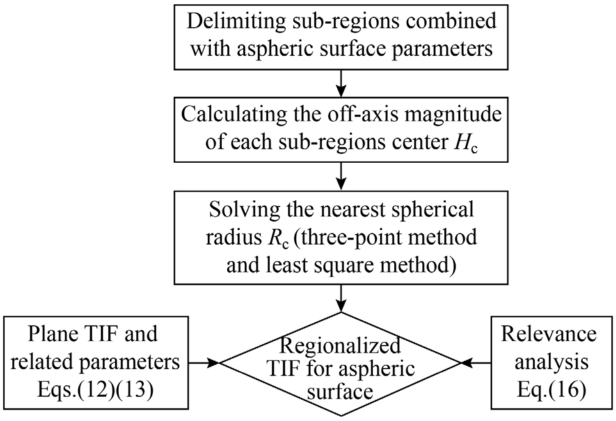


Fig. 12 Calculation flow of regionalized modeling method [99]

Schinhaerl et al. [104] proposed a new dwell time algorithm. The machining time is shortened and the polishing quality of the complex surface is improved. The results of the magnetorheological polishing series show that there is only a 5% deviation between the actual material removal characteristics of the polishing tool and the material removal characteristics expressed by the influence function. Xu et al. [105] proposed a local magnetorheological polishing removal function modeling method for complex surfaces, and solved the dwell time algorithm. The surface error PV value of complex curved surface is converged from 0.216λ to 0.033λ by experiments. It provides a new theoretical basis for wheel-type magnetorheological polishing mechanisms. Peng et al. [106] proposed a compensation machining method for complex surface magnetorheological polishing. The removal function of the spherical curvature closest to the spherical region on the complex surface was selected as the resident point removal function. The dwell time algorithm based on the linear equations model was solved. The dwell time distribution of each resident point and the surface shape residual were obtained by simulation, which improved the certainty and convergence rate of the magnetorheological polishing process. Hu et al. [107] converted the removal function matrix into the coefficient matrix of the linear equations solved by dwell time. The speed variation along the polishing path is obtained by fast iterative calculation based on the sparse matrix. Zhang et al. [108] converted the dwell time deconvolution operation into matrix operation, and used the least squares approximation and the best consistent approximation to solve the optimization model numerically. Li et al. [109] proposed a method for achieving deterministic machining of curve surfaces by using magnetorheological polishing technology under grating machining trajectories. This method is mainly achieved by combining a four-axis linkage machine tool with a variable removal function. The practicality of this method was verified through shaping experiments on a convex sphere with an aperture of 80 mm. Qian et al. [110] established a bow height error model for adjacent polishing points based on a linear grating polishing trajectory. Moreover, the variation pattern of bow height error was analyzed. Based on the variation law of bow height error, precise control of bow height error can be achieved, and processing quality can be improved. Huang et al. [111] proposed a polishing trajectory interpolation method based on an equal proportional feed rate adjustment strategy. This method can significantly improve the solving precision of dwell time and the convergence speed of shape errors in the polishing process. Gao et al. [112] proposed a dwell time optimization method based on particle swarm optimization. The method obtains the optimal selection of each dwell time point by judging the overall dwell time. Li et al. [113] proposed a fast dwell time algorithm based on the matrix computational model, combining the minimum nonnegative multiplication with adaptive regularization. This algorithm effectively solves the problem of high-precision magnetorheological machining of large-aperture optical components. In addition, Li et al. [91] also proposed a generalized surface error mapping extension algorithm applicable to any optical shape. This algorithm simplifies the MPF process effectively. Cheng et al. [114] established a step-by-step multi-level iterative trajectory error compensation method based on spatial similarity. This method can effectively compensate the trajectory error of the robot magnetorheological polishing, effectively improving the machining accuracy. Song et al. [115] proposed a universal post-processing algorithm for processing optical mirrors by grating scanning. Song et al. [116] proposed a constrained nonlinear model to solve the dwell time based on the interior point algorithm. It is considered that the finite and non-negative dwell time can be obtained in the range imposed by the CNC system and machine tool dynamics by using this model and algorithm. In order to suppress the edge effect in the polishing process, Dong et al. [117] proposed a modified dwell time optimization model through iterative and numerical methods. It is concluded that a smooth, continuous and non-negative dwell time graph and root-mean-square convergence rate of 99.6% can be obtained using this workpiece simulation model.

5.1.4 Process research

With the importance of magnetorheological polishing technology in the technological revolution, the practicality of wheel-type magnetorheological polishing technology has been studied. Byung et al. [118] analyzed the effect of each factor on the polishing removal rate by designing a five-factor, two-level orthogonal experiment. It was concluded that the magnetic field strength, carbonyl iron powder volume fraction, and polishing depth significantly affected the removal rate. Peng et al. [61] polished 80 mm × 80 mm KDP crystals by using wheel-type magnetorheological polishing equipment, and obtained a high-quality surface with a surface roughness of 1.2 nm. Li [25] used self-developed MRF360 wheel-type polishing equipment to polish 1.5 m scale off-axis aspherical surfaces and obtained a surface quality of 12.9 nm. The actual picture of its processing is shown in Fig. 13. Their polishing results are shown in Fig. 14. Liu et al. [119] studied the effects of wheel magnetorheological polishing technology on the removal effect of the sub-surface damage layer of quartz glass. After processing, they believed that sub-surface damage layer was reduced from 18 nm to 4 nm. The magnetorheological polishing technology proved to be able to remove the sub-surface damaged layer. Shi et al. [120] explored the inhibitory effect of wheel-type magnetorheological polishing technology on the "comet tail" defect on the surface of monocrystal silicon through experimental and simulation methods. They concluded that reasonable technological parameters could effectively suppress the "comet tail" defect.

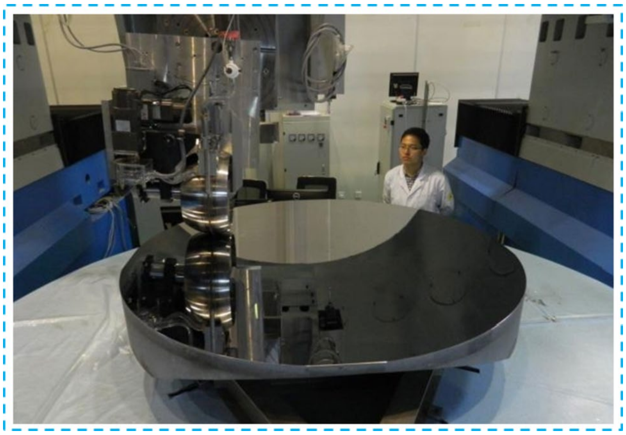
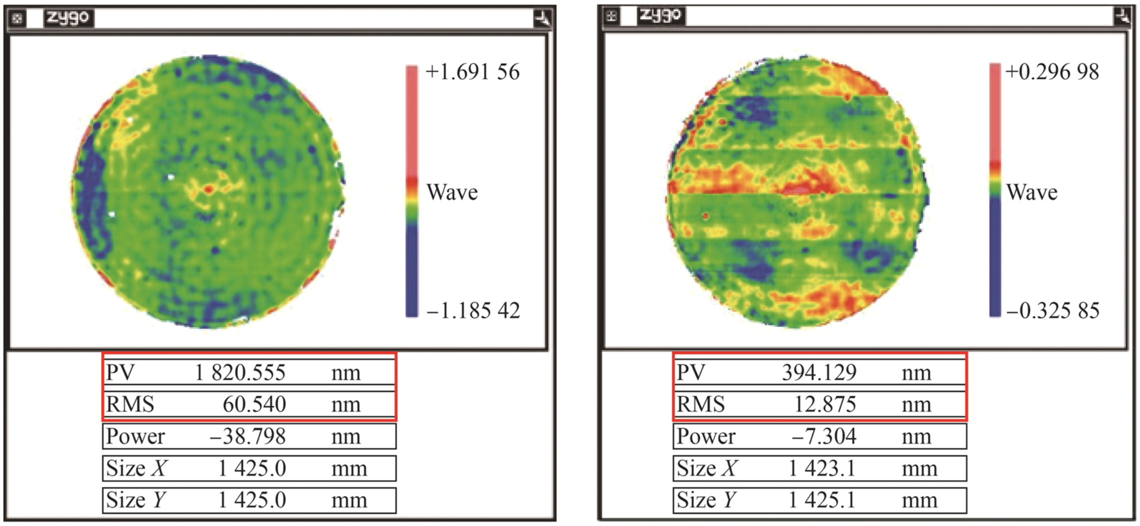


Fig. 13 MRF360 wheel type magnetorheological polishing machine processing physical [25]

In summary, wheel-type magnetorheological polishing technology is the most mature and widely used. It is mainly reflected in the following aspects: many polishing equipments developed which can be used for processing large-size, aspheric, and spherical components. It has a wide range of applications. The theoretical basis is perfect. The theoretical model of material volume removal rate and shear force, and the dynamic model of complex surface local area removal function are established, which has certain guiding significance for practical production. The machining stability is high. The ultra-precision polishing of optical materials such as monocrystal silicon, K9 glass, quartz glass and KDP crystal can be completed. The ultra-smooth, less/no damage machining surface can be obtained.

Although wheel-type magnetorheological polishing is considered as the most mature technology, it has some limitations. It is mainly reflected in the following aspects: the polishing wheel is in point contact with the workpiece when working. The number of abrasive particles involved in material removal per unit of time is small, which makes the material removal rate of the workpiece low. The polishing wheel has a single-motion track. There will be an overlap error between the two motion tracks, so the workpiece surface will have a certain error copy. Wheel-type polishing equipment requires high precision and is mainly made of large machines, which makes the equipment cost expensive. Due to the wheel's size limitation, only aspheric machining of apertures larger than 8 mm is currently possible [121]. Therefore, wheel-type magnetorheological polishing technology still has a certain development space. Further research can be carried out on material removal rate, surface quality, equipment cost and limit size machining.



PV	1 820.555	nm
RMS	60.540	nm
Power	−38.798	nm
Size *X*	1 425.0	mm
Size *Y*	1 425.0	mm

(a)

PV	394.129	nm
RMS	12.875	nm
Power	−7.304	nm
Size *X*	1 423.1	mm
Size *Y*	1 425.1	mm

(b)

Fig. 14 Face shape of large-aperture aspheric surface before and after polishing [25] **a** before polishing, **b** after polishing

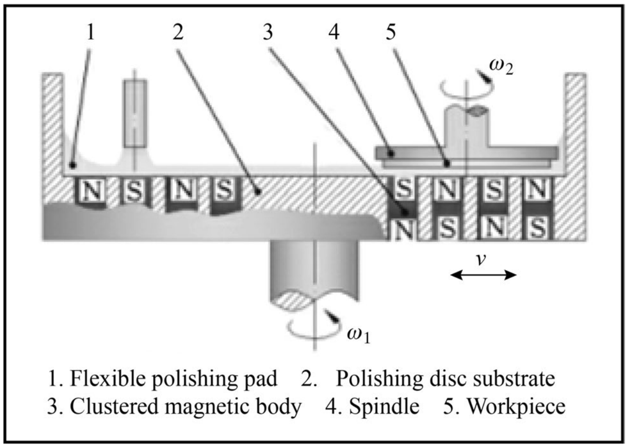


Fig. 15 Principle of cluster-type magnetorheological polishing [122]

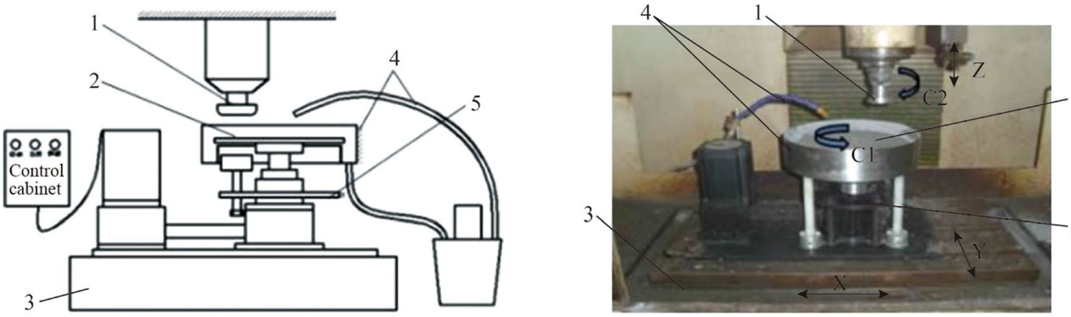
5.2 Cluster-type magnetorheological polishing technology

5.2.1 Principle introduction

The processing feature of cluster magnetorheological polishing technology is "surface contact". Its main application is the processing of planar optical parts. It has high processing efficiency. Its processing principle is shown in Fig. 15 [122]. It embeds several permanent magnets uniformly under the polishing disc according to the cluster principle, thus forming a high-intensity gradient magnetic field. Several micro-abrasive heads are formed in the MPF under the action of the magnetic field. When the workpiece rotates with the spindle, shearing action occurs between the workpiece and the micro-abrasive heads, thus realizing the purpose of polishing the workpiece with high efficiency and flatness [42].

5.2.2 Equipment research and development

Yan et al. [42] developed the first generation of cluster-type magnetorheological polishing equipment. Its structure and physical diagram are shown in Fig. 16. However, the magnetic field of the first-generation polishing equipment is static, which will lead to the poor self-recovery ability of the magnetorheological polishing pad. Thus, the processing efficiency and uniformity of the workpiece are limited. In order to further improve the limitations of static magnetic field cluster magnetorheological polishing technology. Pan et al. [123] and Guo et al. [124] proposed that a dynamic magnetic field was formed by the synchronous eccentric rotation of magnetic poles in a cluster arrangement. Its physical picture is shown in Fig. 17. It can make the distorted polishing pad self-repair in real-time. It overcomes the disadvantages that the deformation of the polishing pad is difficult to recover, and the abrasive is accumulated under a static magnetic field, making the material removal process more stable and the polishing effect better. Further, Yan et al. [125] proposed a variable gap dynamic pressure cluster-type magnetorheological polishing method based on dynamic magnetic field cluster-type magnetorheological polishing technology. Using sapphire as the research object, an experimental study was conducted to compare the two. The experimental results show that this method can increase the material removal rate of the workpiece by 19.5% and reduce the



(a) Structure of the device

(b) Real picture of the device

1. Clamping workpiece device 2. Rotary polishing disk 3. Machine body
4. Recycling and storing device 5. Adjustable magnetic device

Fig. 16 Structure and physical of the cluster-type magnetorheological polishing equipment [42]

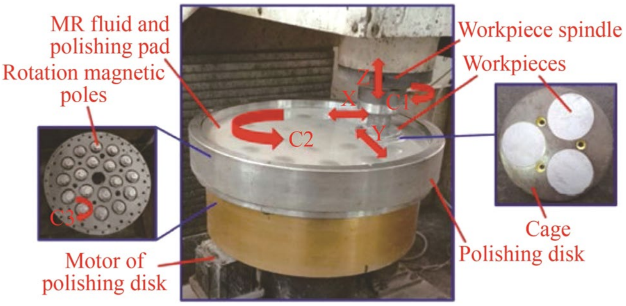


Fig. 17 Dynamic magnetic field cluster-type magnetorheological polishing equipment [123]

surface roughness by 42.96%. Experimental results show that the method is effective. Further, Luo et al. [126, 127] improved the polishing shear force by adding a round hole array to the polishing disc. Orthogonal experiments were used to optimize the size parameters of the round holes, which provided a new hardware basis for the cluster-type magnetorheological polishing technology. The structure and physical diagram are shown in Fig. 18. In addition, Lu et al. [128] of Changchun University of Technology also researched cluster-type magnetorheological polishing technology and developed reciprocating cluster-type magnetorheological polishing equipment. The physical picture of which is shown in Fig. 19.

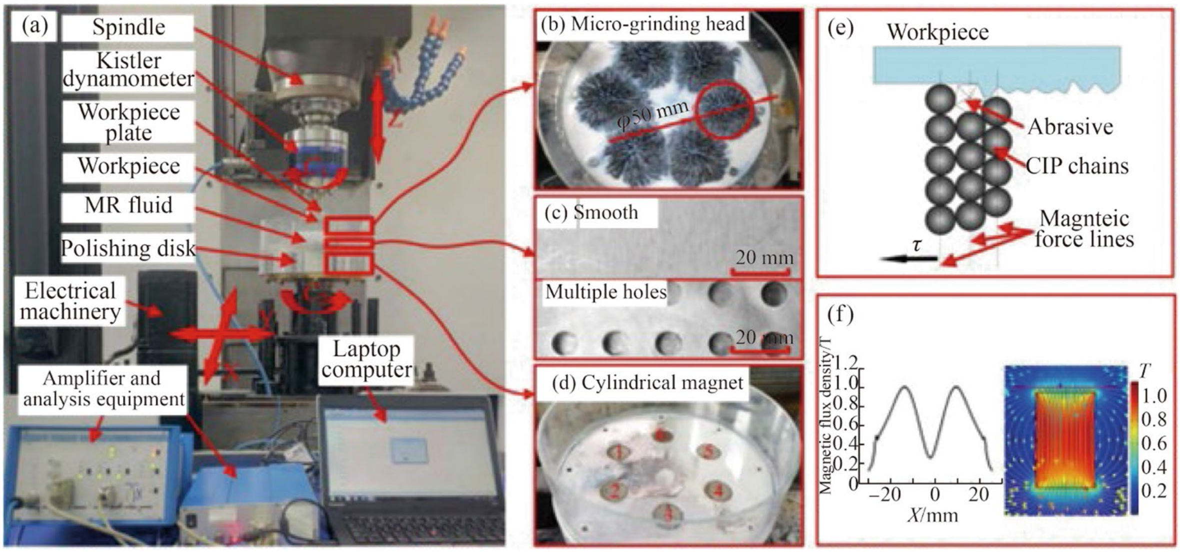


Fig. 18 Circular hole array type dynamic magnetic field cluster-type magnetorheological polishing equipment [126]

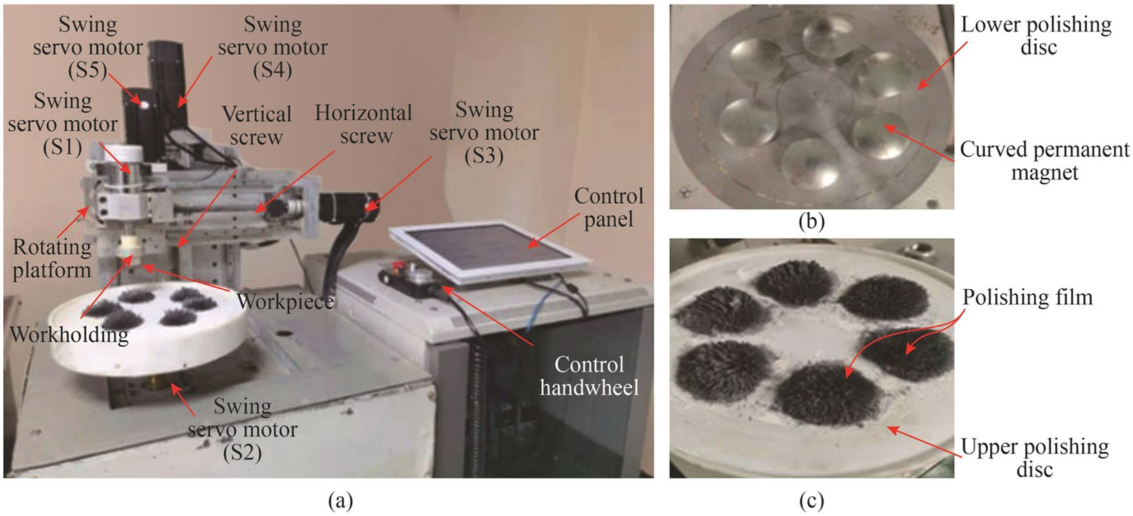


Fig. 19 Reciprocating cluster-type magnetorheological polishing equipment [128] **a** device structure, **b** magnetic field generation device, **c** magnetorheological polishing film

5.2.3 *Theoretical research*

Based on a series of magnetorheological polishing equipments developed by cluster-type magnetorheological polishing technology, many scholars have carried out a lot of theoretical research on material removal model, polishing force modeling, machining trajectory and so on. The Preston equation by introducing a correlation coefficient was modified in Refs. [129, 130]. Moreover, the workpiece polishing pressure was calculated based on the magnetic field distribution in the cluster-type magnetorheological polishing device. The material removal rate model for cluster-type magnetorheological polishing of silicon carbide was established. It provides theoretical guidance for cluster-type magnetorheological polishing technology. Pan et al. [131] studied the characteristics of the polishing force of the magnetorheological effect of a single-point dynamic magnetic field. It was concluded that relative to the static magnetic field, the polishing force and torque under the action of the dynamic magnetic field showed a dynamic behavior with large fluctuations, which enabled the renewal of abrasive particles in the MPF. Pan et al. [123] studied the influences of various process parameters on the polishing pressure of the workpiece surface based on fluid mechanics and the Preston equation. The material removal rate model of cluster-type magnetorheological polishing under a dynamic magnetic field was established to provide theoretical guidance for cluster-type magnetorheological polishing technology. Yan et al. [132] analyzed the mechanism of action of variable gap dynamic pressure cluster-type magnetorheological polishing. It argued that a structurally solid string of body-centered tetragonal magnetic chains was formed under the axial squeezing vibration of the workpiece, which generated greater polishing pressure and abrasive grain binding force. It promotes the reflow renewal of abrasive particles. The material removal efficiency and machining surface quality were improved. The structural changes of MPF under the action of variable clearance are shown in Fig. 20. Luo et al. [133] established the shear force and material removal rate models of solid particles in MPF based on tribological principle. It provides theoretical guidance for the magnetorheological polishing of dynamic magnetic field clusters with circular hole arrays. Luo et al. [134] established a fluid

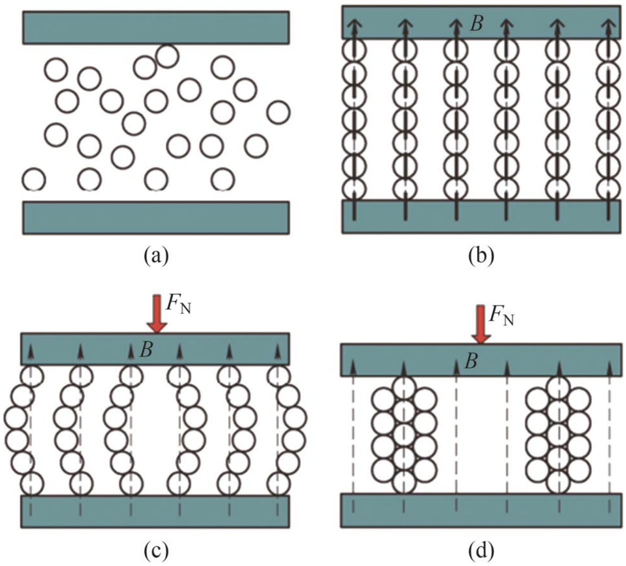


Fig. 20 Structural change of MPF under the action of variable gap **a** no applied magnetic field, **b** chains formed after applying a magnetic field, **c** the deformation of the magnetic chain string after extrusion, **d** the chain is broken and reassembled [132]

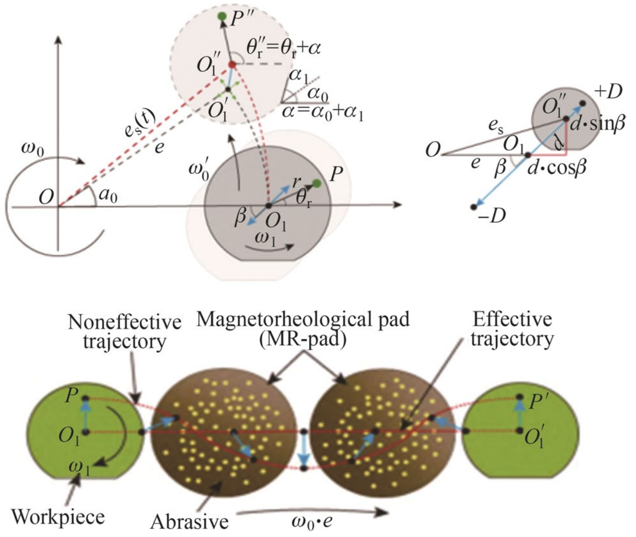


Fig. 21 Numerical model of magnetic track strength [135]

simulation model based on clearance variation MPF to evaluate the influences of changing machining clearance on MPF fluid flow field behavior. It was concluded that MPF with different gaps could improve the polishing efficiency and surface quality by changing the behavior of the flow field. Yan et al. [135] proposed a numerical model of magnetic track strength that included both effective machining track and magnetic track characteristics. This model can effectively optimize the polishing process parameters and improve the machining non-uniformity of the workpiece after polishing. The model establishment diagram is shown in Fig. 21. Zhuang et al. [136] established a material removal model related to the normal pressure, particle size, particle concentration, and the motion path length and verified the model's accuracy through experiments. Subsequently, Zhang et al. [137] optimized the material removal model of fused quartz glass by convolving the dwell time after the Fourier transform with the material removal function. The accuracy of the material removal model is further improved.

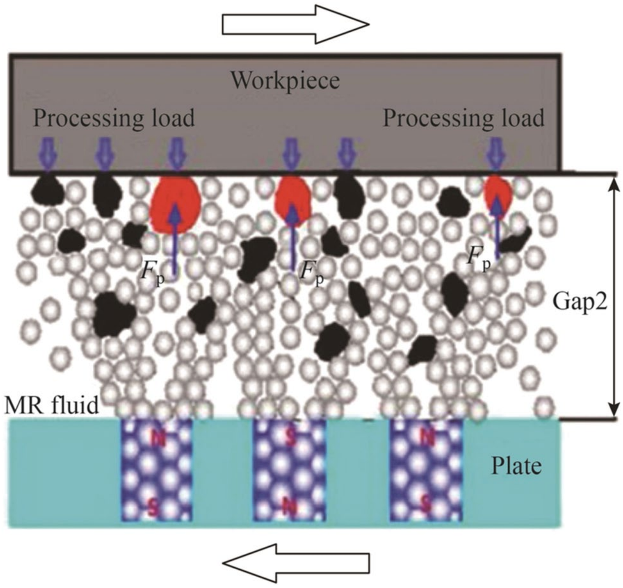
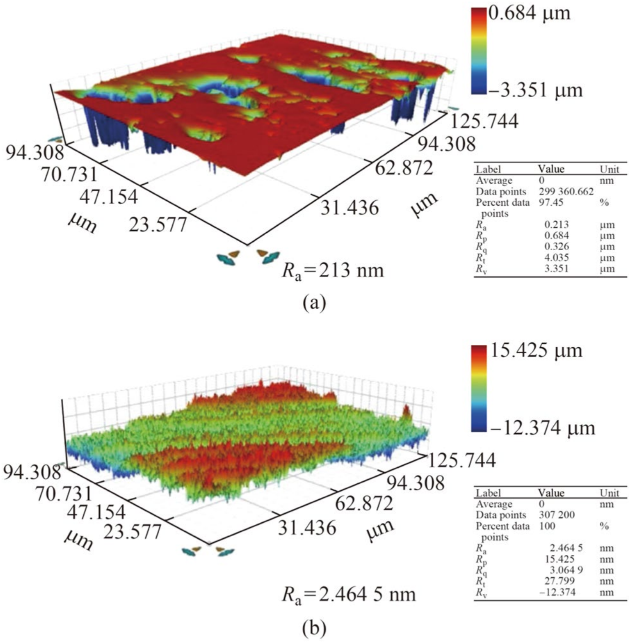


Fig. 22 Diagram of the "tolerance" effect [139]

5.2.4 *Process research*

Based on the polishing equipment and related theoretical basis developed by cluster-type magnetorheological polishing technology, many scholars have explored its process. Yan et al. [138] studied the influences of cluster magnetorheological process parameters (polishing pressure, processing speed, etc.) on the processing effect of K9 glass. The experimental results showed that the polishing method could effectively improve the processing efficiency of the workpiece, which verified the practicability of the polishing method. Bai et al. [139, 140] found abrasive particles' "tolerance" effect in cluster-type magnetorheological polishing. The effect is shown as follows: only the top of the abrasive particles of different sizes in the MPF has contact with the surface of the workpiece, which improves the effect of ultra-smooth flattening of the machined surface accordingly. The schematic diagram of the "tolerance" effect is shown in Fig. 22. Pan et al. [141] conducted polishing experiments on $SrTiO_3$ substrate material, and obtained a high-quality machined surface with a surface roughness of 8 nm and high material removal efficiency of 0.154 μm/min. Pan et al. [123] polished the monocrystalline silicon substrate with a designed three-piece tool head for 4 h, and obtained a super-smooth surface with a surface roughness R_a of 2.464 5 nm. The surface morphology of single crystal silicon before and after polishing is shown in Fig. 23. Further, Pan et al. [64] optimized the process parameters (processing gap, workpiece speed, magnetic pole speed, etc.) for multi-pole dynamic magnetic field polishing of sapphire by orthogonal experiments. The optimal process parameters obtained an ultra-smooth surface with R_a 0.27 nm. Yan et al. [142] and Liang et al. [143] polished single-crystal SiC by adding chemical reagents into MPF. It is believed that the material removal mechanism of SiC is as follows: chemical agents chemically corrode the SiC surface to form the corrosion layer. Abrasive particles remove the corrosion layer of single crystal SiC surface through mechanical action. The whole process is gradual. Lu et al. [20] optimized the magnetic field distribution of 2 mm above the electromagnet by reducing the angle of the iron core and opening annular slots with different edge angles to weaken the edge effect of the magnet. The central magnetic field intensity of the optimized electromagnet is greater than 300 mT, and the maximum magnetic field



Label	Value	Unit
Average	0	nm
Data points	299 360.662	
Percent data points	97.45	%
R_a	0.213	μm
R_p	0.684	μm
R_q	0.326	μm
R_t	4.035	μm
R_v	3.351	μm

Label	Value	Unit
Average	0	nm
Data points	307 200	
Percent data points	100	%
R_a	2.464 5	nm
R_p	15.425	nm
R_q	3.064 9	nm
R_t	27.799	nm
R_v	−12.374	nm

Fig. 23 Surface morphology of single crystal silicon before and after polishing [123] **a** before polishing, **b** after polishing

intensity is 420 mT. It provides an effective optimization method for magnetic field distribution. Zhuang et al. [136] designed a curved permanent magnet with a curvature radius of 55 mm, which effectively attenuated the influence of linear velocity on polishing. After experimental verification, the curved permanent magnet can reduce the average surface roughness from 286 nm to 16 nm and the standard deviation of surface roughness to 0.92.

In summary, cluster-type magnetorheological polishing technology uses several permanent magnets to form several polishing micro-grinding heads to achieve the purpose of high-efficiency flattening and polishing of planar workpieces, which is the more studied magnetorheological polishing technology at present. It is mainly reflected in the following aspects. The development of the polishing device has gone through four stages: static magnetic field, dynamic magnetic field, variable gap dynamic pressure, adding a round hole array on the polishing disc. It already has a piece of more mature polishing equipment. The theoretical research is complete. The shear force model and material removal rate model of solid particles in the MPF are established. The characteristics of the polishing force of the magnetorheological effect of a single-point magnetic field are analyzed. The technology adopts the idea of "surface contact" to increase the contact area between the abrasive particle and the workpiece. So the material removal rate of the workpiece increases. The dynamic magnetic field method is adopted to enhance the self-recovery ability of the polishing pad, which is beneficial to the uniformity of the machined surface.

Although there is much research on cluster magnetorheological polishing technology, some limitations exist. It is mainly reflected in the following aspects: the shape and size of the workpiece are limited to a certain extent by using the processing mode of the workpiece disk and the throwing disc under. The MPF is placed in the throwing disc, which not only limits the circulation of MPF, but also affects the rotation speed of the throwing disc. To a certain extent, the processing efficiency and stability of the workpiece are affected. Therefore, cluster-type magnetorheological polishing technology still has a certain development space. Further research can be carried out to improve the device's applicability and increase the circulation system of MPF.

5.3 Ball-type magnetorheological polishing technology

5.3.1 *Principle introduction*

The processing characteristic of ball-type magnetorheological polishing technology is "point contact". It is mainly used to machinate concave aspheric surfaces and free-form surface optical parts with small curvature radius. High surface quality can be obtained. Its processing principle is shown in Fig. 24. The MPF enters the polishing area from the top of the polishing head through the closed magnetic duct. After being magnetized by the gradient magnetic field generated by the excitation device, a spherical solid-like flexible polishing film is formed on the surface of the polishing head. The polishing film is driven by the rotating polishing head to produce a shearing motion with the workpiece surface to remove the workpiece material.

5.3.2 *Equipment research and development*

Singh et al. [44] from the Indian Institute of Technology developed solid polishing equipment based on the ball-type magnetorheological polishing technology schematic diagram. The electromagnet is used as an exciting device for polishing equipment. The polishing force of MPF on the workpiece surface is controlled by adjusting the size of the coil excitation current, and the required machining surface quality is obtained. The physical polishing equipment is shown in Fig. 25. Subsequently, Sidpara and Jain [144] improved the ball-type magnetorheological polishing equipment. They replaced the electromagnet with a permanent magnet, making the polishing equipment more convenient and practical. Su et al. [46] from the Harbin Institute of Technology also researched on ball-type magnetorheological polishing technology. They developed a small-diameter permanent magnet ball head magnetorheological polishing

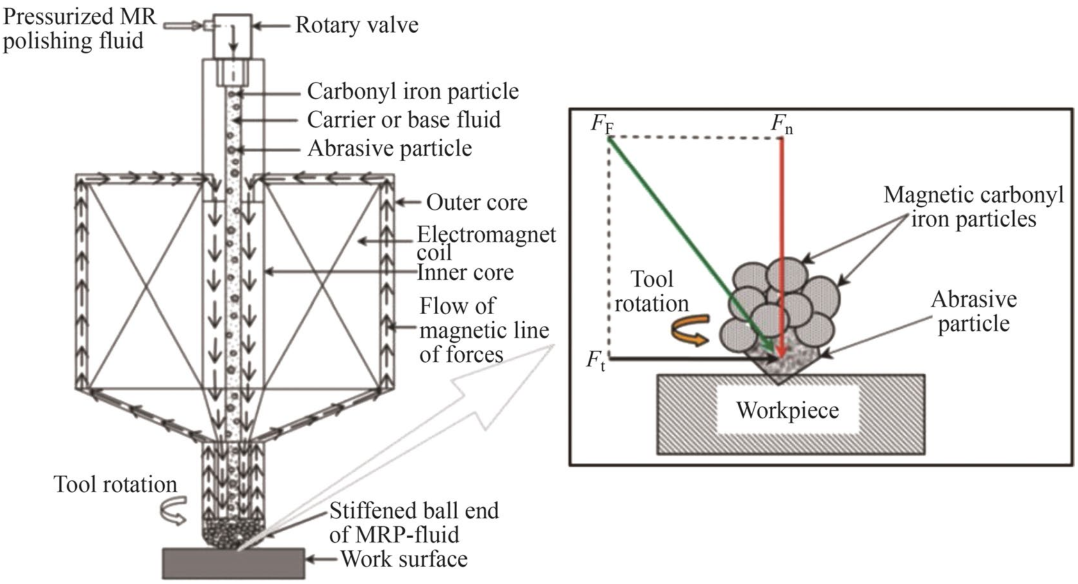


Fig. 24 Principle of ball-type magnetorheological polishing technology [43]

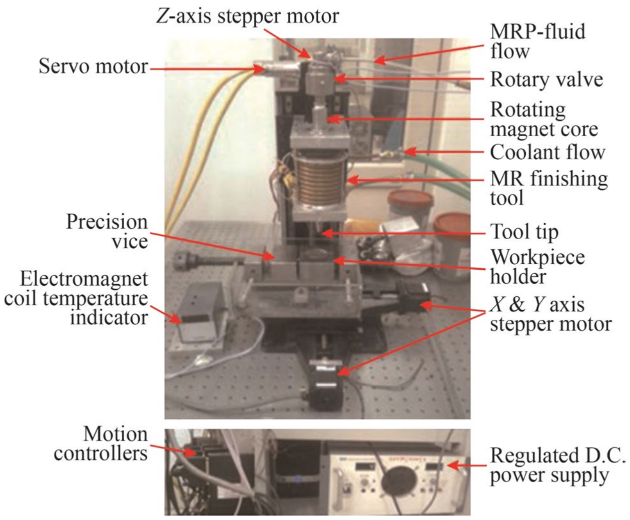


Fig. 25 Physical of the ball-type magnetorheological polishing equipment [44]

prototype, as shown in Fig. 26. Compared with the polishing equipment developed in Refs. [44], the prototype adopts a permanent magnet as the excitation device of polishing equipment. It adopts a four-axis linkage control mode, which makes the polishing head more flexible and can polish the workpiece of various curvations. In addition, the ball-type magnetorheological polishing for small aperture aspherical elements was also researched in Refs. [145–147]. The inclined axis magnetorheological polishing equipment was made, as shown in Fig. 27. The polishing principle is similar to that of the Harbin Institute of Technology, which can effectively avoid interference between the polishing head and the workpiece during processing. Further, Wang et al. [148, 149] of the Harbin Institute of Technology proposed an ultrasonic-magnetorheological composite polishing method. Its processing feature is to increase the contact efficiency of MPF and the workpiece surface through ultrasonic vibration, which effectively improves the workpiece processing efficiency and polishing quality. The developed polishing device is shown in Fig. 28 [150].

5.3.3 *Theoretical research*

Based on a series of magnetorheological polishing equipment developed by ball-type magnetorheological polishing technology, many scholars have carried out a lot of theoretical researches on material removal models, polishing force modeling, subsurface damage, etc. To better understand the relationship between abrasive grains and hydroxylated iron powder particles in a magnetic field. Zafar and Sunil [151] proposed a cell with a body-centered cubic (BCC) structure. They established a theoretical model for surface roughness during ball-type magnetorheological polishing, which provided a new theoretical basis for its mechanistic study. The BCC structure is shown in Fig. 29. Xu et al. [152] established a three-dimensional material removal model for the magnetorheological polishing zone of a small-diameter permanent magnet ball head by combining the analytical methods of lubrication fluid dynamics of sliding bearings. It is considered that the workpiece surface material removal is dominated by shear force removal. Chen et al. [153] performed a hydrodynamic analysis of the magnetorheological polishing zone of a small-diameter permanent magnet ball head. The primary analytical relationships among shear stress and apparent viscosity, flow velocity and dynamic fluid pressure were obtained, as shown in

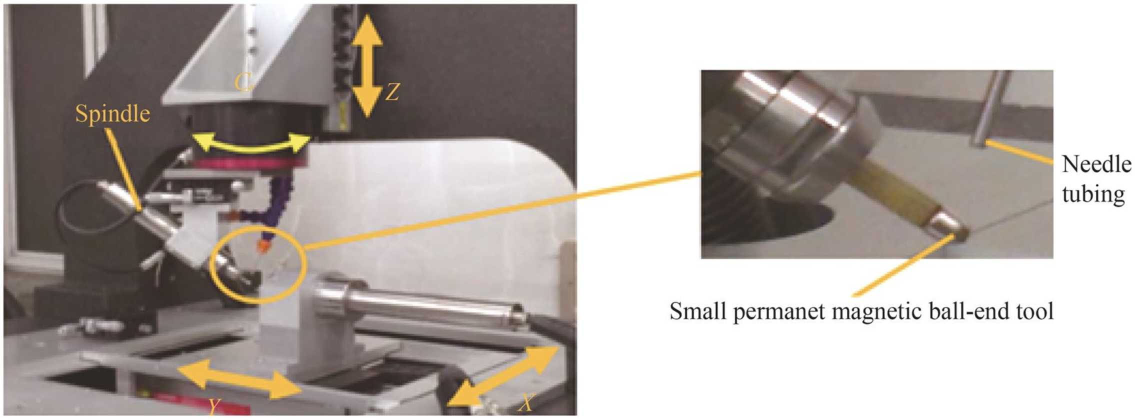
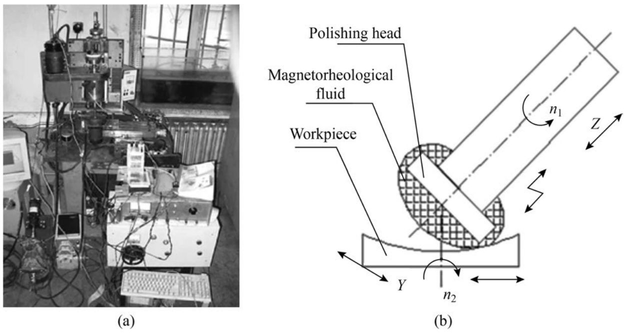


Fig. 26 Small-diameter permanent magnet ball head magnetorheological polishing prototype [46]

Fig. 27 Inclined axis magnetorheological polishing equipment [145]



(a) (b)

Fig. 28 Ultrasonic-magnetorheological composite polishing equipment [150]

Eq. (1). Wang et al. [154] established a material removal function model for ultrasonic-magnetorheological composite polishing and carried out experimental validation, which laid the theoretical foundation for its extension. Liu et al. [155] compared the effect of ultrasonic-assisted polishing with conventional polishing on the surface and subsurface damage of SiCp/Al composites by finite element simulation. It is believed that ultrasonic assistance can reduce the surface and subsurface damage of SiCp/Al composites.

$$\tau = \begin{cases} \eta_0 \gamma + +\mathrm{sign}(\gamma)\tau_0, & |\tau| > \tau_0, \\ 0, & |\tau| < \tau_0, \end{cases} \tag{1}$$

where τ is the shear stress; η_0 is the viscosity; $\dot{\gamma}$ is the flow rate; τ_0 is the fluid dynamic pressure.

5.3.4 Process research

Based on the polishing equipment developed by the ball-type magnetorheological polishing technology and related theoretical basis, many scholars have explored its process. The related processes based on this equipment was studied in Refs. [156–160]. The polishing force of the MPF on the surface of the workpiece is controlled by adjusting the magnitude of the excitation current of the coil. The surface roughness R_a of 16.6 nm was obtained by polishing the planar workpiece of ferromagnetic material. Typical three-dimensional surfaces were polished to obtain a surface quality of R_a of 19.7 nm. BK7 optical glass and copper alloy surfaces were polished with a surface roughness R_a of 22 nm and 28.8 nm, respectively. Further, Sidpara and Jain [161] realized the polishing of the surface of complex free-form knee joint by driving a three-axis CNC milling machine, and the optimal surface roughness R_a was 28 nm. Tian et al. [162] explored the effect of MPF temperature on the material removal rate by developing a hydrodynamic model of the polishing region. It was concluded that increasing the temperature could significantly improve the polishing efficiency and polishing quality. The processing performance is shown in Fig. 30. Singh et al.

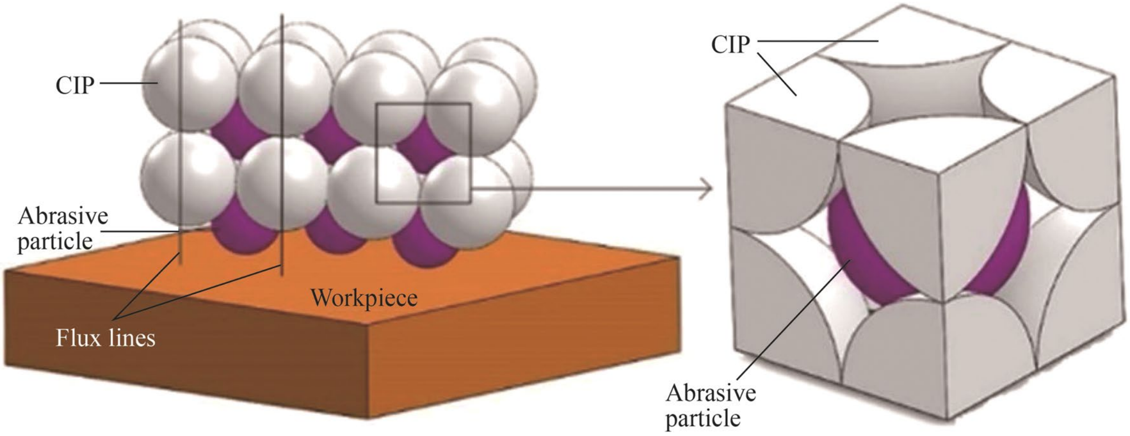


Fig. 29 BCC structure [151]

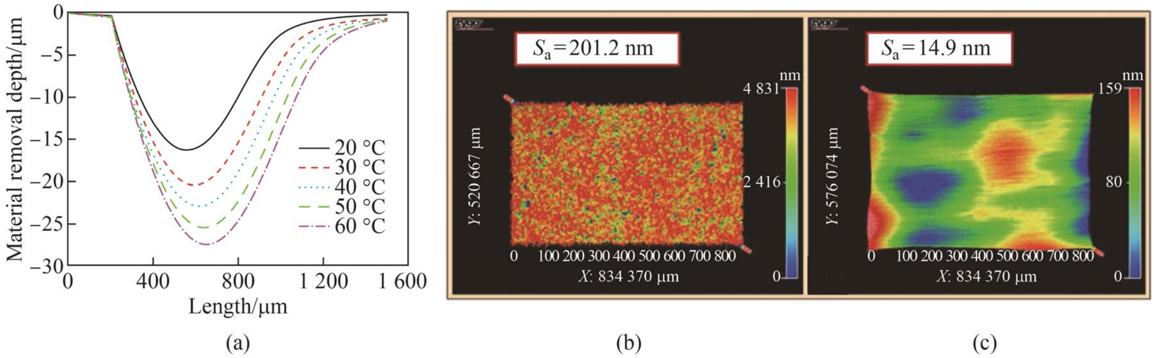


Fig. 30 Effect of different MPF temperatures on the process performance of permanent magnet ball head magnetorheological polishing [162] **a** material removal depth at different temperatures, **b** surface quality of the workpiece before and after polishing at a temperature of 60 °C

[163, 164] used response surface methodology to investigate the effect of process parameters on the percentage reduction of residual stress and surface roughness on the workpiece surface after polishing, which provided a theoretical basis for reducing the residual stress and surface roughness on the workpiece surface. Mayank and Pulak [165] investigated the contribution ratio of different process parameters (polishing speed, abrasive concentration and ultrasonic power) to the removal rate of single crystal silicon material during ultrasonic-magnetorheological composite polishing by response surface experiments. It concluded that ultrasonic power had the highest contribution to MRR at 57.9%, followed by polishing speed (13.3%) and abrasive concentration (12.5%). Hu [166] compared the effects of magnetorheological-ultrasonic composite polishing and magnetorheological polishing on the processing performance of zirconia ceramics. It was concluded that magnetorheological-ultrasonic composite polishing could effectively enhance the material removal rate of zirconia ceramics, but the surface roughness did not change significantly. The processing performance comparison is shown in Fig. 31. In order to reduce the error brought by the traditional measurement method, Lqbal et al. [167] realized in-situ measurement of the workpiece during machining by integrating a focusing sensor into the ball-type magnetorheological polishing equipment. They verified the feasibility of this method through experiments.

In summary, the main target of ball-type magnetorheological polishing technology is a small aperture and irregular optical component. Scholars at home and abroad have carried out a lot of researches. It is mainly reflected in the following aspects: the structure of the polishing device is simple and the polishing head is flexible. It is not limited by the shape and size of the workpiece and has a wide range of applications. The theoretical research is sufficient. The corresponding theoretical models of surface roughness and material removal are established, which can be used to guide practical production. The technology process is relatively mature, and there are corresponding studies on ferromagnetic materials, copper alloys and glass.

Although this technology has unique advantages in processing special-shaped parts and small diameter workpieces, it still

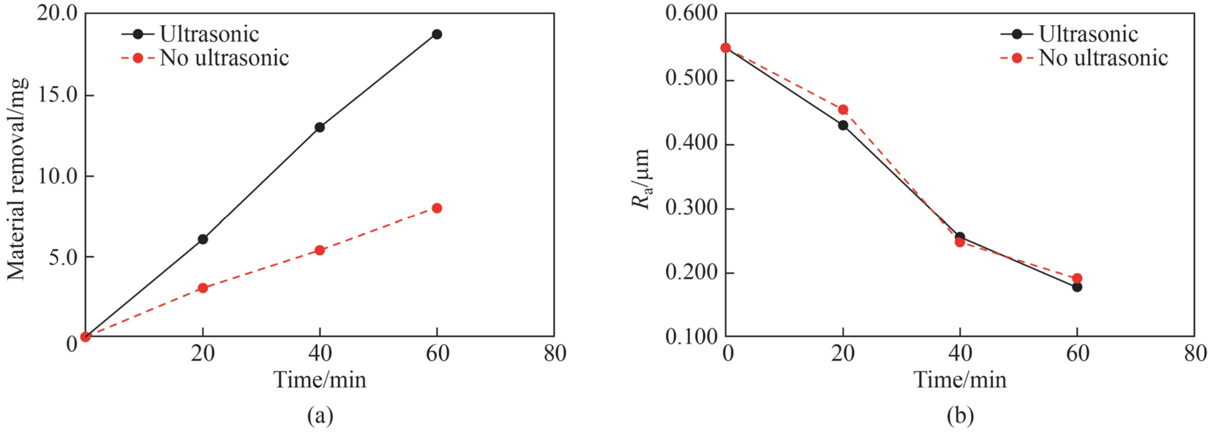


Fig. 31 Comparison of the processing performance of magnetorheological-ultrasonic composite polishing and magnetorheological polishing [166] **a** material removal, **b** surface roughness

has certain limitations. It is mainly reflected in the following aspects: due to the point contact between the polishing head and the workpiece, the material removal rate of the workpiece is low. When the workpiece is processed with complex opposites, a more precise control system is needed to control the precise displacement of the polishing head, increasing the polishing process's difficulty. Therefore, ball-type magnetorheological polishing technology still has a certain development space. Later, the polishing head can be fixed on the mechanical arm to increase its flexibility and controllability.

5.4 Disc-type magnetorheological polishing technology

5.4.1 *Principle introduction*

The processing characteristic of disc-type magnetorheological polishing technology is "surface contact". It is mainly used in the machining of large aperture planar optical parts. It has high processing efficiency and quality. Its processing principle is shown in Fig. 32. The magnetic field gradient is controlled by adjusting the excitation device in the polishing process, thus creating a large rectangular hardened area on the surface of the polishing disc. With the rotation of the workpiece spindle and polishing disc, shearing motion occurs between the workpiece surface and the large polishing tool, thus achieving the removal of material from the workpiece surface [168].

5.4.2 *Equipment research and development*

Based on the principle of Fig. 32, Yin et al. [169] built a magnetorheological plane polishing equipment with a large polishing mode, as shown in Fig. 33a. The equipment adopts the polishing method of workpiece on the top and polishing

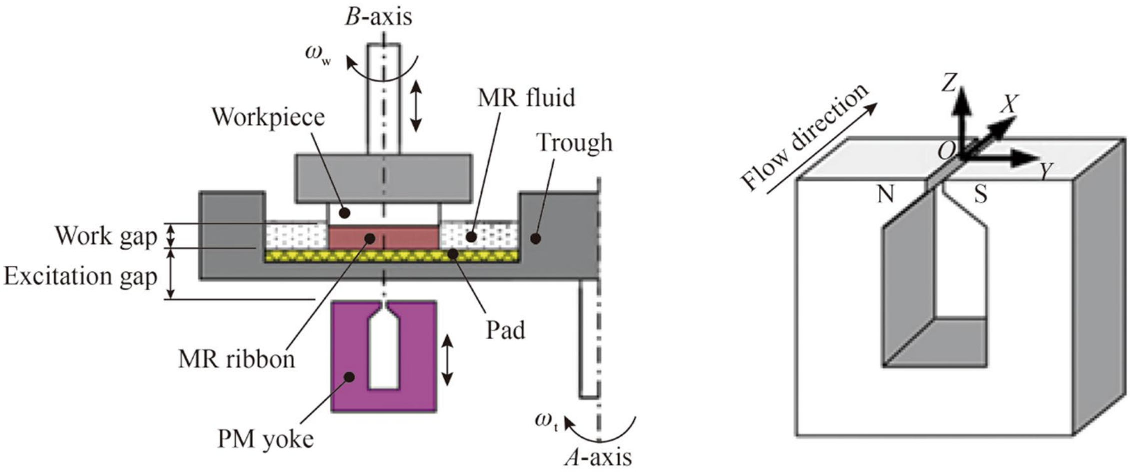
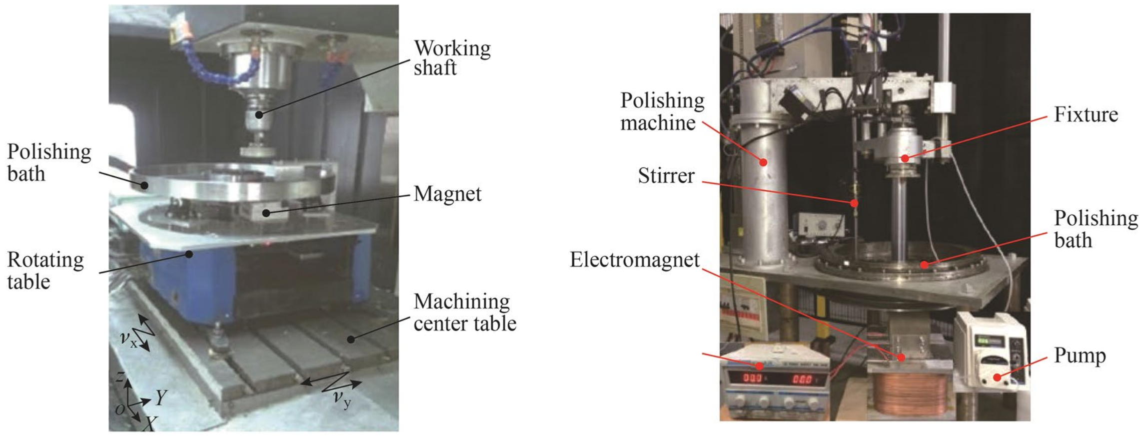


Fig. 32 Principle of magnetorheological polishing of large polished tool [47]



(a)

(b)

Fig. 33 Large polishing mold magnetorheological polishing equipment **a** permanent magnet [169], **b** electromagnet [68]

disc under, and uses permanent magnet as the excitation device. The polishing experiment of K9 glass verifies the practicability of the technology. However, the permanent magnet's magnetic field strength and distribution area are limited, which makes the polishing efficiency and accuracy need to be further improved. Guo et al. [68] improved the excitation device of magnetorheological polishing equipment for large polishing mold, as shown in Fig. 33b. The direct current electromagnet is used instead of a permanent magnet. The structure of the yoke is improved, and the structure of the pole of the array with sharp teeth and curved edges is designed to improve the problem of the permanent magnet. However, whether it is a permanent magnet or an improved direct current electromagnet, it produces a static magnetic field. Only when the MPF passes through the magnetic field processing area can it harden and make the abrasive move. In contrast, the abrasive is easy to accumulate in other areas without magnetic field. Therefore, Wu et al. [170] proposed using low-frequency alternating current as an electromagnet to stimulate the generation of the dynamic magnetic field. The magnetic field line of the dynamic magnetic field is constantly changing, thus promoting the uniform distribution of abrasive particles. The magnetic field motion mode and polishing effect are shown in Fig. 34. In order to further increase the size range of the workpiece to be processed, top-disc magnetorheological polishing based on the methods of small grinding head polishing and large polishing mode plane polishing was proposed in Refs. [171, 172]. Its principle is shown in Fig. 35a, and its processing effect is shown in Fig. 35c. It is worth mentioning that the equipment is equipped with an MPF circulation system, which is the first time that the MPF circulation system is applied to the disc polishing technology. It further promotes the development of technology in the direction of practicality and polishing stability.

5.4.3 *Theoretical research*

Based on the magnetorheological polishing equipment developed by disc-type magnetorheological polishing technology, many scholars have carried out relevant theoretical research on material removal model, polishing force modeling, sub-surface damage, etc. Wang et al. [173] established the motion trajectory equation of the workpiece on the magnetorheological hardening polishing tool, and based on the trajectory equation, the mathematical model of material removal was established. It lays a theoretical foundation for applying large polishing mode plane magnetorheological polishing. Guan et al. [174] established a workpiece material removal model and surface roughness prediction model based on self-developed polishing equipment. They conducted theoretical research on key parameters' influence on material removal efficiency and stability. Further, Luo [175] investigated the mechanism of sub-surface damage generation in the magnetorheological polishing of large polished mode. A mathematical model for damage layer depth prediction was developed and experimentally verified. A high-quality surface with sub-nanometer surface roughness and only a few tens of nanometer damage layers was obtained. The subsurface damage layer is shown in Fig. 36.

5.4.4 *Process research*

Based on the polishing equipment and related theoretical basis developed by disc-type magnetorheological polishing technology, many scholars have explored its process. Wang et al. [176, 177] conducted polishing experiments on K9 glass using a self-designed permanent yoke large polishing tool magnetorheological polishing equipment. An efficient and high-quality polish with the maximum volume removal rate of 0.794 mm^3/min, a face shape accuracy PV of 1 μm and a

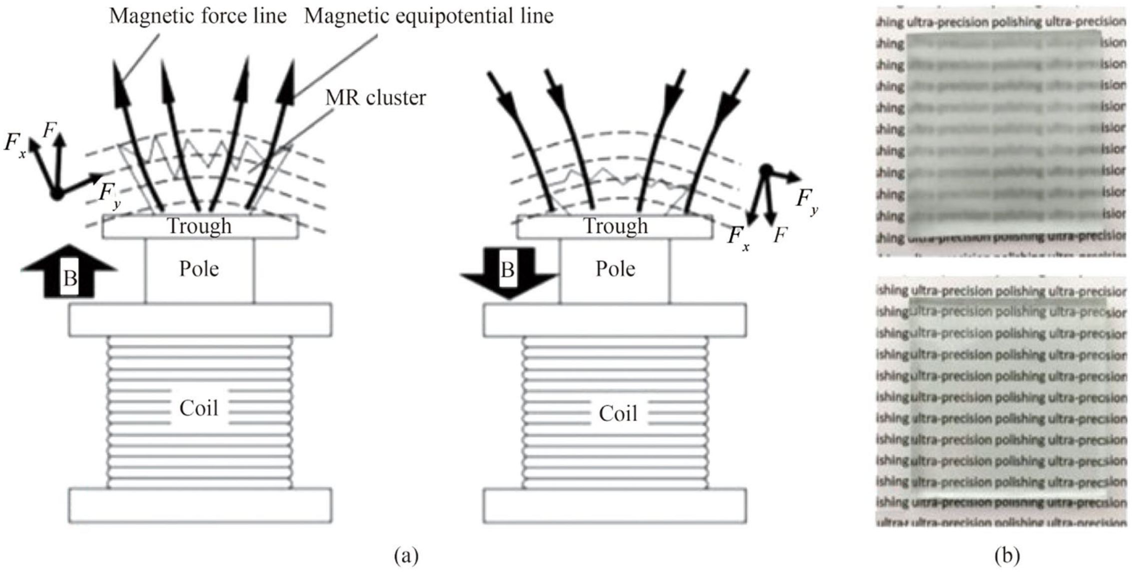


Fig. 34 Magnetic field motion pattern and polishing effect [170] **a** magnetic field motion pattern, **b** polishing effect

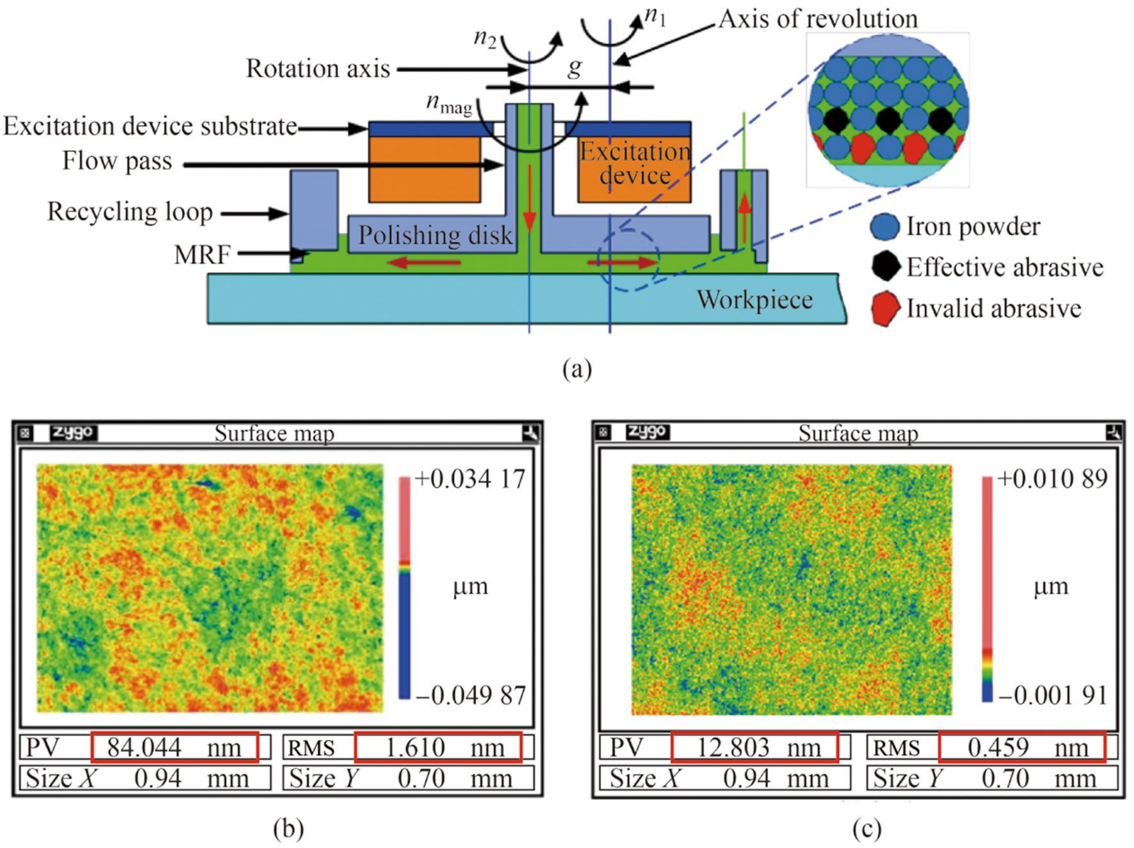


Fig. 35 Disc-type magnetorheological polishing technology [172] **a** principle of disc-type magnetorheological polishing, **b** before polishing, **c** after polishing

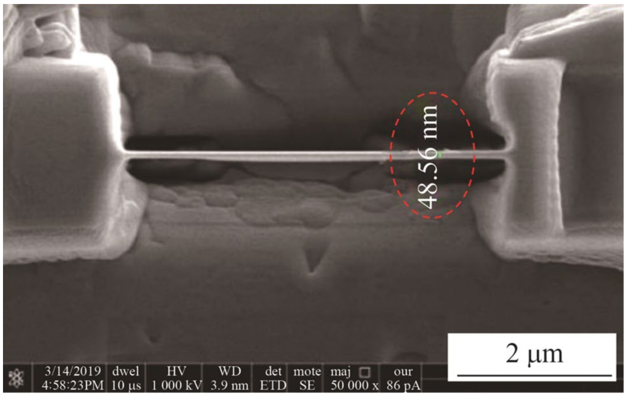


Fig. 36 Subsurface damage layer [175]

surface roughness of 0.6 nm was obtained. The effects of DC electromagnet magnetorheological polishing process parameters (polishing time, working gap and workpiece speed) on the machining properties of zirconia ceramics and monocrystal silicon were studied in Refs. [15, 68]. It is considered that under the optimal process parameters, a super-smooth surface with R_a of 0.7 nm can be obtained for zirconia ceramics, and a super-smooth surface with R_a of 0.4 nm can be obtained for monocrystalline silicon. The processing effect diagram is shown in Fig. 37. Jian et al. [65] composed a complex MPF by adding an oxidant and catalyst. The single crystal Si was polished with the composite polishing solution, and a high-quality surface of R_a 0.5 nm was obtained. Yang et al. [178] optimized the process parameters (polishing pressure, polishing disc speed, etc.) of magnetorheological polishing of sapphire disc by orthogonal method. It was concluded that a surface roughness R_a of 0.31 nm and a material removal rate of 2.68 μm/h were obtained under the action of the optimal process parameters. Yin et al. [179] prepared composite polishing liquid with different reaction systems based on the principle of self-hydration reaction of sapphire and the characteristics of chemical reaction with silica sol. It concluded that the MPF mixed with silica sol and α-Al_2O_3 abrasive had the highest removal efficiency, and obtained an ultra-smooth surface with R_a of 0.3 nm.

In summary, the technology is mainly aimed at the processing of large aperture planar optical parts, and has achieved certain processing results. Among them, Hunan University has carried out the most relevant research. The technology uses a large polishing mode to contact the surface of the workpiece, effectively improving processing efficiency. The technology has also done a lot of exploration in the process, and has accumulated certain experience in difficult materials such as monocrystalline silicon and zirconia. However, this technology also has some limitations, mainly reflected in the technology for the large diameter curved components processing is more difficult. Therefore, there is still some room for development of this technology. Subsequently, the five-axis CNC system can be added to the disc-type magnetorheological polishing equipment, so that it can adapt to the machining of large-diameter curved components.

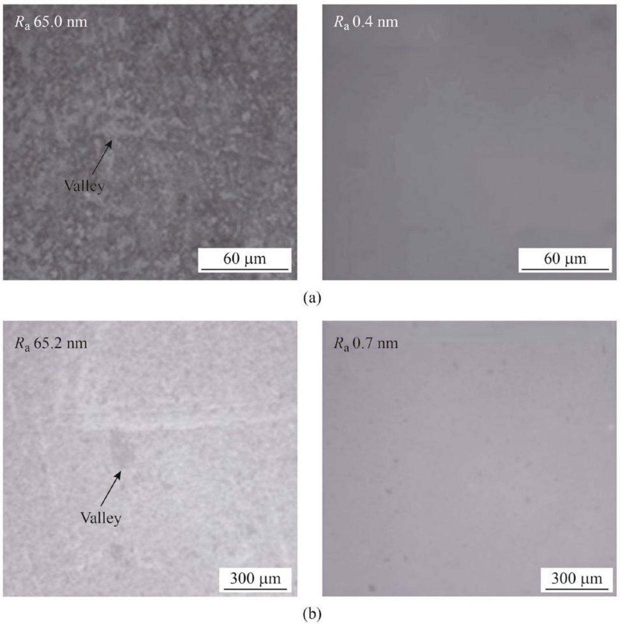


Fig. 37 Processing effects of magnetorheological polishing with DC electromagnet **a** surface quality of monocrystalline silicon before and after polishing [15], **b** surface quality before and after zirconia polishing [68]

5.5 Other forms of magnetorheological polishing technology

5.5.1 Rotation-typemagnetorheological polishing technology

Currently, various finishing parts (including molds for steering rack housings and actuators) have high requirements for blind hole cavities with surface finishing during injection molding [180]. To reduce the frictional characteristics and improve the functional efficiency of the blind hole cavity, Talwinder and Anant [181] proposed a rotation-type magnetorheological polishing technology. It is mainly used in the machining of blind cavity parts. The processing principle is shown in Fig. 38. Cylindrical permanent magnets are fixed to the spindle and MPF is distributed around the permanent magnets to form the polishing head. The polishing head rotates and moves to remove the material from the inner and bottom surfaces of the blind cavity, which results in a high-quality machined surface.

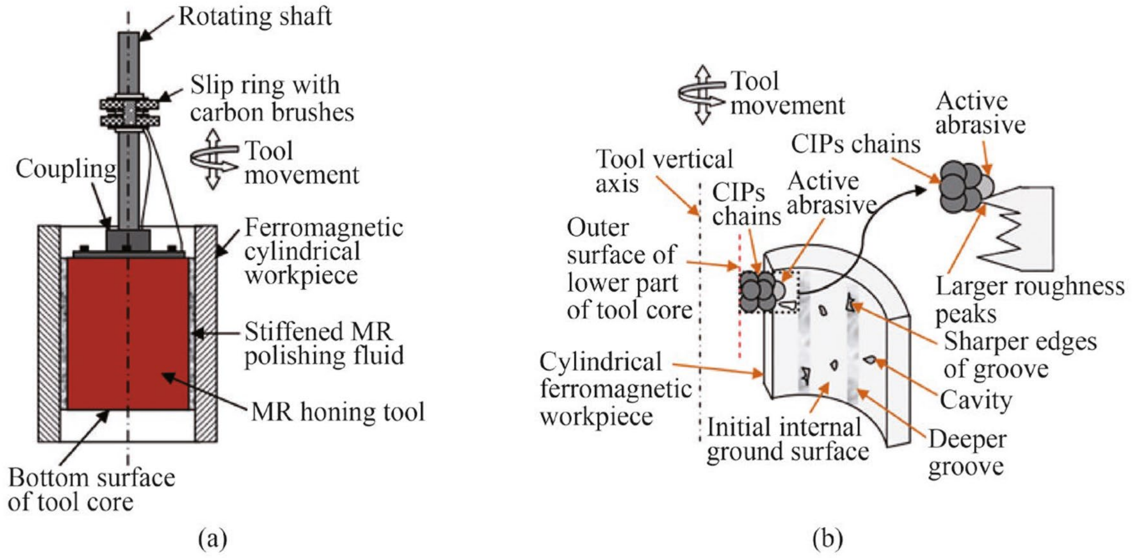


Fig. 38 Rotation-type magnetorheological polishing [181] **a** working principle, **b** material removal mechanism

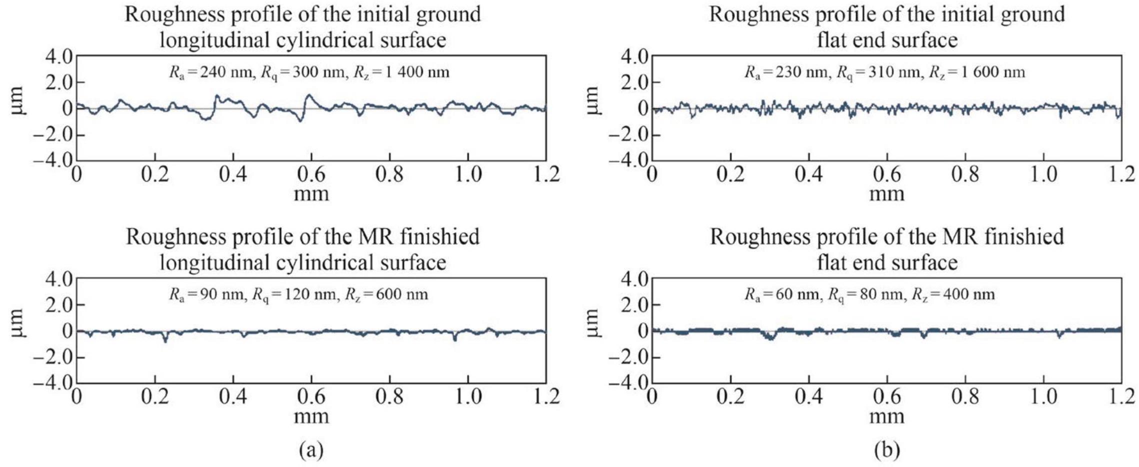


Fig. 39 Comparison of the machining effect between the inner wall and the bottom surface of the cylindrical blind hole [182] **a** inner wall, **b** bottom surface

Aggarwal and Singh [182] used this technology to polish the inner wall and bottom surface of a cylindrical blind hole, resulting in a 72% reduction in the inner wall surface roughness and 79% reduction in the bottom surface roughness, which verified the usefulness of the technology. The comparison of its processing effect is shown in Fig. 39. Further, Aggarwal and Singh [183] optimized the process parameters (working gap, current, workpiece speed, etc.) for the rotation-type magnetorheological polishing technology. The polishing of EN-31 CBH-type cavities was carried out under optimal process parameters and good polishing results were achieved. Sirwal and Singh [184] developed a theoretical model for predicting machined surface roughness. The correctness of the theoretical model was verified by polishing experiments on the side and bottom surfaces of blind-hole workpieces with two forms of polishing heads, while providing a theoretical basis for the development of the technology. Sunil and Auant [185] investigated the effect of the motion behavior of abrasive grains in magnetorheological fluid on the polishing effect. It was concluded that the abrasive grains' simultaneous rotational and reciprocating motion was the main factor in enhancing the polishing effect. Yahya et al. [186] proposed a vibration-assisted rotation-type magnetorheological polishing technology to further improve the processing efficiency of the rotation-type magnetorheological polishing technology. The effect of this technology

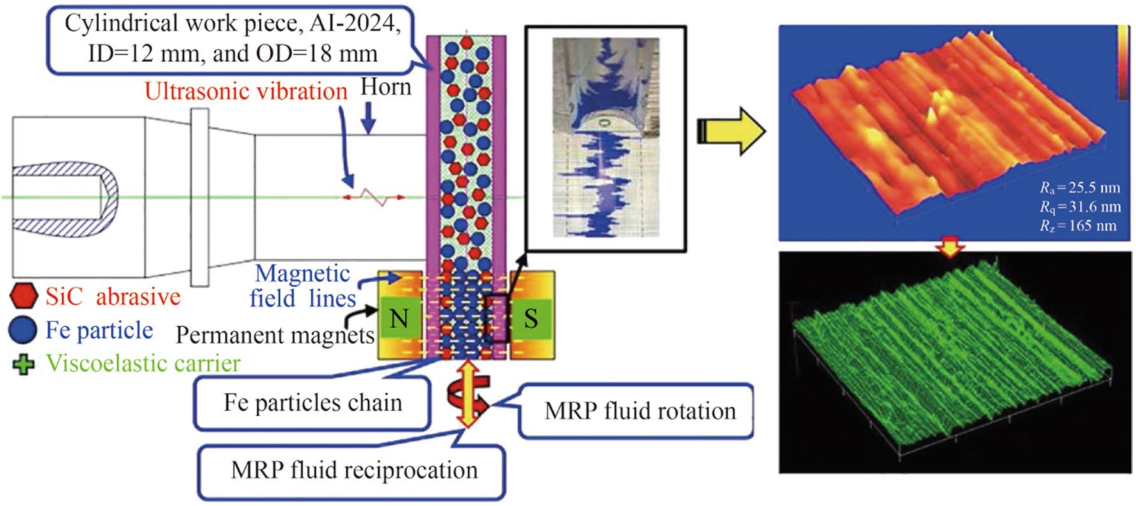


Fig. 40 Working principle and processing effect of vibration assisted rotation-type magnetorheological polishing technology [186]

on the processing efficiency of the aluminum alloy 2024 tube workpiece was experimentally investigated. The technology can effectively improve the processing efficiency of the workpiece and achieve a better polishing effect. The processing principle and processing effect are shown in Fig. 40.

In summary, rotation-type magnetorheological polishing technology removes material from the inner and bottom surface of the blind hole cavity parts by rotating and moving the polishing head up and down to obtain high-quality machined surfaces. This technology successfully overcomes the problems of low efficiency and poor quality of traditional processing technology. This technology has done much work in process research and theoretical analysis, providing a basis for the further development.

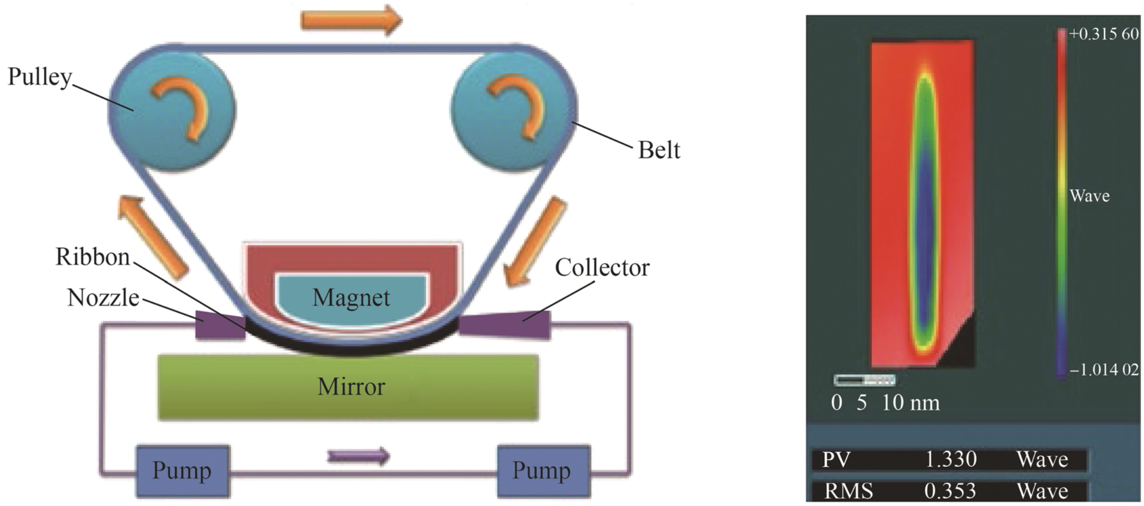
However, the technology has some limitations. It is mainly reflected in the following aspects: the polishing head of the technology is inserted into the cavity of the component, which makes it difficult to cycle the MPF. This technology has relatively high requirements for detection technology and precision control technology in the processing process, while the technical level of existing research is limited. Therefore, rotation-type magnetorheological polishing technology still has a certain development space. Further research can be carried out in the fields of MPF cycle update, detection technology and precision control technology.

5.5.2 Belt-type magnetorheological polishing technology

The processing feature of the belt-type magnetorheological polishing technology is that the box magnetic pole is used as the exciting device to increase the curvature radius of the polishing area, which effectively improves processing efficiency [187]. It is mainly used in the machining of large-diameter flat parts. Its processing principle is shown in Fig. 41a. When working, the MPF is ejected from the nozzle by the peristaltic pump and driven to the working magnetic field area by the high-speed rotating belt. Under the action of a high gradient magnetic field, the MPF quickly forms a ribbon bulge. The relative motion of the ribbon bulge and the workpiece surface achieves material removal. The material removal function is shown in Fig. 41b.

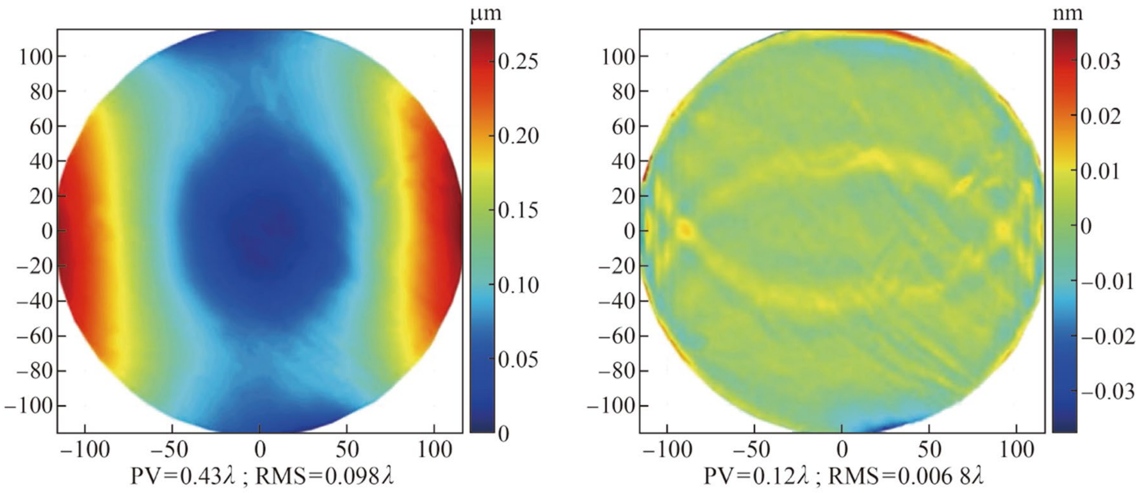
Ren et al. [188] conducted an experimental process study on BK7 glass and SiC based on self-developed belt-type magnetorheological polishing equipment. The experimental results showed that the material removal rate reached 2.52 μm/min for BK7 glass and 1.22 μm/min for SiC. Compared with the existing magnetorheological polishing device, the device can effectively improve the removal efficiency by more than five times. Wang [189] improved the belt-type magnetorheological polishing equipment based on the design of Ren et al. [188]. The problem that the MPF was prone to oxidation by heat was solved. A model of the ribbon magnetorheological removal function's distribution was obtained using the virtual ribbon bump theory and the Preston material removal rate equation. After practical experimental verification, it is concluded that the model can guide the design and selection of the ribbon magnetorheological removal function. Finally, the polishing equipment was integrated into a 2.5 m gantry machine, and a 235 mm SiC plane mirror was processed. The convergence efficiency reached 78%, which verified the belt-type magnetorheological polishing ability and high processing efficiency. The processing effect is shown in Fig. 42.

In summary, this technology increases the radius of curvature of the polishing area, so that the contact area between the workpiece and the MPF increases. That is, the material



(a) (b)

Fig. 41 Belt-type magnetorheological polishing technology [188] **a** principle of belt-type magnetorheological polishing technology, **b** material removal function



PV=0.43λ ; RMS=0.098λ
(a)

PV=0.12λ ; RMS=0.006 8λ
(b)

Fig. 42 Surface morphology of SiC before and after polishing [189] **a** before polishing, **b** after polishing

removal rate of the workpiece per unit time increases. This technology adds an MPF circulation system, which guarantees the stability of the polishing process to a certain extent. The polishing equipment is integrated into the gantry machine, which further increases the application range of this technology.

However, the technology has a single polishing direction, and obvious polishing lines will remain on the surface of the polished workpiece, which limits the further improvement of the surface quality after polishing. Therefore, there are few researches on this technology, which are limited to the research content described in the above literature.

5.5.3 *Reciprocating-type magnetorheological polishing technology*

The processing feature of the reciprocating-type magnetorheological polishing technology is that the magnetic field generating device can move reciprocally during the processing process, which effectively solves the problem of single processing texture caused by other processing methods. Its processing principle is shown in Fig. 43. The workpiece is held by a fixture mounted on the spindle. The liquid carrier tank contains the magnetorheological polishing liquid, and a magnetic field-generating device

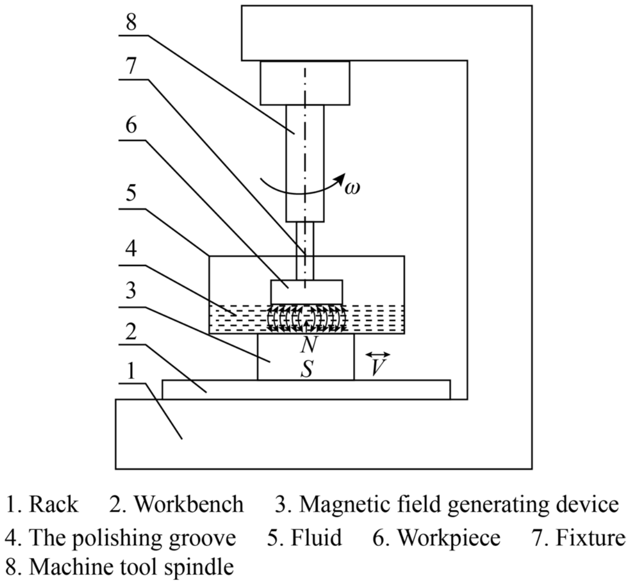


Fig. 43 Principle of reciprocating-type magnetorheological polishing technology [190]

is placed below it. In the polishing process, the rotation of the spindle drives the workpiece to run at high speed, and the reciprocating mechanism drives the reciprocating movement of the magnetic field generator. The purpose of material removal is achieved through the mutual movement of the ribbon protrusion and the workpiece.

Li [190] conducted polishing experiments on K9 glass with self-designed equipment, which reduced the surface roughness of glass by 37% and made the material removal rate reach 10 nm/min. The feasibility of this technology is verified. Ma [191] used an orthogonal experiment to optimize the process parameters and processed K9 glass under the optimal process parameters. The surface roughness of K9 glass was reduced by 88%, and the material removal rate reached 14.1 nm/min. By comparing the processing performance of this technology before and after optimization, it can be seen that the material removal efficiency of this technology is low. As a result, the development of the technology stalled for several years. Until 2021, Wang et al. [192] continued their research on reciprocating-type magnetorheological polishing. Based on the previous study, the permanent magnets used in the magnetic field generation device were replaced with electromagnets, which improved the material removal rate of K9 glass by 67%, reaching 44.3 nm/min. Wang et al. [193] optimized the process parameters (working gap, processing time, etc.) for reciprocating-type magnetorheological polishing of K9 glass by single-factor experiments. It was concluded that a high-quality surface with a surface roughness of 28 nm was obtained with the optimal process parameters. Further, Wang et al. [194] adopted the response surface method to establish the prediction model of MRR and R_a. After experimental verification, the deviation between the actual value of MRR and the predicted value was 2.31%, and R_a was 5.12%. The accuracy of the prediction model is illustrated.

In summary, this technology has carried out relevant research for uniform texture and smoothness of the surface texture of the workpiece, which changes the surface quality of the processed workpiece to a certain extent. The equipment structure is simple and the cost is small.

However, this technology still has certain limitations. It is mainly reflected in the following aspects: after experimental studies, it was confirmed that the material removal rate of this technology was low. Although the processing quality of the workpiece is improved to a certain extent, there is still a big gap compared to other polishing technologies. Moreover, the processing materials of the existing studies are only for optical glass, and no other materials are involved. Therefore, the technology needs further development.

6 Comparison of several magnetorheological polishing technology and the proposal of curvature adaptive magnetorheological polishing technology

The processing accuracy of magnetorheological polishing technology not only changes with the need for scientific and technological reform, but also varies with the material, use and processing difficulty of the workpiece being processed in the same period. Therefore, MRR, R_a, surface uniformity and application range of the above typical magnetorheological polishing technologies were compared, as shown in Table 4.

As mentioned earlier, wheel-type magnetorheological polishing technology is widely used to finish aspheric and sphere surfaces. Because of its advantages, such as, mature equipment, good stability, and not being limited by the shape of the workpiece. However, its material removal rate is low. Cluster-magnetorheological polishing technology has the advantages of all-round, high-efficiency and high-quality processing. However, the MPF of this technology is difficult to circulate and renew, and complex surface processing is difficult. Ball-type magnetorheological polishing technology has unique advantages in processing shaped parts and small-diameter workpieces. However, its material removal efficiency is low and unsuitable for efficient and low-cost ultra-smooth surface polishing processing. Disc-type magnetorheological polishing technology effectively improves the processing efficiency of workpieces. However, the MPF is difficult to circulate and renew and unsuitable for complex surface polishing. The rotation-type overcomes the problems of low processing efficiency and poor processing quality of traditional machining technology. It is mainly used for the

Table 4 Comparison of several typical magnetorheological polishing technologies

Category	MRR	R_a	Uniformity	Application
Wheel-type	Low	Smaller	Better	Aspheric surface and sphere, etc.
Cluster-type	Middle	Small	Good	Mainly planar
Ball-type	Low	Smaller	Good	Free-form surface, plane, etc.
Disc-type	High	Smaller	Better	Mainly planar
Rotation-type	High	Small	Better	Blind hole, cavity, etc.
Belt-type	High	Middle	Bad	Large aperture plane
Reciprocating-type	Middle	Middle	Bad	Mainly planar

machining of blind cavity parts. However, this technology has high requirements for detection technology and precision control technology in the machining process, and the technical level of the existing research is limited. The belt-type increases the curvature radius of the polishing area and makes the contact area between the workpiece and the MPF increase. That is, the material removal rate of the workpiece per unit time increases. However, the polishing direction of this technology is single, and obvious polishing lines will remain on the surface of the polished workpiece, which limits the further improvement of the surface quality after polishing. The reciprocating-type has simple structure and small cost, and is mainly used for the processing of flat parts. However, its material removal rate is poor, and the MPF circulation is difficult.

In summary, "point contact" can be adapted to processing various face-type workpieces, but its material removal rate is low. "Face contact" is only applicable to the processing of flat workpieces. The MPF circulation renewal also plays a big role in the polishing effect. Therefore, the author proposed a curvature adaptive magnetorheological polishing technology with a circulatory system to achieve high efficiency and high-quality machining that can adapt to various surface shapes. This technology takes into account the idea of "point contact" and "surface contact". The control system can correct the position accuracy of the polishing head and workpiece according to different face shape requirements, thus improving the efficiency of workpiece processing. At the same time, the timely renewal of MPF also provides an important guarantee for the polishing effect. The polishing principle is shown in Fig. 44. Currently, the research in this area is still in the initial stage.

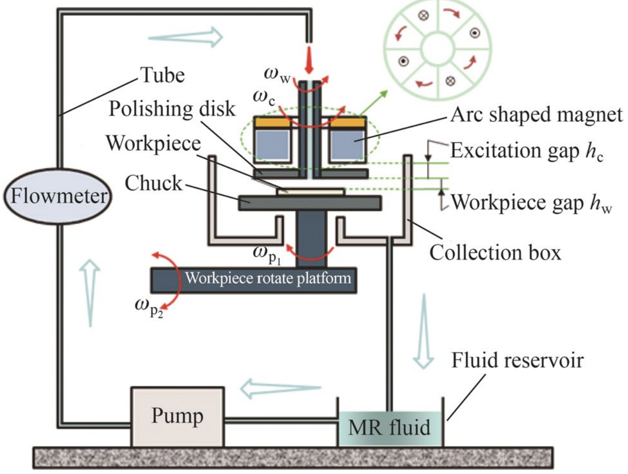


Fig. 44 Principle of curvature adaptive magnetorheological polishing technology with circulatory system

Magnetorheological polishing technology can provide an effective solution in areas requiring high-precision surface polishing. Suzhou Langxin Precision Optics Co., Ltd provides two MRP series of magnetorheological polishing application examples. Case 1, magnetorheological polishing equipment of the MRP series, was used for 25 h to polish a 422 mm calibre, coaxial paraboloid, microcrystalline glass. The RMS of the microcrystalline glass was made to converge from 0.333 2λ to 0.011λ. Case 2, magnetorheological polishing equipment of the MRP series, was used to polish a 200 mm calibre, secondary surface, fused silica for 12 h. The RMS of fused quartz converges from 0.308 2λ to 0.010 2λ. Li [25] of Changchun Institute of Optical Machinery also mentioned an example of magnetorheological polishing in his doctoral thesis. A self-developed wheel-type magnetorheological polishing equipment was used to polish a 1 500 mm calibre, off-axis aspherical, SiC for 40 h. The PV value of SiC was rapidly converged from 1 820.6 nm to 394.1 nm. The high efficiency and precision deterministic machining of large aperture aspherical magnetorheological polishing is realized. In addition, the United States QED company also provides magnetorheological polishing examples on the official website. Q series polishing equipment is used to polish the concave spherical surface with a large aperture and small curvature, and a high-quality machining effect is obtained. However, the application examples of magnetorheological polishing are limited, and subsequent development is still needed.

7 Development trend of magnetorheological polishing technology

Magnetorheological polishing technology has been an emerging ultra-precision machining method in recent years. It has attracted many scholars at home and abroad to study and made positive progress. In order to further promote the engineering application of magnetorheological polishing technology, the following prospects are proposed.

(i) Diversity of processing materials. Currently, the most important applications of magnetorheological polishing technology are on non-magnetic materials such as optical glass, ceramics, and some alloys. Few studies have pointed out that magnetorheological polishing technology can be applied to process magnetic materials. Therefore, the application range of magnetorheological polishing technology in machining materials can be expanded.

(ii) Focus on economic and environmental protection. The magnetorheological polishing mentioned above is processed using conventional abrasive grains. However, the manufacturing and processing of the abrasive itself cause energy and material consumption, and the configuration of the MPF containing chemical components can cause environmental pollution. In addition, the circulation of the MPF during the magnetorheological polishing process is one of the key factors affecting its cost. Therefore, future research on developing new green MPFs and optimizing the design of circulation devices can be carried out. This will also become an important research direction of magnetorheological polishing technology.

(iii) Enrich the theoretical system. At present, the research theory on magnetorheological polishing still needs to be completed. It is still in the developmental stage for studying the mechanism of microscale processing of material nanoscale surfaces. Some things could still be improved in applying the existing mathematical material removal model by magnetorheological polishing to guide production. Therefore, a complete system can be established to explain the mechanism of nanoscale microscale processing of materials. A complete mathematical material removal model can be established to guide production, considering the actual working conditions. In addition, the future can continue to carry out thermal, optical, electrical, acoustic and chemical multi-field coupling processing. A new method of magnetorheological composite polishing was explored to provide a new theoretical basis for magnetorheological polishing.

(iv) Intelligence. The control strategy and magnetorheological polishing method is also a hot topic in current research. Researchers have always pursued intelligent equipment to reduce the dependence of human experience and the influence of interference from external factors on experimental results. Therefore, the intelligent degree of magnetorheological polishing equipment is directly related to the stability and efficiency of machining. At present, the intelligent degree of magnetorheological polishing equipment needs to be improved, and collaborative control among various systems needs to be developed. Therefore, the design of magnetorheological intelligent polishing equipment can be studied in the future.

(v) Online inspection. For the surface quality inspection of the workpiece after magnetorheological polishing, the most used is still offline inspection, which will affect the workpiece's processing efficiency and quality to a certain extent. The use of in-line inspection technology can avoid the above problems. However, at present, online inspection technology still needs to be improved. The main reasons are limited by various conditions, such as the difficulty of detecting sensor installation and magnetorheological fluid flow. Therefore, relevant research on the online detection of magnetorheological polishing technology can be carried out in the future. This will also be an inevitable trend.

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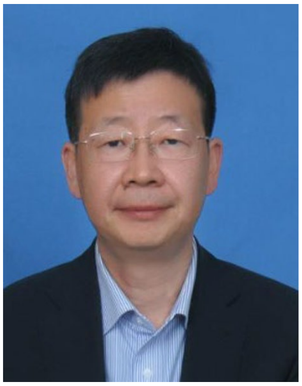

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