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REVIEW ARTICLE

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Review on the progress of ultra-precision machining technologies

Abstract Ultra-precision machining technologies are the essential methods, to obtain the highest form accuracy and surface quality. As more research findings are published, such technologies now involve complicated systems engineering and been widely used in the production of components in various aerospace, national defense, optics, mechanics, electronics, and other high-tech applications. The conception, applications and history of ultra-precision machining are introduced in this article, and the developments of ultra-precision machining technologies, especially ultra-precision grinding, ultra-precision cutting and polishing are also reviewed. The current state and problems of this field in China are analyzed. Finally, the development trends of this field and the coping strategies employed in China to keep up with the trends are discussed.

Keywords ultra-precision grinding, ultra-precision cutting, ultra-precision polishing, research status in China, development tendency

1 Introduction

Improving product quality and precision is the permanent pursuit of modern manufacturing science and technology. Recently, ultra-precision machining technology is a kind of technology that ensures machining accuracy in the range of 0.1–100 nm and surface roughness R_a less than 10 nm. However, the definition of "ultra-precision" is being updated continuously as the latest achievements in science and technology are adopted to improve the form accuracy and surface quality. The term "ultra-precision" not only refers to the specific indexes of profile accuracy and surface quality, but also considers the difficulties involved in achieving specific targets under certain technical levels. In some applications, ultra-precision machining technology is an issue at the nano level (i.e., machining accuracy is approaching several nanometers), although surface roughness is already at the sub-nano level. At present, research efforts are exerted to achieve the ultimate level of precision, that is, atomic scale precision.

Current ultra-precision machining technologies are categorized into four fields: 1) Ultra-precision cutting, 2) ultra-precision grinding, 3) ultra-precision polishing, and 4) ultra-precision non-traditional machining (e.g., electronic beam figuring and ion beam figuring). This paper mainly focuses on ultra-precision cutting, grinding, and polishing.

Ultra-precision cutting refers to the cutting technology that uses tools made of super hard materials, such as diamonds, with the surface roughness of machined surfaces reaching several nanometers. Ultra-precision cutting has various branches: Ultra-precision turning, milling, boring, and compound machining (e.g., combination of ultra-precision cutting with ultra-sonic vibration).

Ultra-precision grinding, which uses grinding wheels with fine/ultra-fine grits and grinders with high performance, is a machining method that can achieve a high material removal rate, machining accuracy of less than 0.1 μm, and surface roughness of less than 25 nm. Among various machining technologies, ultra-precision grinding ensures machining precision, surface quality, and efficiency.

Ultra-precision polishing combines the mechanical and chemical actions of fine abrasives with the assistance of soft polishing tools, chemical fluids, or electric/magnetic fields, and is often employed to obtain super smooth surfaces with non/less surface/sub-surface damage and high surface quality. At present, ultra-precision polishing is the main finishing method employed to achieve machining accuracy of several nanometers and surface roughness at

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sub-nanometer levels. Furthermore, the amount of removed materials during ultra-precision polishing is very small (below several microns). The precision range of typical ultra-precision machining methods is demonstrated in Fig. 1.

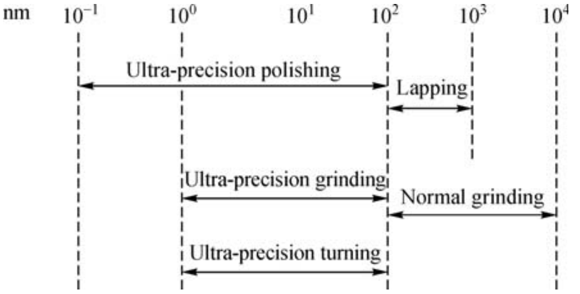


Fig. 1 The machining accuracy of ultra-precision methods

Ultra-precision machining technologies comprise the foundation of high-tech industries, represent trends in modern manufacturing science [1], and serve as supporting technologies for national defense. Almost all the experimental devices and instruments employed in modern science research are supported by ultra-precision machining technology. Currently, manufacturing at the nano level is at the forefront of research in this field and has attracted increasing research attention from developed countries.

Ultra-precision machining technology has a wide range of applications, including metals (e.g., soft metals), hard-to-machine materials (e.g., hardened steel, stainless steel, high speed steel and hard alloy), as well as hard-brittle non-metal materials (e.g., semi-conductor materials, ceramics, and glass). The pursuit of machining precision in modern mechanical industries is mainly driven by the following objectives: 1) Improving the performance, quality, stability, and reliability of products; 2) promoting the miniaturization of products; and 3) improving the interchangeability of components so as to increase the assembly efficiency and the degree of automation. Given that more rigid accuracy and surface integrity are required in modern industries and high-tech products, research on ultra-precision machining has become increasingly relevant. Ultra-precision machining technology also has a significant influence on other high-tech areas, such as nuclear, national defense, and aerospace.

As it combines the latest achievements of mechanical technology and new technologies in electronics, optics, sensors, and computer fields, ultra-precision machining has become the indicator of a country's economic strength and the barometer of its science and technology development. Due to its increasing relevance, this field of study has roused great attention from the governments of many developed countries. As a result, some countries have initiated research projects, including the National Nanotechnology Initiative Plan implemented by the US in 2001, the Interdisciplinary Research Collaboration (IRC) in nanotechnology proposed by the UK, and the Nanotechnology Support Project implemented in Japan in 2000. Making the transition from macro to micro manufacturing is considered a developing trend in the related industries. In sum, ultra-precision machining technology is not just at the forefront of modern manufacturing technology, it also serves as the basis for future manufacturing technologies.

At present, China's manufacturing output ranks fourth in the world, making up about 5% of the total global output value. However, its unit energy and material consumption is the highest in the world (4–10 times higher than those of developed countries). Although China has an ability to produce various precision products, these remain limited and the production yields are very low. This is because some key components and equipment, such as aero engines and high-grade computer numerical control (CNC) machines, still depend on imports. In 2002, China imported machines valued at 4.2 billion USD, with the average price of a single imported precision CNC machine pegged at 33000 USD. In contrast, China produced 6 million simple and cheap low-precision machines with a total value of 380 million USD; the average price of a single machine was only 60 USD, which is 550 times lower than the cost of imported ones. Some large precision machines and instruments are banned in China. Furthermore, China is far behind developed countries in terms of the development of ultra-precision machining processing, which means that the performance of imported ultra-precision machines is generally superior compared with that of local ones. In other words, China's manufacturing industry lacks the core competitive power to support the country's attempt to be a strong contender among manufacturing industries in the world. Thus, great efforts must be exerted to improve the current state of ultra-precision machining technology in China.

2 Development of international ultra-precision machining

2.1 Development stages of ultra-precision machining technology

The development of ultra-precision machining technology can be categorized into three stages, which are discussed below.

1) The initial establishment (1950s–1980s). To satisfy the demands in the fields of aerospace and national defense, the single-point diamond turning (SPDT) technology was first developed in the US at the end of the 1950s. SPDT was then used in the machining of reflective mirrors for laser fusion as well as for spherical and aspherical components for tactical missiles and manned

spacecraft. By 1966 and through the years that followed, various ultra-precision diamond turning technologies were developed by several companies, such as Union Carbide Company (USA), Philips (Netherland), and Lawrence Livermore National Laboratories (LNLL, USA), but their applications remained limited to experimental studies for national defense or scientific research by several powerful companies and institutes. Spherical and axisymmetric aspherical lenses made of ductile metals, such as copper and alumina, were the main machining objects by SPDT during this stage.

2) Initial applications in the civil industry (1980s–1990s). Companies like Moore from the US; Puri Tektronix Inc., Toshiba, and Hitachi from Japan; and Cranfield from Europe gained support from their respective governments, and exerted great efforts to commercialize ultra-precision processing equipment to produce civil precision optical lens. However, ultra-precision machining equipment remained scarce and expensive. During this period, the ultra-precision diamond grinding technology and grinders for hard metals and hard-brittle materials first emerged, although machining efficiency was still poor compared with the diamond lathe. In the 1980s, huge amounts of resources (money and manpower) invested by the US government allowed LLNL to develop a large optical diamond lathe. The micro inch ultra-precision machining of large parts was thus realized. Since then, this equipment has become a typical representative of ultra-precision machine tools used during this period.

3) Wide range of applications in civil industries (1990s–present). The development of automobiles, energy technologies, medical instruments, information, optoelectronics, and communication industries in the 1990s led to rapidly increasing demands for ultra-precision machining equipment in many typical applications (e.g., aspherical lenses, Fresnel lenses, ultra-precise mold, magnetic head and substrates in disks, and semiconductor wafers). During this stage, key techniques for ultra-precision machining equipment, such as the use of controllers, laser interferometers, aerostatic precision spindles and guide rails, hydraulic bearings and guide rails, friction drives, became more widespread. Ultra-precision machining equipment are now commonly used in civilian industries, and various other types are being continuously introduced by different companies. Aside from SPDT and diamond grinding, novel techniques like five-axis milling and fly cutting were also developed for the machining of non-axisymmetric aspherical lenses. Today, machining accuracy has reached the nanolevel and its applications continue to expand.

At present, the US, Europe, and Japan are ahead of the pack when it comes to ultra-precision machining technology. Researchers in Western countries, especially the US, have carried out research on machining large-aperture reflective mirrors mounted on large UV or X-ray telescopes with continuous enormous investments from their respective countries. For example, the Space Development Project promoted by NASA aimed to detect shortwave signals (0.1–30.0 nm wavelength), which required precision reflective mirrors with apertures greater than 1 m. Considering the high-energy density of the X-ray, the surface roughness of a reflective mirror should reach the Å-scale to improve reflectivity. Lightweight silicon carbide with good thermo-conductivity was selected as a mirror material, but its ultra-high hardness significantly increased the machining difficulty. Meanwhile, the ultra-precision machining technology developed by Japan mainly focused on the machining of civilian products, such as disks, polygonal mirrors of office equipment, and aspherical lenses of optical components. As a result, Japan has become highly competitive in the ultra-precision machining of small and ultra-small electronic and optic components.

Current ultra-precision machining technologies aim to achieve the ultimate machining indexes, namely, profile and size accuracy, surface roughness, and surface integrity. Several factors affect machining precision, such as machining mechanism, workpiece materials, machining equipment and tools, fixtures, error detection and compensation, machining environment (e.g., temperature, vibration, and cleanliness), machining process. Fortunately, systematic studies conducted by researchers around the world have led to continuous advancements in this field.

2.2 Development of fundamental research on ultra-precision machining

Ultra-precision machining refers to the combination of micro deformation or the material removal effect of every local machining spot. Different mechanisms for various machining scales and anisotropies of workpiece materials (i.e., original flaws or flaws caused by machining) are shown in Fig. 2 [2].

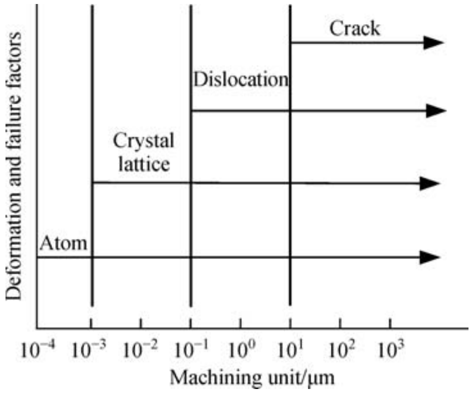


Fig. 2 Deformation and failure factors in different machining units [2]

Brittle damage with massive micro cracks can occur on the surfaces of hard-brittle materials (e.g., ceramics, single crystal silicon) when the surfaces are grooved using a hard-cutting head. The model of deformation induced by indentation is shown in Fig. 3 [3], in which a is the radius of indentation, R_s is the length of the surface crack, and c is the boundary of elastic deformation. This model explains why some machining marks induced by plastic deformation can be observed during the grinding process of brittle materials, except machining marks with brittle cracks. If the amount of material removal is controlled and reduced to a certain level, material removal process with only ductile damages caused by plastic grooving can be realized. Although a smooth surface in the ductile region can be obtained during machining process, sub-surface damage like dislocation and slip cannot be ignored. If the material removal amount can be further controlled at the molecular or atomic level, the chemical properties of the materials can dominate the material removal process and non-damage machining can be expected.

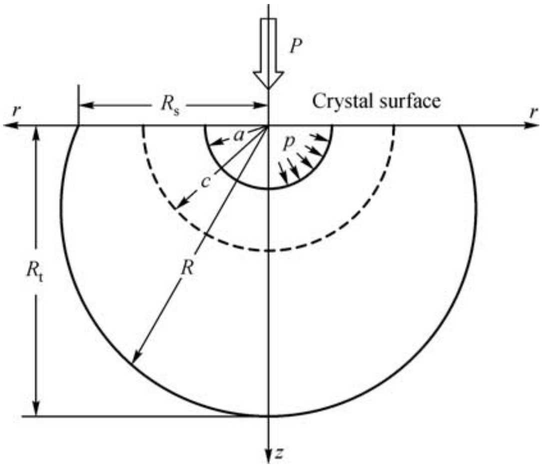


Fig. 3 The model of range of deformation

Meso-physical phenomena, such as small-scale effects and quantum size effect, can occur when the material removal process is at the nano level. The macro cutting theories are not sufficient to describe the machining process and meso-phenomena, thus making it difficult to explain the surface generation mechanism. Modern fundamental theories, including molecular dynamics, quantum mechanics, and atomic physics, must be adopted to further study the machining process. Then, the material removal model at the nano level should be established to guide the actual ultra-precision turning process. Molecular dynamics simulation can set different kinds of machining parameters, material properties, and cutting tool geometry without the limitation of machining equipment and conditions. Thus, research on cutting mechanisms based on molecular dynamics simulation has attracted increasing attention in recent years.

In 1986, a steady cutting process with a cutting depth of 1 nm was realized by LLNL and Osaka University [4]. The Molecular dynamics simulation of a cutting process at the nano level was first conducted by LLNL at the end of the 1980s. Similar studies were also carried out by researchers from Japan and in other countries [5], including Harbin Institute of Technology (HIT) in China, which conducted fundamental research on this topic. However, limited by the calculation scale, some problems emerged in current molecular dynamics simulation of the cutting process at the nano level, such as the small amount of analyzed atoms, single simulated materials (mainly focused on single-crystal materials with no flaws and less attention on the multi-crystal materials), small simulation range of geometry, and limited mechanical properties of the machining surface. At present, explaining the actual cutting mechanism at the nano level based on molecular dynamics simulation, and comparing the simulation results with experimental ones remain difficult tasks. In future studies, material removal mechanism should be examined at the micro-mechanical perspective, and new theories of material removal and surface generation mechanism should be established.

2.3 Development of ultra-precision machining technology

2.3.1 Ultra-precision machine

Having a high-quality ultra-precision machine is the most important and fundamental condition for ultra-precision machining. For the ultra-micro material removal process of cutting and grinding, high dynamic rigidity and highly accurate machine and micro-feeding system are also essential aside from sharp cutting tools or fine abrasive tools. An ultra-precision machine represents the integration of basic theories on key and functional components and technologies as well as those technologies pertaining to tools, measurement and analysis, error processing, processing, motion control and reconstruction, and phenomenon, among others. Such machines have been developed to high technological levels. Today, many companies and institutes manufacture ultra-precision machines. The performances of typical ultra-precision machines are listed in Table 1.

The main producers of ultra-precision machines, namely, Moore (USA), Precitech (USA), and Taylor Hobson (England), have gained control of most of the market. Some other famous companies, such as Toshiba, Toyoda, Funac, and Nachi from Japan, and Satisloh and Opto-Cal from Germany also produce ultra-precision machines.

At present, the US researchers have reached the top level

Table 1 Performance of typical ultra-precision machines

Machine producer	Max. workpiece diameter/mm	Accuracy	Surface roughness, R_a/nm	Type
Union Carbide, USA: Type 1	380	Profile accuracy: ±0.63 μm	25	Aspherical turning
LLNL, USA: DTM-3	2100	Roundness: 12.5 nm (P-V) Flatness: 12.5 nm (P-V) Profile accuracy: 27.9 nm	4.2	Turning
LLL, USA: LODTM	1625	Precision of spindle rotating and linear feeding (in the X and Z directions): $\leqslant 50$ nm	–	Turning
Cranfield Company, England: OAGM 2500	2500	Profile accuracy: 1 μm	–	Grinding
Toyoda, Japan: ANN 10	100	Profile accuracy: 50 nm	25	Turning and grinding
Toyoda, Japan: AHN60-3D	600	Profile accuracy of the cross-section: 0.35 μm	16	Axisymmetric and non-axisymmetric turning and grinding
Moore, USA: Nanotech 500 FG	250	Profile accuracy: 0.3 μm/Ø75 mm	10	5 axis free form grinding
Precitech, USA: Nanoform700	700	Profile accuracy: 0.1 μm	40	5 axis free form milling and grinding
Rank Pneumo, England: Nanoform600	600	Profile accuracy: 0.1 μm	10	Aspherical grinding

of precision machining. Apart from the production of small and medium ultra-precision machines, companies also developed large machines to meet the demands of national defense and other top technologies. The most famous large ultra-precision machines include the DTM-3 and LODTM turning machines, which were developed by LLNL in 1983 and 1984.

England started the study of ultra-precision machining technology relatively early. Cranfield, a company famous for its precision machining technology, has developed a series of ultra-precision machines, such as HATC 300. In 1991, a large ultra-precision machine with a machining size of 2.5 m×2.5 m was developed by Cranfield to machine the reflective mirror mounted on an X-ray astronomical telescope. At present, this is one of the few companies to have the ability to produce large ultra-precision machines.

Compared with the US and England, Japan only began its research on ultra-precision machining technology in the mid-1970s. However, due to the great efforts of the Japanese, they have been able to achieve significant progress, especially in the field of small and medium ultra-precision machines. Multi-functional and high-efficiency special machines have good development trends in Japan, thus promoting the development of micro-electronic and household appliances industries.

2.3.2 Ultra-precision cutting technology

1) Single-point diamond turning

As mentioned previously, SPDT marked the beginning of ultra-precision turning method. SPDT can achieve nano-level surface roughness based on aerostatic bearing spindles and slides, high rigidity and accuracy tools, feedback control, and environmental temperature adjustment [5]. The main cutting tool used in SPDT is a large piece of single-crystal diamond with a small cutting edge diameter (about 20 nm) [6]. At first, SPDT was used for the machining of planar or aspherical surfaces made of copper, but eventually, it was also used to precisely machine acrylic, plastic materials (e.g., plastic lenses of camera, contact lenses), ceramics, and other compound materials. Years later, the multi-point diamond turning method was also developed.

A smooth surface with a less damaged layer can be obtained through micro cutting. The minimum cutting depth depends on the radius of the cutting edge. The smaller radius of a cutting edge corresponds to a smaller minimum cutting depth. Thus, the design and fabrication of ultra-precision cutting tools with a nano-scale cutting edge is one of the key techniques driving ultra-precision cutting technology.

A smooth surface with a very thin affected layer can be achieved by micro cutting. Here, the minimum thickness depends on the rounded cutting edge radius of the diamond cutter, such that the smaller the cutting edge radius, the smaller the minimum cutter thickness. At present, the theoretical rounded cutting edge radius of a diamond micro cutting tool can reach 3 nm. Hence, the design and manufacture of the cutting tool with a nano-scale cutting edge is one of the key steps to achieving the goals of micro cutting. Some famous corporations that employ this technology include Osaka Kohki in Japan and Contour Tools in the UK.

As serious abrasions have been observed when turning steels with diamond tools, some studies have attempted to use single-crystal cubic boron nitride (CBN), metals with ultra-fine grain, and ceramics as the cutting tool materials.

Those studies made some advancements but have yet to reach commercialization level. One possible way to reduce the wear of diamond tools for hardened steel cutting is to coat the cutting tools. Moreover, micro-tools are needed in machining micro-components like micro-electromechanical systems (MEMS) assemblies. At present, the sizes of micro tools range from 50–100 μm, but these are still too large, especially now that the machining geometry is marching towards the sub-micron or even the nanometer level. One trend in the fabrication of micro cutting or milling tools with extra-small tool sizes is the adoption of nano materials, such as nanotubes. Hence, tool materials and fabrication of micro tools are expected to be important issues in future studies on ultra-precision machining technology.

2) Complex surface cutting technology

The cutting technology has been widely applied in the machining of complex curved surfaces. Recently, with the wide applications of the complex non-spheric surface of off axis and array, new cutting technologies of complex non-spheric surfaces, such as fast tool servo (FTS), slow tool servo (STS), and tool normal contour, have been developed [7].

During the FTS process, an FTS element is mounted on the T type lathe, as shown in Fig. 4, which also indicates that the complex surface of the workpiece is decomposed to the rotational symmetry surface and the micro structure on it. The cutting trace for the rotational symmetry surface is controlled by the *X* and *Z* axes feeding. The cutting tool is driven by the FTS element; it moves along the *Z* axis within a small range and at a high frequency to generate the micro structure. This process is suitable for machining the complex aspherical surface with discontinuous surfaces or those that display sharp variations. The high profile accuracy and the low surface roughness value can be obtained in only one process. Kim et al. [8] developed a new piezoelectric ceramic FTS system with a 432 μm stroke to process a high-gradient copper ball surface (Ø50 mm). A surface with form accuracy of 0.15 μm and surface roughness of 11 nm was obtained in that study. Rakuff and Cuttino [9] developed a voice coil-type FTS system with a 2 mm stroke. Surface roughness ranging from 20–30 nm was achieved when the system was used to process a petal-shaped aspherical surface (Ø30 mm). However, the FTS also has several defects: The spindle is not controlled by the conduct servo and the error of position estimation easily causes a confused machining contour.

STS technology added a *C* axis on a T-type machine tool to attain an accurate angular position of the spindle. Meanwhile, hydraulic static pressure bearing and linear motor driving are adopted in the linear guide sliding board to improve its movement frequency response. As shown in Fig. 5, STS control can be realized by the combination of *C* axis and sliding board. Compared with FTS, STS has longer stroke but lower feeding speed; hence, the latter is more suitable for the processing of non-rotational symmetric continuous surfaces. A series of processing experiments were carried out on Nanotech 350UPL in Moore Company, in which a three-phase plate (27 mm× 27 mm, zinc sulfide material) was processed. A surface with form accuracy of 0.26 μm and surface roughness of 4.6 nm was obtained. An off-axis aspherical surface (Ø75 mm, aluminum) was also processed. The obtained accuracy and surface roughness were 0.33 μm and 5.6 nm, respectively [10]. STS has the advantages of simple structure, easy control, good processing precision, and short processing cycle, but the requirements for machine tools are relatively high. Specifically, no friction, low heat of the motor and bearings (e.g., static pressure bearing), high resolution feedback system, and high bandwidth displacement control system are needed.

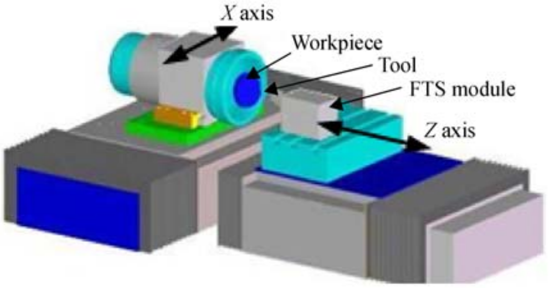


Fig. 4 Schematic of the fast tool servo

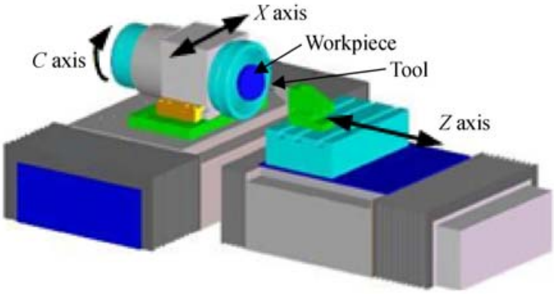


Fig. 5 Schematic of the slow slide servo

In the processing of a large drop aspheric surface, such as a LED collimator, a cutting tool may interfere with the surface of the workpiece due to the structural restriction. Moreover, the whole aspheric surface cannot be completed at one time [11]. In response, TNF technology has been developed to solve this problem. As shown in Fig. 6, a rotational *B* axis mounted with a tool carrier is added to an ordinary T-type machine tool. While cutting, the *X*, *Z*, and *B* axes are controlled simultaneously, and the tool nose and the normal of workpiece surface are maintained so that the whole aspheric surface can be completed at one time. However, the cutting point on the tool arc should be adjusted to make it consistent with the rotation axis of the

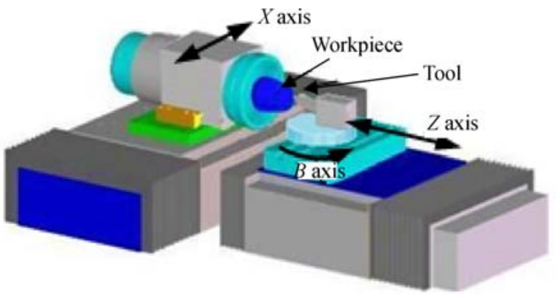


Fig. 6 Schematic of the tool for normal forming technology

B axis, which takes a long time. In addition, machining with the single point of the same circular arc blade results in serious cutting edge wear.

3) Micro cutting and micro structure cutting

Compared with silicon-based MEMS, high-energy beam machining, LIGA, and other micro machining technologies, micro cutting has the advantages of carrying out 3D structure machining, machining flexibility, working efficiency, and lower processing cost. Micro structure cutting is a new research direction of ultra-precision cutting, and Germany and Japan are currently the leaders in this field. By using the single-crystal diamond micro cutter, the Fraunhofer Institute for Production Technology in Germany fabricated a micro pyramid-shape prism array structure with a feature size less than 100 μm as well as a micro thin wall structure with a wall thickness of 1.5 μm and height of 200 μm. By using FTS, an integrated lens with micro reflecting surface array [12] (shown in Fig. 7) was also fabricated. Various micro structures, including Fresnel lens with micro planar and curved wave structure, laser fusion target with two-step surface, diffraction grating, and micro prism array, were fabricated by precision machining laboratory at Bremen University with micro cutting. A micro sine grid surface, shown in Fig. 8 [13], was fabricated by Tohoku University in Japan using FTS technology. The surface profile consisted of sine waves along the X and Y axes. The wavelength and P-V value of the sine wave were 300 and 0.3 μm, respectively [14].

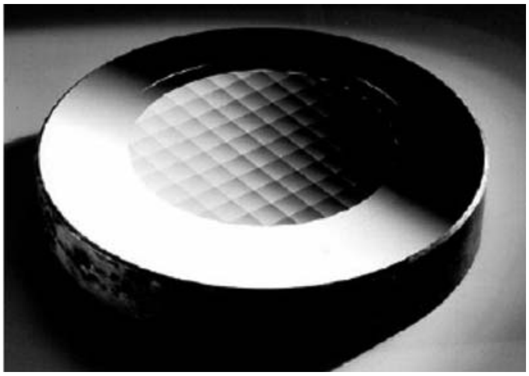


Fig. 7 The lens with curved wave structure

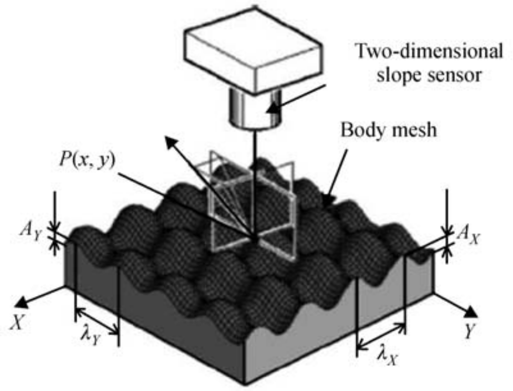


Fig. 8 Micro sinusoidal grid surface (Tohoku University)

The manufacturing technology of using a diamond cutting tool for micro structures has attracted increasing attention. Companies such as Contour Tools and Osaka Kohki Co., Ltd. have developed design and manufacturing processes for these cutting tools. However, relevant news and articles can be seldom found due to the corporate secrecy typically surrounding these new technologies.

4) Micromilling

Micromilling is widely studied and applied in hard-brittle material micro aspheric mould processing. Matsumura et al. [15] proved that milling with a large radial depth and high feed rate can also obtain fine glass surface without brittle crack. Matsumura et al. [16–18] systematically studied the influence of processing parameters on the micro-milling processing of a glass material. Suzuki et al. [19] used a polycrystalline diamond (PCD) milling tool to fabricate an aspheric non-adhesive tungsten carbide mould (Ø2.4 mm). The form accuracy and surface roughness of the processed surface were less than 100 and 15 nm, respectively.

For wafer-level micro aspheric array mould processing, the depth of the aspheric surface fabricated by mask lithography can only reach tens of micrometers, and micro turning is limited by such factors as clearance angle of tool and processing efficiency. Micro milling has been developed in response to such problems. Mould materials include aluminum, copper, and other non-ferrous metals and alloys, as well as plastic and some crystals. The main milling tool is the ball head diamond cutter, and the processing method is similar to that employed in STS. Kaleido Technology in Denmark used micro milling technology to fabricate a copper mould with a 1310 micro lens array (lens radius: 1.286 mm, depth: 257 μm, and slope: 37°). The form error was less than 200 nm, and the surface roughness was less than 10 nm [20].

2.3.3 Ultra-precision grinding technology

Historically, the grinding process was ignored in the early stage of the development of ultra-precision machining technologies. This may be explained by the limitations imposed on the improvement of grinding accuracy by the irregularity of wear and the random distribution along the radial direction of cutting edge height on grinding wheel. With the development of a super hard grinding wheel and dressing technology, ultra-precision grinding technology has gradually developed over the years.

1) Super abrasive grinding wheel

Super abrasive grinding wheel using a diamond or CBN abrasive is the main tool used in ultra-precision grinding. A diamond wheel is suitable for hard-brittle nonferrous metals, carbide alloys, and high hardness, high brittleness metalloid materials, such as optical glass, ceramics. The CBN wheel can be used to grind hardened steel, heat-resistant alloys, and high hardness, high ductility metal materials. These two kinds grinding wheels complement each other and can almost cover all machined materials. The specifications of the super abrasive grinding wheel are shown in Table 2 [21].

Metal-bonded super abrasive wheels have some advantages, such as high hardness, high strength, strong shape-preserving ability, and good wear resistance. These are typically used in precision and ultra-precision grinding and form grinding. However, the outstanding problems encountered in the practical application of multi-layer metal-bonded super abrasive wheels [22] include the small space for chips and the difficulty of self-sharpening. Iridium was used to coat the surface of the abrasive grain; as a result, the bonding strength of abrasive holding force increased with the chemical reaction and the diffusion effect between active metal and abrasive. The iridium-plated wheel has been proposed in another previous work [23]. Meanwhile, to solve the problem of the difficulty of self-sharpening, the porous metal bond was manufactured with a pore structure [24]. Electroplating and high-temperature brazing wheels first appeared in the 1990s [23,25] and have shown the ability to overcome the abovementioned problems.

Using the principle of electrophoretic deposition (EPD), some scholars in Japan conducted research on the feasibility of superfine grinding wheel by using electrophoretic characteristics of the ultrafine grains. This method can effectively solve the problems encountered during the manufacture of traditional grinding wheels, such as easy agglomeration and poor uniformity, absence of pores, and the tendency to be easily blocked off. Grinding experiments on silicon wafer and sapphire substrate by using silicon dioxide abrasive wheel were carried out by Ikeno et al. [26] in Japan, whose work obtained a fine surface with R_a of 0.6 nm. Some Japanese companies have already produced the vitrified bond diamond wheel with grain sizes of 1.3, 1 m, and even finer grains (usually made into pellets); these diamond wheels have a wide range of applications in the field of ultra-precision grinding on silicon and sapphire substrate. The obtained surface roughness of the silicon wafer was less than R_a 20 nm after processing.

2) Online dressing technology of super hard grinding wheels

The dressing technology of grinding wheels has direct effects on machining accuracy and efficiency. The traditional dressing method typically removes the grinding grain by shearing and squeezing action, which has some disadvantages, including control difficulty, low dressing precision, and high grinding wheel loss. Therefore, domestic and foreign scholars have proposed various of dressing methods, such as electrolytic in-process dressing (ELID) [27], electrochemical in-process controlled dressing (ECD) [28], dry ECD [29], electro-contact discharge dressing (ECDD) [30], electro-chemical discharge machining, (ECDM) [31], laser-assisted dressing [32], water-jet in-process dressing [33], and ultrasonic dressing [34]. Among these methods, ELID technology has the most mature application. The technology was first proposed by Dr. Omori of RIKEN in 1990. The electrolysis effect was used to dress the metal-bonded wheel, as shown in Fig. 9, thus achieving a highly precise mirror surface after machining. ELID grinding experiments on silicon wafer were conducted by Omori with a #30000 iron-bonded diamond grinding wheel. A super fine surface with $R_{\max}$ 23.4 Å and R_a 3.29 Å was obtained [35].

3) Deterministic micro-grinding

The grinding of hard-brittle materials, such as ceramics, is an uncertain and time-consuming process, especially when the requirements of surface roughness and profile accuracy are very high. The Optical Machining Center at Rochester College proposed deterministic micro grinding (DMG) using a high-stiffness, high-precision, and high-stability grinder. By precisely controlling several parameters (i.e., cutting depth, grinding speed, feed, and

Table 2 The specifications of super abrasive grinding wheel [21]

Layer type	Bond type	Bond material	Pore	Bond strength	Truing
Multilayer can be dressing	Resin bond grinding wheel	Resin	None	Not high	Difficult, need dressing
	Ceramic bond grinding wheel	Ceramic	Have	High	Easy
	Metal bond grinding wheel	Metal	None	High	Difficult, need dressing
Single layer	Electroplating grinding wheel	(Metal)	–	Not high	None necessary
	Brazing grinding wheel	Metal	–	High	None necessary

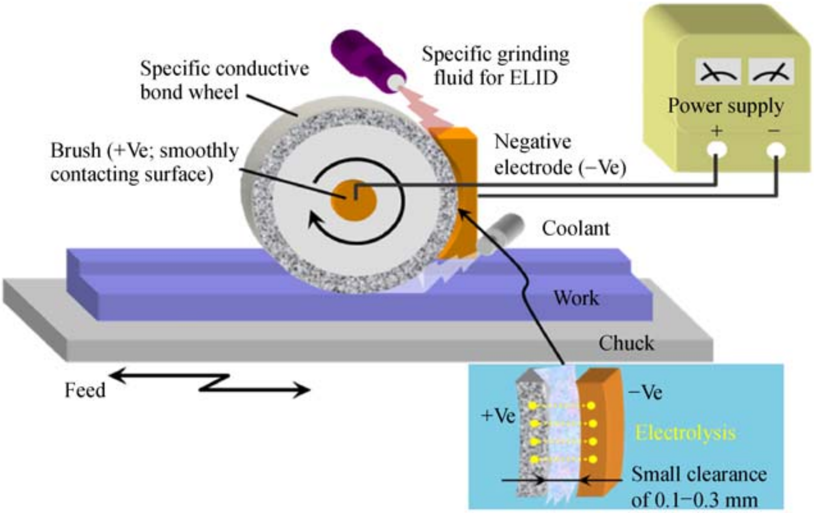


Fig. 9 Schematic illustration of the ELID device

vibration between the grinding wheel and the workpiece), the uncertainty during the grinding process and the subsurface damage were reduced to achieve high precision and better surface quality. The efficiency of DMG processing is almost ten times that of lapping efficiency and a hundred times that of polishing efficiency. The surface roughness is almost the same as the polished surface, and the residual stress after DMG is less than that after lapping [36]. DMG can process all kinds of hard-brittle material aspheric surfaces can meet the quality requirements of optical components. Rochester College used Nanotech 150AG to machine Ø40 cm BK7 aspheric elements. After 4 min of rough grinding and 30 min of fine grinding, the P-V value of the surface was 0.0548 μm, and surface roughness was 3.6 nm [37]. However, DMG has a strict requirement on machine tool, and the corresponding process is still in research.

4) High surface quality grinding technology

If the normal load of a single grain can control less than the critical load of the median, radial, or lateral cracks, then the workpiece may not suffer from elastic deformation and ductile regime machining or damage-free processing can be realized. Even though the high surface quality of ceramic materials in ductile regime machining can be obtained, large metamorphic layers involving amorphous, dislocation, and plastic deformation layers remain. This is because the critical load of radial crack is far less than that of lateral cracks. The remaining 1 μm damaged layer on the surface of the silicon wafer can be processed by ELID grinding with 0.01 μm diamond grits.

As shown in Fig. 10, Zhou et al. [38] from Ibaraki University in Japan proposed chemical mechanical grinding (CMG) with 1–3 μm CeO_2 phenolic resin grinding (abrasive particle volume fraction of 70%) on mono crystalline silicon. Compared with the result of chemical mechanical polishing (CMP) processing, the surface roughness and flatness were similar to each other (R_a 0.76 nm, P-V 5.22 nm; CMP: R_a 0.79 nm, P-V 5.42 nm); however, CMG had a 3 nm damaged layer. The principle of CMG demonstrates that CeO_2 and Si have a solid-state reaction during the dry process. The hardness of CeO_2 lower than the production of reaction, and the CeO_2 abrasive can remove the reaction product without any damage to the workpiece. As shown in Fig. 11, the silicon wafer can be reduced to a thickness less than 30 μm.

Fig. 10 CMG grinding wheel

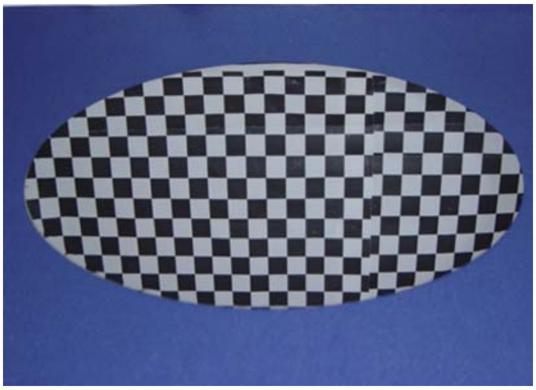


Fig. 11 Silicon wafer after CMG

Hang et al. [39] conducted grinding experiments on a typical soft-brittle material ($LiTaO_3$ (LT)) with a #3000 diamond grinding wheel. As shown in Fig. 12, with the control of coolant temperature and the use of electrolyte solution, the thickness of the LT wafers was eventually reduced to less than 100 μm.

2.3.4 Ultra-precision polishing technology

1) Non-/less-damage polishing

In order to guarantee the performance of the functional elements identified earlier, super smooth, damage-free polishing is required. Non-damage surface polishing technology is a micro removal machining method that does not destroy the surface crystalline structure [40]. Here, the mechanical action of the abrasive particle assisted by the polishing plate has a direct effect on the surface roughness of a workpiece, and a super smooth workpiece surface can only be obtained when mechanical action is minimized to a certain level. The elastic material of the polishing plate can be regarded as the fixture of the abrasive. Water and gas are considered as the softest materials that can be used on a polishing plate. The formation of a metamorphic layer during polishing is caused by the mechanical action of the abrasion and the friction effect of the polishing plate. Polishing methods with gentle mechanical action, such as chemical mechanical polishing, elastic emission machining (EEM), and floating polishing method, can achieve damage-free processing. Quantum mechanics theory must be introduced into the analysis given that chips at the atomic or molecular level are formed on the processed surface.

At present, material removal during the polishing process can now be achieved at the nano and sub-nano levels, and in this process scale, the chemical action cannot be neglected [41]. Figure 13 shows the compound polishing methods using physical and chemical actions [42]. As shown in Table 3, in the last 30 years, many scholars have developed a series of ultra-precision polishing methods that can avoid the formation of metamorphic layers and damages on the surface.

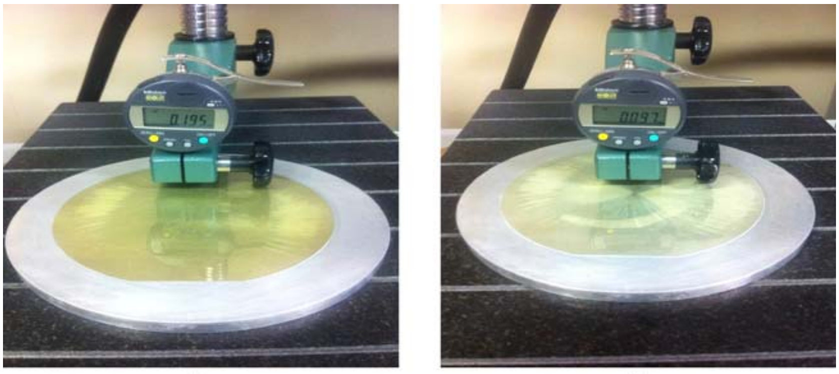
Non-damage polishing methods can be divided into several categories, namely, mechanical micro removal polishing, chemical polishing, and chemical mechanical polishing. As shown in Fig. 14, mechanical actions include the action of micro-removal and friction. The chemical effects include electrolysis, melting, and film formation.

2) Non-contact polishing technology

During non-contact polishing, the workpiece does not come into contact with the polishing pad, and the work material is removed just by the compact action of the fine particle in the slurry. The amount of materials removed from the surface is very tiny (at the level of tens of atoms) to ensure perfect surface and precision form. EEM, first proposed by Mori et al. [43], is a typical non-contact polishing method. Here, fine abrasives (tens of nanometer in size) in the polishing slurry are driven by a high-speed spinning polyurethane ball that comes into contact with the surface of the workpiece. The workpiece material is removed by the mechanical and chemical action between the abrasive and workpiece. This process is extremely advantageous for machining functional crystal materials, because no plastic deformation or lattice defects are produced on the surface of the workpiece. Mori et al. [43] also employed ZrO_2 abrasive to polish mono crystalline silicon with EEM, and a fine surface with R_a of 5 Å is obtained. Meanwhile, EEM has been adopted by Canon in machining the pre-fabricated equipment VS1 [44] for extremely ultraviolet carved plan. The surface roughness after EEM is lower than 0.1 nm. Other typical methods of non-contact polishing include hydrodynamic polishing [45] developed by Watanabe et al. and float polishing [46] developed by Namba and Tsuwa.

3) Interface reaction polishing

Part of the mechanical energy produced by the interface friction between the abrasive and workpiece can convert to heat. The contact area of the interface is in an unstable state under high temperature and pressure, and this can easily



(a) (b)

Fig. 12 LT wafer (a) before and (b) after grinding

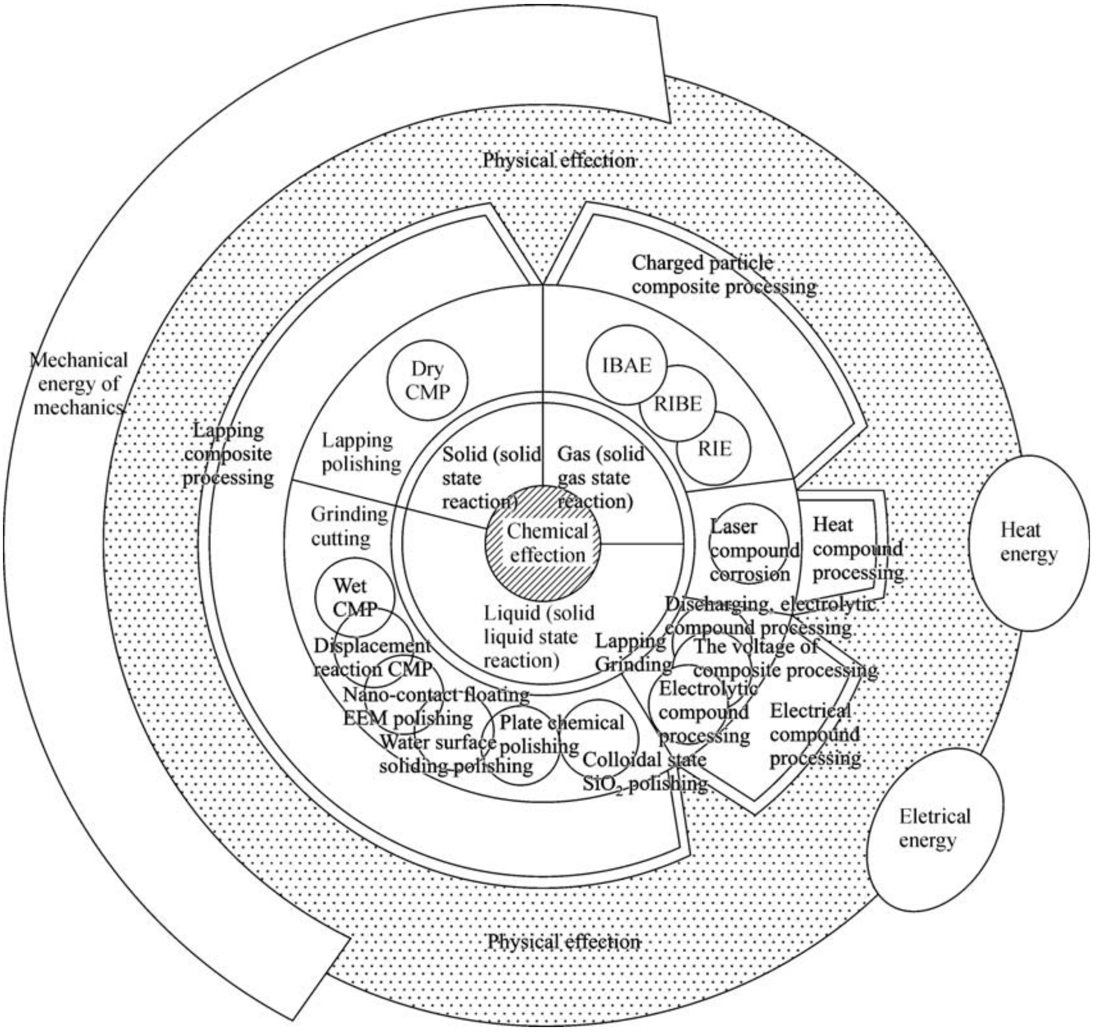


Fig. 13 The compound machining method with physical and chemical effect

Table 3 Ultra-precision polishing methods employing new concepts

Polishing method	Abrasive
Chemical mechanical polishing polishing method	Chemical solution and abrasive particle
Mechanical chemical polishing	Soft abrasive (solid phase reaction with the workpiece)
Hydration polishing	Super-heated steam
Non-pollution polishing	Pure water or ice
Hydroplane polishing	Chemical solution
Suspension polishing	Soft abrasive
Elastic emission machine	Soft abrasive
Magnetic fluid polishing	Magnetic fluid
Electrophoresis polishing	Electric control of abrasive
Magnetic levitation polishing	Magnetic fluid
Magnetic abrasive finishing	Magnetic abrasive

lead to the interpenetration between the materials. The polishing method based on this phenomenon is called “interface reaction polishing,” and is used to realize non-/less-damage polishing. CMP and hydration polishing are two typical examples of this method.

So far, CMP is considered the most widely used and

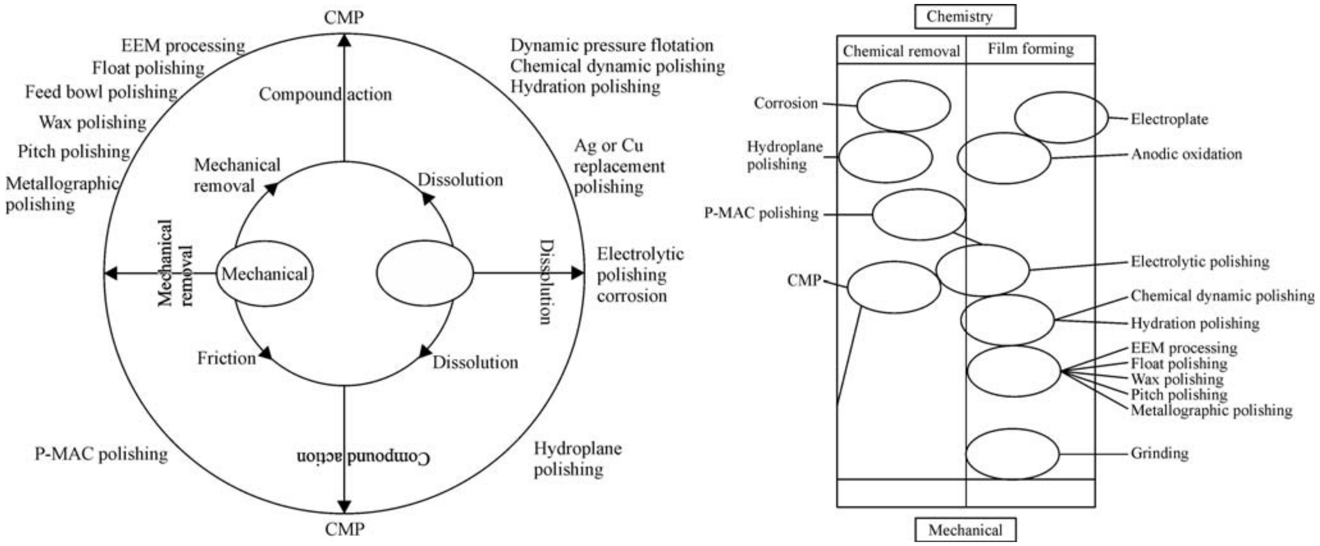


Fig. 14 Classifications of processing principles for different polishing methods [3,42]

most matured among non/less damage polishing technologies. Super-smooth and non-/less damage surface polishing can be successfully obtained through the mechanical and chemical reaction among the abrasive, workpiece and environment. Yasunaga et al. [47] first proposed and validated the concept of CMP, and obtained the super-smooth surfaces of the sapphire, silicon, quartz, and other workpieces. In the mid-1980s, IBM developed CMP technology for semiconductor materials and very large scale integration. The schematic illustration of this polishing device is shown in Fig. 15. Given that CMP technology can meet the needs of overall flattening ultra-large scale integrated circuits, CMP has been extended to the entire semiconductor industry, and its applications continue to be expanded [48,49].

Fig. 15 Schematic diagram of CMP

4) Electric and magnetic field-assisted polishing

Electric and magnetic field assisted polishing utilizes the electric and magnetic field to control the force of abrasive particles acting on a workpiece. Magnetic field assisted polishing mainly includes magnetic abrasive finishing (MAF), magnetic fluid polishing (MFP), and magnetorheological finishing (MRF). MRF will be introduced in the next section. MAF is a method of using a magnetic abrasive (mixed with abrasive and iron powder, sintered and then smashed to a certain size) to lap and polish the surface of a workpiece [50]. Meanwhile, MFP can be divided into two types: Suspension and separation; the former mixes abrasives into magnetic fluid, and realized polishing with the "floating" effect of the magnetic fluid in the magnetic field. The latter does not mix with the abrasive in the magnetic fluid, but uses the characteristic of magnetic fluid (moving to the direction of the stronger magnetic field) to squeeze the abrasive through rubber or other elastomers [51]. The term "electric field-assisted polishing" mainly refers to electrophoretic polishing, which uses the electrophoresis of colloidal particles in the electric field to realize the polishing [52].

5) Curved surface polishing

During this process, material removal is controlled by the path planning and the dwell time of the polishing head, which in turn, is controlled by a computer. A parabolic mirror with 500 mm diameter and f/3.5 was processed by the first computer controlled optical surfacing (CCOS) machine tool developed by Itek [53]. After three months of processing, the surface accuracy RMS is up to 0.04 μm, and the surface roughness is less than 5 nm. To date, CCOS has been widely used in processing medium- and large-aperture aspheric mirrors. Furthermore, this technology been applied in ultra-precision machining of free curved surface molds under the assistance of CAD/CAM technologies. Processing robots (Fig. 16) for free curved surface molds have been developed in Japan, the US, and Germany.

Despite its advantages, CCOS also has its share of shortcomings. For example, the polishing head cannot match the complex curved surface very well, and ensuring form accuracy is quite difficult when using this process. Apart from these, high frequency error is easily generated,

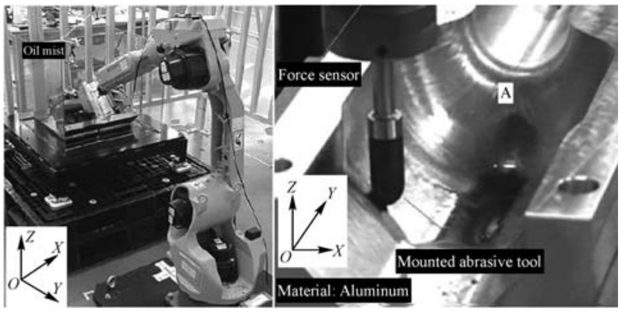


Fig. 16 Curved surface mold of robot processing technology

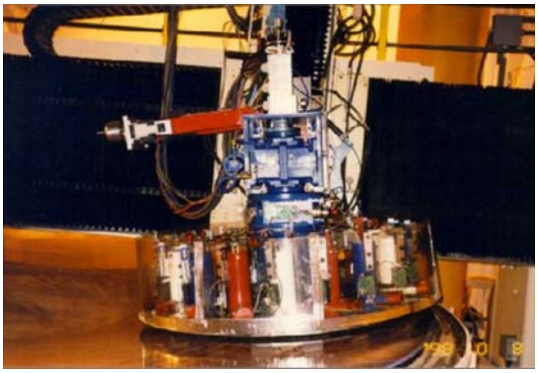


Fig. 17 Large size elastic optical plate after stress plate polishing

and the material removal rate is low, which leads to a long processing time. Many different CCOS-based polishing methods for aspheric surface processing have been developed in order to solve the conflict between efficiency and accuracy. These polishing methods mainly include flexible contact and non-contact modes. In flexible contact polishing method, the flexible polishing head is used, and the basic mechanism of the flexible contact polishing includes the deformation-controllable polishing head and the intelligent material polishing head. The latter can be deformed to match the surface of a workpiece, and the deformation is controlled by a computer. This kind of method mainly includes stressed lap polishing (SLP) and Bonnet polishing.

As shown in Fig. 17, a large elastic plate is adopted as a base disc in the SLP device, and drivers and shafts are set around the elastic plate. The surface of the polishing head can be adjusted to the desired shape in real time via the drivers and shafts. Middle and high frequency errors can be well controlled by SLP, and the polishing efficiency can be improved effectively [53]. The SLP technology makes a great contribution to the development of a super large astronomical telescope (caliber 4–8 m, relative caliber 1.5–1 m). In addition, primary mirrors with 1.8 mf/1.0 VATT, 3.5 mf/1.5 SOR, 6.5 mf/1.25 MMT, LBT8.4 mf/1.14, and 8.4 mf/2.14 GMT have been processed by Steward Observatory Mirror Lab in Arizona University. After polishing, full caliber surface roughness and form accuracy reached 20 nm and less than 1 μm, respectively [54].

Bonnet polishing was first proposed by Walker et al. [55] at the Optical Science Laboratory of University College London and Zeeko. As shown in Fig. 18, a spherical air bag with a certain level of inflation pressure is used as the polishing head, and the precession theory is integrated into the bonnet polishing. The advantages of this method are as follows: The flexible bonnet polishing head well matches the workpiece surface, and the polishing efficiency and the surface quality of the workpiece can both be controlled by adjusting pressure inside the air bag. An IRP series multi axis polishing equipment has been manufactured based on the principle of bonnet polishing. Using this equipment, the caliber of the processed workpiece ranges from 200 to 1200 mm, the surface accuracy is 80 nm, surface roughness is 3 nm, and the material removal rates are 2.0 mm^3/min and greater than 0.25 mm^3/min in rough and fine polishing, respectively. An axially symmetric convex aspheric surface with fused silica (diameter: 200 mm and radius of curvature: 450 mm was processed by using the IRP600 polishing machine) [56]. After 120 min of polishing, the surface accuracy P-V decreased from 2 to 0.19 μm, and surface roughness is recorded at 1.8 nm.

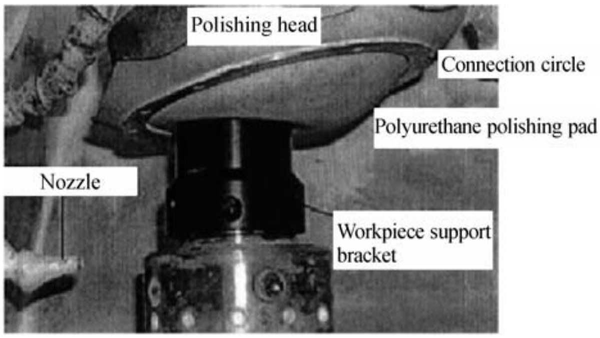


Fig. 18 Schematic diagram of bonnet tool polishing

An intelligent material polishing head consists of some intelligent materials that can be converted to different states under the external field. MRF, electrorheological polishing, and electromagneto-rheological polishing are typical polishing methods that use an intelligent material polishing head. MRF is considered as one of the most effective polishing methods at present. As shown in Fig. 19, when the magneto rheological (MR) fluid is transmitted to a small gap with high speed, it becomes a viscoplastic Bingham medium under high gradient magnetic field, after which strong shear force is produced on the contact area between the workpiece and the Bingham medium. As a result, material removal is achieved. Jacobs et al. [57] employed MRF to process SLAM55 material aspheric surface (Ø50 mm). In that work, they removed 5 μm sub-surface damage layer, and the P-V value decreased from 3.7 to 0.2 μm after 2 hours of polishing. At present, MRF has been used in commercial applications

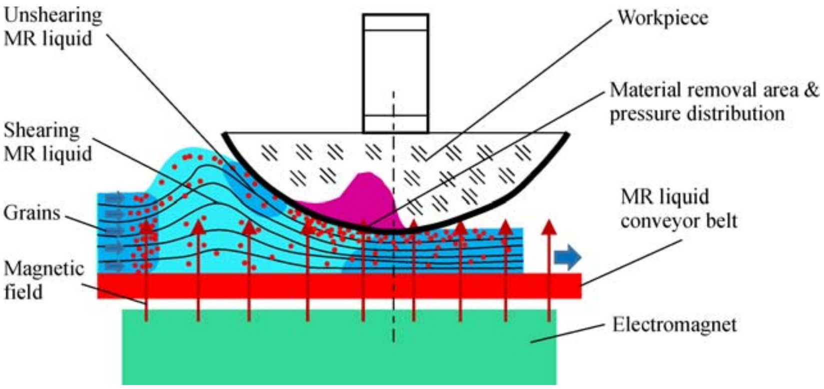


Fig. 19 Schematic diagram of MRF [45]

and in the processing of camera lens, aspheric moulds, and other complex surface parts. QED Technology Company also launched a series of MRF equipment.

The flexible non-contact polishing method employs the continuous material flow, which uses kinetic energy to form a small flexible polishing head. This method involves fluid jet polishing (FJP) and magnetic fluid jet polishing (MJP).The aspheric surface with large gradient change requires small tools, and it is also difficult to achieve this during production. In FJP, the abrasives are jetted with water to the workpiece under high pressure and high speed. Deterministic material removal can be realized by controlling the pressure, direction, and dwell time of the jet flow. The illustration of an FJP device is shown in Fig. 20 [58]. The FJP processing tool is a small non-wear liquid flexible head; it facilitates steady removal, and the material removal rate can be controlled to within 2 nm/min to 2 μm/min. The form accuracy is also easy to control, and high frequency error and edge effect can be well limited. To date, FJP technology is already commercialized. For example, a six-axis FJP equipment FJP600 was developed through a cooperation between the Zeeko Company and the Holland Applied Science Physical Electronics Laboratory [59]. The form accuracy of the manufactured equipment is better than 60 nm, and the surface roughness of RMS is 1 nm after polishing the aspheric surface. Meanwhile, FJP-1150F was developed by the Machinery FJP Company in Canada. The maximum size of the workpiece that it can process is 150 mm× 150 mm. The form accuracy is RMS 3 nm, and the surface roughness is RMS 1 nm.

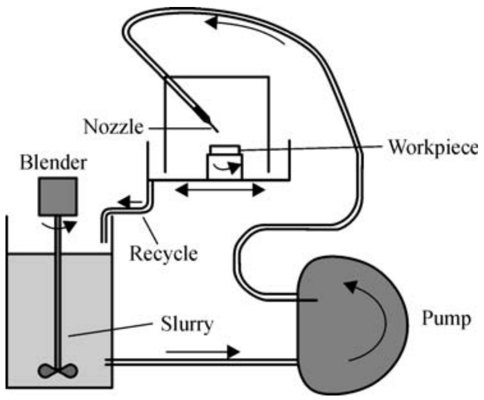


Fig. 20 FJP instrument developed by Delft University of Technology [58]

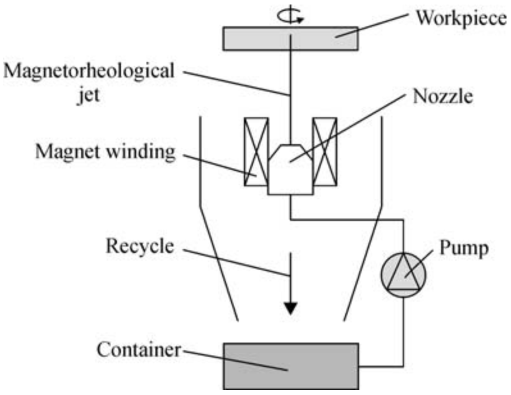


Fig. 21 Principle of magnetic jet polishing [60]

The stability of the jet flow is easily affected by the impact distance. MJP has been proposed to solve this problem, and its processing principle is shown in Fig. 21 [60]. MF near the exit of the nozzle is converted to a viscoplastic Bingham fluid under magnetic field. The stability of the jet flow is improved significantly. MJP process can achieve steady material removal, and the diameter of the jet flow is not changed at a long distance, as shown Fig. 22 [61]. Thus, this process is very suitable for polishing high-gradient aspheric surfaces (e.g., conformal deep concave surface) and other complex surfaces. Shorey et al. [60] in the QED Company used MJP to process a concave aspheric optics element with a diameter of 23 mm and curvature radius of 20 mm at the top point. The form accuracy with P-V 44.5 nm and RMS 6.1 nm are achieved in that work.

3 Development of ultra-precision machining in China

In China, mirror cylindrical grinders have been developed since 1965, producing machined roundness greater than 0.3 μm, and surface roughness less than R_a 0.01 μm. In 1968, single-crystal diamond mirror lathes were manufactured, which were capable of achieving surface roughness of brass below 0.025 μm. In the late 1970s, high-precision disk lathes were also manufactured, and their spindle rotation accuracy proved to be better than 0.2 μm. Since the 1980s, various industries have invested more human and material resources to the development of ultra-precision machining technology and equipment, and as a result, some super precision machining equipment have been successfully developed successively. Especially in the late 1990s, non-spherical ultra-precision machining equipment were successfully developed by many units, thus bringing ultra-precision machining equipment standards to new levels.

HIT is one of the earliest institutes to have carried out research on ultra-precision machining technology. In 1996, the sub-micron ultra-precision machine tool was developed by HIT, which also carried out research on machining mechanisms, tool wear and tear, and ultra-precision cutting removal mechanisms of brittle materials under the micro nano machining process. A large, planar ultra-precision milling machine was developed by HIT in 2006, and this was used for the ultra-precision machining of the key parts of laser nuclear fusion KDP (ferroelectric potassium dihydrogen phosphate). Another institute that has carried out research on ultra-precision machining technologies in China is the Beijing Machine Tool Research Institute, which developed the NAM-800 type nano NC lathe, a next-generation nano scale machining machine tool. The resolution of the control system is 5 nm, the positioning accuracy is ±0.2 m/400 mm, and the repeated positioning precision is ±0.1 m/100 mm. Beijing Precision Engineering Institute Aircraft Industry has formed its own methods in developing ultra-precision cutting processing and equipment, and has successfully developed the Nanosys-300 non-spherical surface super precision machining system.

In the cutting technique of complex curved surfaces, Fengzhou Fang from Tianjin University carried out numerous fruitful research on this subject. In one work, Cheng et al. [62] proposed a non-spherical ultra-precision cutting technology based on error correction method; by using this technology, they achieved aluminum aspheric surface with a diameter of 50 μm. After two rounds of modifications, they achieved final form precision and surface roughness values of 0.17 μm and 5.16 nm, respectively. In another study, Fang et al. [63] also investigated the possibility of ductile regime machining for glass materials. They found that the ductile regime machining of glass materials can be realized with the negative rake angle of –30° and feed depth that is less than the depth of cut (DOC, usually less than 0.1 μm). Meanwhile, Guan et al. [64] of the National University of Defense Technology used STS technology for processing 2D sine array with a diameter of 30 mm. They achieved processing time of about 12.5 min and surface roughness of 5 nm. Li et al. [65] used STS technology on the brass material processing and achieved a micro lens array with a diameter of 1 mm and surface roughness of approximately 30 nm. A tool path generation software for optical free-form surface was also developed for ultra-precision machining of free surfaces, such as reflecting mirror and F-theta lens for automobiles, in the advanced optical manufacturing center of the Hong Kong Polytechnic University [66]. In the Chinese mainland, Dongming Guo's team [67] in Dalian University of Technology has successfully developed the first wafer grinding machine to achieve a diameter of 300 mm; they also developed a soft grinding wheel for sapphire processing, and it can obtain surface roughness of less than 0.67 nm.

Ultra-precision abrasive belt grinding has played an important role in the manufacture of curved surfaces. Yun Huang and his team [68] from Chongqing University developed the 2MY55200-6NC-type steam turbine complex blade with high efficiency and precision machining six-axis linkage CNC abrasive belt grinding machine that is meant for ultra-precision machining of complex curved surface parts of steam turbines and aero engines. These tools fill the gap of backward technology and address the domestic industries' long-term dependence on a senior fitter manually polishing the blade.

The representative tools of CCOS technology include the numerical control (NC) aspheric surface Machining Center FSGJ-I, FSGJ-II, and FSGJ-III developed by the Changchun Institute of Optics, as well as the optics aspheric surface composite machine tool (AOCMT), which combines milling with grinding, lapping and polishing, and one-stop contact detection. The latter was developed by the National University of Defense Technology in 2002. A 600 mm×300 mm SiC off-axis aspheric mirror was machined by FSGJ-II at the Changchun Institute of Optics [69] and obtained surface form accuracy of 13 nm. AOCMT was used to machine a Ø500 mm f/3 parabolic mirror to achieve a surface form accuracy of 9.4 nm [70].

Many institutes in China have conducted research on MRF. For example, the MRF equipment KDMRF-1000, which can process a 1 m caliber, was developed at the National University of Defense Technology. Recently, a Ø200 mm f/1.6 optical glass parabolic mirror was processed by this equipment to achieve an accuracy of RMS 0.009λ. Sun et al. [71] from HIT processed K9 optical glass sphere with R_a 41.3 mm and Ø20 mm by MRF to achieve surface roughness of 8.44 nm and form accuracy of 57.9 nm. The main research institute on ion bean finishing (IBF) in China is led by Liao et al. [72] from the National University of Defense Technology. In 2006, they developed the IBF equipment KDIFS-500 with the ability to conduct aspheric processing (Fig. 23); the largest diameter of the workpiece can reach Ø500 mm. The RMS value of plane as well as the spherical and aspheric surfaces processed by this equipment are at the nanometer level. They processed a spherical mirror of Ø200 mm f/1.6 from an initial mirror shape accuracy of 48.6 to 6.1 nm (Fig. 24).

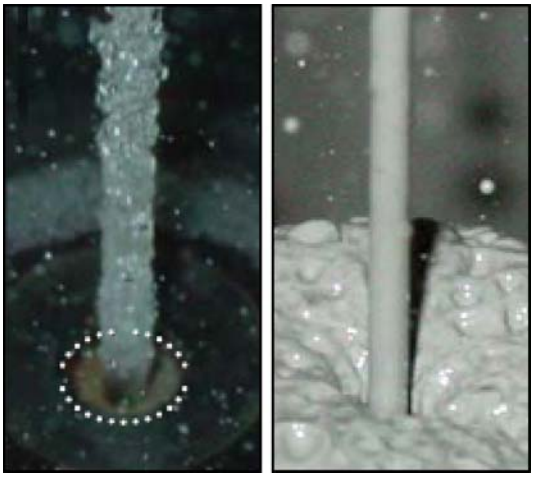


Fig. 22 Comparison of the stability of the jet beam and the magnetic jet beam [61]

Fig. 23 IBF equipment (KDIFS-500) developed at the National University of Defense Technology

Soochow University [73] and the National University of Defense Technology [74] have also carried out MJP and FJP research, respectively. The research team at Soochow University specifically processed an aspherical mirror of Ø90 mm to a P-V of 0.36λ and surface roughness of 2.25 nm using this equipment. Meanwhile at HIT, atmospheric plasma polishing was performed at HIT, and the processing test for single-crystal silicon wafer achieved a material removal rate of 1.46 mm^3/min and surface roughness of 0.6 nm [75]. SLP was also investigated at the Institute of Optics and Electronics of the Chinese Academy of Sciences and at the Nanjing Institute of Astronomical Optics and Technology. Air bag polishing was investigated at HIT and at Zhejiang University of Technology. Hunan University and Zhejiang University of Technology jointly launched intelligent polishing technology and equipment, sphere of ultra-precision efficient processing technology with complete sets of CNC equipment, as well as semi-bonded abrasive ultra-precision machining technology. Furthermore, other aspects of the research work have resulted in valuable achievements. To date, the above-mentioned institutes have all achieved great progress in their respective projects.

Meanwhile, domestic scholars have successfully introduced many new original polishing methods. Zhang et al. [76] developed an MR brush finishing technique that can process high-gradient concave aspherical surfaces. Hong [77] mixed the abrasive material with the electromagnetic rheological fluid as the polishing liquid, and then employed the electromagnetic rheological synergy effect to form micro-grinding tools at the top of the electromagnetic pole. This approach can be used for the ultra-precision machining of glass, ceramics, and other hard brittle materials. Li et al. [78] presented a shear thickening and polishing method, in which the shear thickening effect of the polishing solution was used to form a “flexible fixed abrasive” for high-efficiency and high-quality polishing of complex surfaces. Zhao et al. [79] developed the dielectrophoretic polishing method by employing the dielectric electrophoresis effect of wear particles in an inhomogeneous electric field to improve the dwell time of the polishing abrasive particles in the polishing area. By using this approach, the polishing efficiency and the uniformity of the workpiece surface can be achieved.

The traditional ultra-precision abrasive machining method includes fixed abrasive machining (e.g., grinding and honing) and free abrasive machining (e.g., lapping and polishing). Despite the high efficiency of fixed abrasive machining, sub-surface damages may appear after machining. Moreover, although the resulting surface quality of free abrasive machining is high, the processing efficiency is low. Hence, the cleanliness of the working environment and the size of the abrasives must be strictly controlled to prevent surface damage caused by hard and large particles that come into contact with the processing surface. However, the cost of such a procedure is extremely high. To meet the requirement of high-precision and high-efficiency machining of various ultra-precision products, Yuan et al. [80] from the Ultra-precision Machining Center of Zhejiang University of Technology proposed the semi-fixed abrasive machining (SFAM), which integrates the advantages of fixed and free abrasive machining. The main innovations and breakthroughs of the technology are listed below.

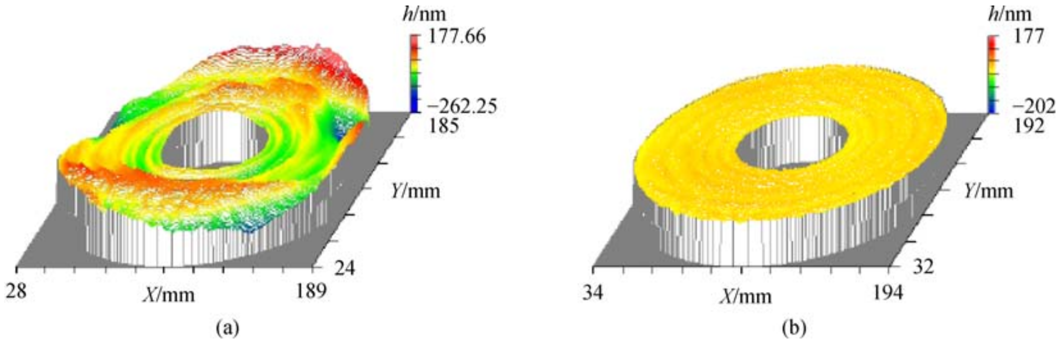


Fig. 24 Processing result for the Ø200 mm f/1.6 aspherical mirror IBF (KDIFS-500). (a) Before processing (RMS 48.6 nm); (b) after processing (RMS 6.1 nm)

1) The bond material with properties of plastic deformation and low bonding strength is developed. The material ensures the uniform pressure of the abrasive grains on the abrasive tools and enables self-sharpening of the abrasive tool, thereby preventing adverse phenomena (e.g., reduction in processing efficiency and poor surface quality caused by "blockage").

2) Although some large and hard particles enter the processing area because of the plastic properties of semi-fixed abrasive plates, such particles falling into the grinding tools at the level of other particles (i.e., the SFAP "trap" effect) would not cause any damage on the machined surface.

3) Ultra-precision polishing can be realized in either dry or wet (plus water) conditions by using soft and fine abrasive particles, which can initiate solid-state reactions with the material being processed.

4) SFAM abrasive tools can be mainly made into plane, spherical surfaces, and non-spherical surfaces without sintering, making them appropriate for ultra-precision machining for workpieces with various types of surface shapes.

5) Ultra-precision, non-damage processing can be realized under the conditions of general purifying environments.

6) Due to the SFAM grinding tools with similar rigidity as the grinding wheel and with good shape accuracy, the shape accuracy is higher than those of free abrasives.

7) The material removal rate and the machining efficiency of the former are greater than those of the latter, because the abrasive particle distribution density of SFAM abrasive tools is much larger than that of the traditional polishing solution.

8) SFAM can be used in the classical polishing process. Due to the uniform surface quality and minimal damage on the machined surface, the time of the final polishing can be significantly shortened.

At present, SFAM abrasive tools can be made with various abrasives, such as Al_2O_3, SiC, SiO_2, CeO_2, and Fe_2O_3. The batch processing rate of finished products is high, and the processing time is shortened several times compared with traditional polishing. The surface roughness reaches Å level. At present, high-efficiency and ultra-precision machining of non-metallic and metallic materials for sapphire wafer, quartz wafer, silicon wafer, and stainless steel has been realized. Given that SFAM technology has the above advantages, it is expected to play an important role in the field of ultra-precision machining.

Traditionally, the main technologies of advanced electronics manufacturing in China has been entirely dependent on imports, the core technologies for which are consistently blocked by foreign countries. Accordingly, the development of Chinese electronics technology is greatly restricted. Qi et al. [81] of the State Key Laboratory of Tribology, Tsinghua University, achieved significant progress in their efforts to comprehensively investigate ultra-precision polishing, modification, and testing technology, and the industrialization of such technologies. The main innovation and breakthrough of the results are as follows: In the aspect of computer hard disk substrate ultra-precision CMP, the behavior mechanism of ultra-precision surface nano particles is proposed and the law of chemical and mechanical equilibrium has been identified; after polishing, the surface roughness and the degree of roughness are both less than 0.1 nm. Meanwhile, with regards sub-nanometer polishing on the surface of the computer magnetic head, nano diamond particles have been introduced into the surface polishing of the magnetic head for the first time. Technical difficulties, such as nanoparticle dispersion, classification, modification, and polishing process, are solved. Nano diamond polishing liquid and polishing technology have been developed; the surface roughness of the magnetic head is reduced from 0.48 to 0.2 nm. In addition, the scratches, black spots, and other defects are also removed. The technology has reached an advanced level internationally, and has successfully been used by the largest computer head manufacturers in the world, namely, SAE Magnetics and Nanker Group, which are popular electronic manufacturing enterprises. Su et al. [82] from Dalian University of Technology has developed CMP technology and successfully obtained diamond sapphire film surface with roughness of 0.187 nm. The significant economic and social benefits obtained now play an important role in promoting further scientific and technological progress in the field of electronic manufacturing technology in China.

To date, batch manufacturing of high-precision balls both here and abroad is characterized by low processing efficiency, low processing precision, and low consistency. Yuan et al. [83,84], researchers from Ultra-precision Machining Center of Zhejiang University of Technology, theoretically proposed "the principle of machining path uniform full envelope for ball forming." Here, the high precision and batch consistency of precision ball machining are guaranteed by the principle of the ball forming. To batch process high precision balls, researchers developed the fixed abrasive grinding plate of the precision ball grinder Olymball-E600 (Fig. 25) by double disk rotation eccentric V-shaped groove grinding method and double rotation lapping disk ultra-precision ball lapper Olymball-D600 (Fig. 26). These are characterized by a spherical error of 0.05 μm, ball diameter change momentum of 0.05 μm, ball batch diameter change momentum of 0.08 μm, and surface roughness of 3 nm. The ball double disk rotation eccentric V-shaped groove machining method, double rotation grinding disk grinding method, precision ball high efficiency lapper Olymball-E600, and ultra-precision ball lapper Olymball-D600 are all civil initiatives. However, the project research results and equipment performance reached international recognition, achieved important theoretical significance, and generated significant social and economic benefits.

Fig. 25 Ultra-precision ball lapper Olymball-E600

Fig. 26 Ultra-precision ball lapper Olymball-D600

Most ultra-precision machining equipment and processing techniques in China continue to be developed for research work. Due to the fact that research power is still distributed throughout different research units, commercial products and industrial applications of ultra-precision machining remain limited. Thus, the needs of the ultra-precision machining industry in China cannot be satisfied completely. However, efforts in this area have produced enormous economic benefits and social benefits. For example, many foreign companies have lifted the embargo on China on certain items, and prices have fallen sharply owing to the development of aspherical ultra-precision machining equipment in the country.

4 Development trends and forecasts

The wide application of ultra-precision machining technologies in civil products as well as the batch processing of low cost products and those with high precision, quality, efficiency, and consistency are becoming increasingly important. In the future, ultra-precision cutting and grinding will follow the high accuracy trend of ultra-precision polishing. By contrast, ultra-precision polishing will follow the high efficiency trend of ultra-precision cutting and grinding. In this context, the novel machining method that considers efficiency and accuracy has been a new research focus, and the CMG and SFAM methods are the embodiments of this trend. Compound machining methods, such as electrolytic MAF and MR abrasive flow finishing, comprise the other aspects of this trend.

The general development trend of ultra-precision machining technologies is as follows: 1) Large-scale, micro-miniaturization, numerical control, and intelligent machining equipment; 2) compound and non-damage processing technologies; 3) ultra-precision, high-efficiency, and low-cost batch processing technologies; and 4) high-precision and low-cost special detection devices used in production workshop. Table 4 shows the development trends and technical forecasts of ultra-precision machining technologies in the future.

5 Differences between the developments in China and the international research community

At present, China still has a long way to go—in fact, more than 15 years—to catch up to the international advanced level of ultra-precision machine tools, especially in terms of completeness, reliability, and accuracy retention. A great gap in testing equipment also exists. Hence, the development of high technology and national defense modernization are seriously hindered based on the aspects listed below.

1) Performance of machine tools: Processing of some complex parts require two-axis ultra-precision machine tools. Five- and six-axis ultra-precision machine tools have been commercialized by foreign manufactures, such as Precitech and Moore. However, only two- and three-axis ultra-precision diamond cutting machine tools have been commercialized in China thus far.

2) Comprehensive accuracy and stability: Although the single technical indexes of spindles and guides made in China are close to those of foreign products, a certain gap remains in the comprehensive accuracy and stability of the machine tools made in China. The accuracy and surface quality of workpieces machined by Nanoform200 and Precitech are 0.15 μm/Ø75 mm and 2 nm, respectively, whereas those of workpieces machined by Nanotech200 and Moore are 0.05 μm/Ø15 mm and 1.0 nm, respectively. In comparison, workpiece accuracy at the sub-micro levels cannot yet be achieved by Chinese machine tools.

3) Control system: Dedicated control systems, such as Delta Tau developed by Moore and UPX™ Control System Precitech, are highly used in this field. In China, some control systems are self-developed and others are based on general numerical control systems. The performance of these systems is much lower than those proposed by international researchers.

4) Reliability of ultra-precision machining equipment: The commercialization of ultra-precision machining equipment has been ongoing for 20 years, and the resulting products have attained considerable maturity and reliability. However, the development processes of most ultra-precision machining equipment in China have only undergone one round of prototype testing. Many basic technologies are far from being considered mature, and thus, the reliability of the equipment is not satisfactory.

5) Appearance design and anthropomorphic design: This aspect has considerable room for improvement in the domestic research context.

6) Accessory functions of the machine tool: Some accessory functions (e.g., cutting tool testing and adjusting system and workpiece errors) in position measurement and compensation system can be found in advanced ultra-precision machining equipment, thereby simplifying the processing of a workpiece. However, the corresponding research in China is far from sufficient, and the operation

Table 4 Development trends and technical forecasts of ultra-precision machining technologies in the future

Corresponding techniques	Development trend	Technical forecasts
Machine tool bed	Higher rigidity and more stable accuracy	New materials, new technology and new structure
Spindle and drive system	Higher accuracy, rigidity, and speed	New principle, new material and new structure
Numerical control system	Process intelligent control	Intelligent numerical control, expert process database and on-line detection
Online detection and error compensation	Higher accuracy and speed	New detection principle/algorithm and new control/executive mechanism
Processing environment control technology	Higher stability and lower maintenance cost	Process or station area control
Vibration isolation system	Higher stability and lower cost	Magnetic suspension, etc.
Machine tool transmission system	More concise mechanism, higher accuracy and speed	Motor direct drive
Diamond tool manufacturing	Special grinding device	Intelligent processing detection
Super hard abrasive grinding wheel dressing	Special dressing system	Integration of online detection and dressing
Non-damage grinding wheel and polishing pad	Better surface quality and higher efficiency	Abrasive tool with chemical mechanical properties
Environment of grinding and polishing	Green and no pollutant emission	New processing principle and new material tools
High efficiency and no damage machining	Automation, batch process, process integration	New processing principle and new material tools
High precision detection devices used in production workshops	Non-contact, high precision, high speed, and popularization	Simplified function
Ultra-small workpiece machining	Complex micro mechanism	Nano structured material cutting tool
Ultra-thin substrate processing	Tens of microns in thickness	New processing principle grinding tool

of ultra-precision machining equipment still relies heavily on the experience and technical expertise of the operator.

7) Basic components and parts: Advanced foreign countries are home to professional manufacturers of basic components and parts used in ultra-precision machining equipment. For example, Load Point is a professional manufacturer of ultra-precision spindles and guides. In comparison, high-level drive motors, encoders, and grating cannot yet be produced in China. In most cases, China still relies on imports and remains limited by various restrictions.

8) Integration technology of machine tools: This aspect includes high-accuracy parts machining, parts and equipment assembly, as well as assembly and system debugging.

9) Manufacture of cutting tool and cutting technologies for special materials and microstructures: The processing technology of high-accuracy arc blade diamond cutting tools has not yet advanced in China. Furthermore, systematic investigations into the ultra-precision processing method of microstructures have yet to be carried out along with diamond tool design and manufacture for micro structures.

10) Ultra-precision grinding: Ultra-precision grinding has been markedly mature and successfully applied in the in the machining of photoelectric crystal substrate and optical aspherical surface as well as in the flattening and back thinning of large diameter silicon wafers. Chinese researchers have also obtained significant achievements in material removal mechanism, grinding process control, grinding wheel, and process optimization. Several research units, such as HIT, National University of Defense Technology, and Changchun Institute of Optics, achieved effective results. However, considerable differences in grinding accuracy, stability, and efficiency have been found, and no commercial ultra-precision grinder has yet to be developed; for example, the grinding equipment and technology for large diameter silicon wafer (> Ø300 mm) have not been fully investigated. Moreover, most advanced grinding wheels rely on imports. Furthermore, R&D of grinding equipment and technology for the aviation, aerospace, military, microelectronics, optoelectronics, energy, and automobile fields is seriously lacking. Unfortunately, the situation of long-term dependence on imports of high-end equipment and restrictions of foreign embargo heteronomy cannot be changed overnight.

Meanwhile, research on ultra-precision machining is usually carried by the cooperation between universities and companies, and the results can rapidly be converted to products. In China, they are mainly led by universities, and limited results are applied to commercial products.

Based on the above, the outstanding problems of ultra-precision machining in China are as follows: Weak independent development capability, an immature professional supporting system, lag in functional component development, low production automation, and the production of machine tools with poor reliability and accuracy.

6 Conclusions and prospects for the future

China has listed the high-end CNC machine tools and basic manufacturing equipment in the "Outline of the National Medium- and Long-term Science and Technology Development Program." The goals of this special project are as follows.

1) China must be able to form independent capabilities to develop high-end CNC machine tools and basic manufacturing equipment by 2020.

2) The overall level is expected to reach the international advanced rank, and a portion of these products must be recognized as international leaders.

3) A technology innovation system led by enterprises and combined production and research must also be created.

4) High-quality R&D teams must be established and developed.

5) About 80% of the demand for high-end CNC machine tools and basic manufacturing equipment in the aerospace, marine, automotive, and power generation equipment manufacturing industries must be supported by domestic manufacturers.

The implementation of this project has considerable significance to improve China's independent innovation capability and core competitiveness in the fields of ultra-precision machine tools and basic manufacturing equipment industry.

Based on the actual situation of China and the development trends, the research must be conducted on several important aspects of ultra-precision machining: 1) Basic theories and processes of ultra-precision cutting, grinding, and polishing; 2) key technologies, accuracy, dynamic characteristics, and thermal stability of ultra-precision machine tools; 3) precision detection, online detection, and error compensation for ultra-precision machining; and 4) materials for ultra-precision machining.

China's progress can be expected to reach advanced levels internationally in 10–15 years if the micro level machining production and application are stabilized and expanded, respectively. Furthermore, the research on nanometer machining technology and equipment can be carried out with the support of various national programs. Breakthroughs are also suggested for the following key technologies and equipment:

1) High-efficiency, ultra-precision, and non-damage processing technology and equipment.

2) Accuracy and stability of ultra-precision machine tools.

3) Key functional components of ultra-precision machine tools (e.g., spindles, guide rails, micro feed systems, and direct drive systems).

4) Design and manufacture of high-efficiency and ultra-precision tools (e.g., non-damage and non-pollution tools).

5) Ultra-precision machining technology and equipment

for large parts (e.g., planes and spherical and aspherical surfaces).

6) Development of a series of high-precision CNC precision machine tools (e.g., large lens, bearings of wind driven generators, bearings of high-speed trains, bearings of high-precision machine tool, and ultra-precision cutting, grinding, and polishing equipment).

7) Establishment of an expert database of ultra-precision cutting, grinding, and polishing processes.

8) Intelligent control technology of ultra-precision polishing process.

9) Ultra-precision on-line and in-situ detection technology for polishing.

10) Ultra-precision measurement technology and equipment (rapid, non-contact measurement of large-sized spherical and aspherical surfaces).

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