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Foundation of the Aspheric Optical Polishing Technology

1.1 Advantages and Application of Aspheric Optics

1.1.1 Advantages of Optical Aspherics

It is relatively simple to process small plane and spherical optical mirrors with traditional processing techniques that are used to manufacture highly accurate products; however, an optical system made up of spherical mirrors remains to face certain image quality restrictions. Consisting of a plano-convex spherical surface, the lens bring all parallel incident light together to the optical axis, but no perfect light focal point can be found along the optical axis, which affects the quality of imaging, such as clarity decline, distortion, and aberration. The traditional optical design uses a combination of different types of spherical mirrors to eliminate its aberrations. If the greater field of view is needed, then more lenses are required in the optical system. As a result, its size and weight increase, and the reflection of light within the lens increases, which causes certain unfavorable factors to emerge as a flare phenomenon. On the contrary, aspherics provides a new solution to these problems of an optical system. Rationally designed aspheric plano-convex lenses make all the incident light parallel to the optical axis, converging to the point, which eliminates aberrations. [1]

Aspheric optical components, which are made by the spherical surface together with a high order curvature rate, have a great number of advantages. Aspheric lens eliminate the aberration of light transmission process, which improves accuracy of focus and calibration without increasing the number of independent lens. By increasing the number of independent variables, aspheric lens promote the freedom of aberration correction and the freedom of system design. [2,3] Furthermore, aspheric optical components are used on special occasions, such as lens system design of aplanatic imaging in full aperture or progressive glasses, and so on. [2] The application of aspheric lens produces excellent sharpness and higher resolution. Therefore, an aspheric optical system displays its advantages of correcting its aberrations, improving its

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image quality, expanding its field of view, increasing its acting distance, reducing its optical losses, obtaining the effect of high-quality images with high-quality optical properties and being designed as smaller ones. These advantages make aspheric optical elements more widely used in the fields of aviation, aerospace, defense, and high-tech civilian areas. [2,3]

1.1.2 The Application of Aspheric Optical Components in Military Equipment

According to a survey of the U.S. Army in the 1980s, more than 234,600 pieces of aspheric optical components were needed in the products of military laser and infrared thermal imaging optoelectronic, the number of which was only a little less than the demand of spherical parts of 635,900 pieces. [4] For instance, by using five aspheric lenses, XM-35 fire control system of 20 mm cannon in AH-1 Cobra helicopter reduced its weight of more than 7 lbs. to 3 lbs.

Laser, with the speed of light, has transferred its energy to its target for the purpose of interrupting or destroying it. The intense laser beam, a weapon of strong lethality, with flexible movement in any fire directions, has no constraints on target's motion or on self-gravity. A high-energy laser weapon consists of two major hardware components: a high-energy laser device and a beam direction finder. The beam direction finder is composed of a large-aperture laser launch system and a precision tracking system.

The large-aperture laser launch system is applied to firing laser beam to a far-distance target, to converge a spot at its target and to form a spot power with density as high as possible in order to destroy it within the shortest period of time. The precision tracking system makes a launch telescope keep tracking and aiming at the goal, which makes the target locked in the fixed spot, at the certain position of the target, where the laser beam will destroy or damage it effectively. Therefore, it is necessary to have the telescope with a primary mirror of enough diameters, and its secondary mirrors play the role of focusing quickly according to the various distances to the target.

According to statistics, the United States and the former Soviet Union launched more than 4000 units into space, about 75% of them for military purposes, of which 40% were for military-to-ground observation, during the 40-year period from the first man-made earth satellite to the year 2004. The number of launched imaging reconnaissance satellites of the United States amounted to nearly 260 and those of Soviet Union up to over 850. Besides the purpose of military reconnaissance, these satellites have many applications for the space guidance and confrontation, search, tracking, monitoring, and early warning. High-resolution earth observation satellites are also used for land resources surveys, such as prospecting, yield assessment, geological and geomorphological mapping, weather, and disaster forecasting (meteorological, oceanographic observations) for other civilian purposes.

1.1.3 The Aspheric Optical Components in the Civilian Equipment

Aspheric optical components have broad applications in the civilian fields, such as the information display system of aircraft flight, the various parts of a camera (including the viewfinder, zoom lens, infrared wide-angle horizon, and a variety of optical measuring instrument lens), video recording microscope read head, medical diagnosis products (including indirect ophthalmoscope, endoscope, progressive lenses), digital cameras, VCD, DVDs, CD-ROM, CCD camera lens, large-screen projection TV, and other image processing products. With the trend of miniaturizing optoelectronic systems, the application of micro-optical components has a good prospect in the engineering field. An important application of micro-optical components is connecting devices of an optical fiber communication system. In our daily life, many products also use micro-optical components such as the micro lens array of liquid crystal display, laser spectroscopic, and laser scanning F-θ lens, and so on. Another important application is for a mobile phone camera; consumers require that the camera take high-quality images with less weight for convenience. Micro-optical lens brings about the improvements of high image quality, small size, and light in weight. Since the aspheric has these advantages of reducing wave phase difference and the like, it becomes inevitable that micro-aspheric lens replace traditional lens thanks to their high quality of imaging, lower camera weight, and auto focusing of their optical zooming process.

The largest optical lenses are used for astronomical telescope, which is a powerful tool for the exploration of the universe. The world's largest telescopes that exist and that are still to be built include the CELT (California Extremely Large Telescope) and GMT (Giant Magellan Telescope) with 30-m primary mirrors; the main mirror with a 20-m of CFHT (Canada France Hawaii Telescope) plan in Canada; the EURO50 with 50-m primary mirror, which is established by Switzerland, Spain, Finland, and Ireland; and the OWL (Overwhelmingly Large) with 100-m-long primary mirror of European Southern Observatory; the sub-mirrors in EURO50's splicing and off-axis aspheric mirrors are 2 m in diameter each.

It is far superior for an observation to have its telescope mounted in space to that on the earth. For example, the famous Hubble Space Telescope was launched successfully in 1990 by the National Aeronautics and Space Administration (NASA) of the United States. The diameter of its primary mirror is 2.4 m, with 4.5 m^2 in area, so it observes the distance about 12 billion light-year [5,6] far away in galaxies, and its optical manufacturing capability is 1.0 m^2/year.

NASA is doing research on the Next Generation of Space Telescope (NGST). The James Webb Space Telescope (JWST) is planned to launch in 2018, and its primary mirror diagonal reaches 6.5 m, with its area of 25 m^2 (made up of 18 hexagonal sub-mirrors), and its optical manufacturing capability is higher than 6.0 m^2/year.

The requirements for the primary mirror of the Hubble Space Telescope (HST) and JWST show the developing tendency shows the developing tendency of optical manufacturing capacity for other NASA space projects. [7] The Single Aperture Far-infrared Space Observatory (SAFIR), with 10 m of its primary mirror diagonal length and 100 m^2 of its area, is planned to be launched in 2018, with the manufacturing capacity of its optical components rising to an amazing 240 m^2/year. However, at present, the processing capacity for the biggest mirrors of the world is less than 50 m^2/year. [8]

1.2 The Characteristics of Manufacturing Aspheric Mirror

1.2.1 Requirements of Modern Optical System on Manufacturing Aspheric Parts

In the twenty-first century, the competition is becoming more intense in the market of international optical industry, and the requirements are becoming tighter on manufacturing aspheric parts, such as on their aperture, their relative aperture, machining accuracy, degree of lightweight, processing efficiency and production costs, and so on.

1.2.1.1 Aperture of Optical Components

According to the Rayleigh criterion, to distinguish two points of the far field, an optical system has to obtain the angular distance as $\Delta\theta = 1.22\lambda/D$, where D stands for the effective aperture of the optical system; therefore, increasing D is the basic way to improve the resolution ability of the optical system. For example, a space camera of a satellite about 200–300 km of height above the earth should have at least 0.5–1 m of aperture in order to obtain high resolution. [9]

1.2.1.2 Relative Aperture of Optical Components

Relative aperture is the ratio between the effective aperture and the focal length of the main mirror. Imaging sharpness and imaging illumination are related to relative aperture. If the aperture remains the same, increasing relative aperture, which is capable of improving image sharpness and illumination, thereby improves image quality. In addition, increasing relative aperture results in the axial distance of optical system shortening and the reduction of its weight. For a space optical system, increasing relative aperture also can reduce launch costs. According to scientists' prediction, the relative aperture of the primary mirrors in large reflecting telescopes will be distributed between the ratio of 1 to 1.5 and 1 to 1 in the twenty-first century. Due to the limit of the diameter and the focal length, an optical system of a space camera has a small relative aperture (is below 1 to 4), whereas it is intended to be larger in the future. [10]

1.2.1.3 The Machining Accuracy of Optical Components

Machining accuracy of optical components affects the performance of an optical system directly. Traditionally evaluating the surface accuracy of some optical components is related to certain standards, such as "Peak-to-Valley" (PV) value, "Root-Mean-Square" value (RMS), and surface roughness [11,12] of the reflected or transmitted wavefront. The wavefront error of each spatial frequency band reduces the performance of an optical system due to the following areas: low-frequency error reduces the peak intensity of the system, affecting the performance of focusing; medium frequency error increases the spot size by accompany of reducing the peak intensity, thus affecting the image quality; high frequency error, corresponding to large angle scattering, reduces the contrast or the signal-to-noise ratio of the system. To improve the performance, modern optical systems have to fix new requirements on the quality evaluation of optical components, which means that quality evaluation and controlling should be based on the spectrum distribution of the wavefront error. For example, in the National Ignition Facility (NIF) of the Inertial Confinement Fusion (ICF) Engineering of the United States, there are more than 7000 pieces of large optical components of this optical system. According to their impacts on the optical performance, the surface errors are divided into three space-bands by the NIF [13] as follows: The low-frequency surface error, with the wavelength greater than 33 mm, mainly determines the focusing properties, controlled by the RMS gradient. The medium frequency error, with wavelength between 0.12 and 33 mm, affects the tail of focal spot and near-field modulation, controlled by the power spectral density (PSD). The high-frequency roughness, with wavelength less than 0.12 mm, has a major impact on filamentous, controlled by the RMS roughness. In addition, there are more stringent requirements on small-scale manufacturing errors in the high-resolution imaging system; for instance, the secondary mirror of Terrestrial Planet Finder Coronagraph (TPFc) (the length of its long axis is about 890 mm) requires that the disturbance of five cycles (in full aperture scale) is less than 6 nm RMS; the disturbance from 5 to 30 cycle scale is less than 8 nm RMS; the disturbance more than 30 cycles is less than 4 nm RMS; and the disturbance of JWST's secondary mirror (diameter Ø738 mm) is 34 nm RMS, 12 nm RMS, and 4 nm RMS in the corresponding scale, respectively. [14]

1.2.1.4 The Lightweight Rate of Optical Components

The deformation caused by self-weight and thermal expansion has been the new problem in the field of manufacturing optical components, when the diameter of optical components and the system weight are increased significantly. Currently, some major methods are used to improve the lightweight of optical systems to reduce launch costs and deformation of their optical parts, by using new materials, centrifugal casting, welding and forming, machining lightweight, and so on.

Zero-expansion glass and fused silica materials are used for a large mirror's body, which is the mainstream of lightweight currently. The zero-expansion glass material is the dominant product in domestic markets and international markets. The Computer Numerical Control (CNC) milling machining method is used for forming and molding zero expansion glass, and the diamond wheel grinding and etching method is used to lightweight the mirror body. The lightweight rate of a large-diameter mirror is up to 50–60% in China.

The light primary mirror can be constructed by the honeycomb sandwich structure with the method of fusing its quartz front and its back plate together. It is a mature technology that can make an 8-m-diameter mirror body. The Institute of Optoelectronic Technology of Chinese Academy of Sciences, in Chengdu City, has developed the technology of fusing its quartz body to manufacture a mirror, and the Institute has produced a series of fused mirrors of Φ400–Φ1300 mm with the lightweight rate up to 70%.

The areal density is the index of evaluating lightweight for optical parts. The Hubble Space Telescope has a crucial significance for space telescopes in that it uses a lightweight primary mirror of 2.4 m in diameter made by fused silica glass, which reduces about 70% of its weight, with the areal density of 240 kg/m^2. JWST, which still is in research, will enhance its own lightweight rate, and its areal density will be reduced to approximately a tenth of the Hubble Space Telescope. [7]

Table 1.1 lists the areal densities of the primary mirrors in certain optical systems developed by the United States, and a variety of material properties are shown in Table 1.1 [15] for producing space mirrors.

Table 1.1 shows that the stiffness of beryllium and of SiC is much better than that of other materials. One of the shortcomings of Be material is that it will cause toxic impact if beryllium dust is inhaled into human lungs. In order to eliminate the inhaled beryllium dust, a series of stringent protective measures should be taken; as a result, the manufacturing cost increases. The processing reflector of Be mirrors requires a large quantity of material, and the utilization rate of the material is quite low. Although recent technologies, such as the new technique of

Table 1.1 A variety of optical mirror material performance.

Material parameters	Be	Si	Al	Cu	Mo	SiC	SiO_2	So-115 M	Zerodur	ULE	Expect
Density, 10^3 kg/m^3	1.85	2.3	2.7	8.9	10.2	3.05	2.2	2.5	2.5	2.21	Low
Modulus of elasticity E, GPa	280	157	69	115	325	390	70	92	92	67	High
Specific stiffness, E/10^6 m	15.1	6.8	2.7	1.3	3.2	13	3.2	3.7	3.7	3.1	High
Thermal conductivity, W/mK	159	160	220	400	145	185	1.38	1.2	1.67	1.3	High
Coefficient of thermal expansion, 10^{-6} K^{-1}	11.4	2.5	23.9	16.5	5	2.5	0.55	0.15	0.05	0.03	Low
Coefficient of thermal deformation, 10^{-8} m/W	7.2	1.6	11	4.1	3.5	1.4	40	12.5	3	2.3	Low

manufacturing near net shape and the emergence of new beryllium alloys, can reduce the manufacturing cost greatly, processing mirrors in Be still costs much higher than in the material of SiC.

The research of SiC as a mirror material began in the 1980s. Over the two decades of research and development, SiC has been a novel optical material of broader application due to its excellent physical properties and its good process performance. Compared with beryllium, SiC has distinctive advantages as follows: isotropic, non-toxic, and no requirements of special equipment. It has optical thermal stability from the room temperature environment to the low temperature environment. The newly developed technology of body manufacturing process can make complex shapes of near net size shape; it is not only useful to produce a lightweight mirror, but also can reduce manufacturing costs afterward. With high stiffness, SiC can be manufactured as a light reflector of the 3-m diameter, which works normally both in the space of weightless environment and at an extremely low and changeable temperature environment.

Today's trends of SiC mirror development are given as follows. (a) Maximization: for example, the most diameters of the large-scale mirrors will be more than 1 m. (b) Lightweight: for instance, the backs of the mirrors are formed from open structure to closed structure, and lose 75% of their weight. With this method, various forms of mirrors can be made, such as ultra-lightweight mirrors, ultra-thin, and abnormity form reflectors. (c) Ultra-smooth surface after surface material modification: for example, by using the method of coating SiC or Si, the surface roughness after polishing can be less than 10 Å RMS and 5 Å RMS respectively. [16–23]

1.2.1.5 The Processing Efficiency and Production Cost

The efficiency and costs of optical processing directly reflect a country's level of modernization in the industry. The evaluation standards of efficiency and costs are the ratio of cost per unit area and the ratio of manufacturing area per unit time. To meet these standards, manufacturing aspheric parts should be improved more efficiently and should cost less, so as to achieve a bigger quantity of optical components, to shorten the production cycle, and to cut down cost. For example, the processing efficiency of JWST program is six times higher than that of the HST, whereas its cost is only 30% of HST.

1.2.2 The Processing Analysis of Aspheric Optical Parts

1.2.2.1 The Difficulty Coefficient for Processing Aspheric

The aspheric surface is one kind of surface that deviates from the spherical surface. Thus the greater the deviation from sphere, the more difficult it is to process. The spherical surface has a curvature with the same radius, and normal lines of each point on the surface are converged in the same focus. As the radius of the aspheric surface's curvature is different on each point, the surface is more complex than the spherical one. For example, for the deep paraboloid surface that has relative aperture of 1 to 1, its radius of curvature decreases gradually from the vertex to the edge, which at the edge point is 90% of that at the vertex point; therefore, the difference is about 10%.

For an aspheric surface, one sphere can be found, which has minimum departure from this aspheric and passes the vertex and the edge of the aspheric surface. This sphere is called "the closest sphere." The asphericity refers to the deviation between aspheric surface and its closest sphere.

The asphericity reflects the difficulty of processing, but asphericity is not the only element to affect difficulty, which also relies on the diameter of the processed aspheric surface. For example, an asphericity of parabolic can be describe as the following formula:

$$\delta_{\max} = 2.44 \times 10^{-4} DA^3 \tag{1.1}$$

where D is the effective aperture of a paraboloid; A is the relative aperture, and $A = 2D/R_0$; R_0 is the vertex radius of curvature.

The formula shows that the manufacturing difficulty of a parabolic is proportional to the cube of A (the relative aperture) and to D (the effective aperture).

Makytof's opinion holds that the relative aperture of 1 to 2 is the limit point of the classical processing methods. [9]

Therefore, the difficulty coefficient is truly reflected by the gradient of the change or the steepness of its aspheric surface. Foreman [24] describes μ_F as the processing difficulty coefficient of an aspheric. It depends on the ratio of the distances from curvature R to the surface radius in the meridian plane and from curvature R to the optical axis. Its expression in formula is presented as follows.

$$\mu_F = (dR/dx)_{avg} = [R(x_2) - R(x_1)]/(x_2 - x_1) \tag{1.2}$$

Where, x_1 and x_2 are two points in the meridian plane; $R(x_1)$ and $R(x_2)$ are curvature radius at x_1 and x_2 respectively.

The greater the gradient, which is the slop of aspheric surface deviating from the closest sphere, is, the more difficulty the aspheric processed is. Foreman pointes out that it is quite difficult to process the aspheric surface when the difficulty coefficient is over 5 (as $\mu_F > 5$).

1.2.2.2 The Curvature Effect of an Asphere [25–28]

From the viewpoint of contact mechanism between polishing tools and workpiece, the curvature is an important factor that determines the contact area. The curvature effect is not obvious, when the radius of curvature of large aspheric workpiece is much larger than the size of the polishing tools; however, for a small aspheric workpiece, if the radius of curvature of a polishing tool approaches more closely to that of a base circle of the polished aspheric, then the partial contact area between the workpiece and the polishing tool changes severely along with the radial position moving. The unmatched discrepancy between the polishing tool and the workpiece will affect partial removal shape and the roughness of a mirror in the polishing process. To properly polish aspheric mirrors, it is necessary to make the curvature radius of a polishing tool at each contact position far less than that of the polished aspheric. A small polishing pad is a sufficiently small plane fitted to the aspheric surface. In theory, there are always "fitting errors," but the deformation of the polishing mold reduces the fitting errors. In order to polish properly, the radius of a wheel-polishing tool is also required to be less than that of the partial curvature of the concave region. For example, the limit of a minimum curvature radius arises when a MRF (Magnetorheological Finishing) wheel polishes a concave surface, but there is no limitation for polishing a convex surface. For example, Q22-XE, the polishing wheel with the diameter of 20 mm, can be used to polish a concave part with the aperture of the minimum size of 5 mm in aperture and of 15 mm in curvature radius. A polishing wheel of 35 mm in radius still can be used to polish a convex parabolic surface with the curvature radius of 15 mm.

In order to maintain the adaptation of a tool and an aspheric surface, the diameter of the tool is usually about 1/5 to 1/10 of the full aperture of the workpiece. The greater the aspheric steepness is, the smaller the tool's size should be. For rigid tools, the small size affects the stability of removal function, and it is difficult to achieve stability when using the too small size of the polishing pad. Water jets and magnetic jet polishing technique use a flexible liquid column as a polishing tool, and it can be replaced by using different nozzles, so it can change the size of the polishing tool or polishing spot size easily; compared with a polishing pad, the precision polishing for complex shape is easy to implement.

1.3 The Manufacturing Technology for Ultra-Smooth Surface

1.3.1 Super-Smooth Surface and Its Applications

The stringent requirements of the component surface roughness is proposed on the basis of the performance requirements of the optical system. The surface roughness of optical components required to achieve 12 nm Ra for reflection, refraction of the conventional optical system.

The scientific development of modern short-wave optics, strong light optics, electronics, IC technology, information storage, and thin film technology, the requirements of surface quality are more demanding, we call the surface roughness, which is better than nanometer scale, an ultra-smooth surface.

In order to obtain the highest reflectivity of optical surfaces, optical components do not only require high form accuracy, but need low-scattering properties or very low roughness values as well. Functional components should have high reliability, high frequency response, and high sensitivity. As most functional components are kinds of brittle or brittle and soft crystal materials, more attention should be paid to the integrity of the surface lattice, which is related to the surface roughness. Different characteristics from ultra-smooth surface can be applied to different areas:

1.3.1.1 The Soft X-Ray Optical System

Soft x-ray wavelength ranges from 1 to 130 nm; within this band, all of the materials have a strong absorption of lights. Since its optical systems are reflective mostly, the reflectivity is a most important indicator. To improve the reflectivity of the multilayer film of a mirror, where σ is RMS value of roughness, its general requirement is $\sigma/\lambda < 1/10$, and roughness of the super-smooth mirror must be better than less than 1 nm RMS. On the other hand, with the thickness of the cycle of the X-ray multilayer up to nanometer scale, the ordinary smooth surface will cause uneven film thickness of each layer deposition and cross affection, thus affecting the reflectivity. Accordingly, the multilayer mirror substrate must be ultra-smooth surface.

In order to obtain a better image quality, it is more stringently imperative to take account of the scattering of x-ray and the surface roughness of soft x-ray optical components. For example, the surface roughness of the microscope 20× Schwarzschild with 12.5 nm band and others is of 0.1 nm RMS. [29]

1.3.1.2 The Laser Plane Mirror and the Optical Window

The ultra-smooth technology is one of the key technologies for high-precision laser gyro manufacturing. Specular scattering will lead to performance degradation. The reflector of laser gyro is required to reduce backscatter as much as possible, and that surface roughness is the main cause of the scattering. For example, for the laser gyro mirror in the fighter plane, using Zerodur material with zero thermal expansion coefficient, its reflectivity must be larger than 99.99%, flatness is better than 0.05 μm, and the surface roughness can be small than 0.7 Å Ra.

In the high-energy laser systems, optical components must withstand high radiation intensity, such as the power density of laser beam in laser fusion engineering that should be more than 10^{12} W/cm^2. The output power of continuous wave supersonic oxygen-iodine laser (COIL) is up to megawatt level. Because an ordinary mirror is under such a strong irradiation, the surface will be burning and damage; consequently, it is necessary to improve the anti-laser damage threshold of the mirror. Specular scattering is an important factor to cause surface damage; while the scattering comes from the mirror surface roughness and subsurface damage, it is essential to only use ultra-smooth surface in order to improve the anti-laser damage threshold of the mirror.

Sapphire is an ideal material for optical window used for medium-wave infrared (3–5 μm). Residual stress in the sapphire lens after processing will affect the light propagation, which must be annealed after polishing lenses to eliminate the stress of processing. In processing technology of ultra-smooth sapphire lens, the roughness must reach 0.3 nm RMS, its residual stress also should be extremely small, and its light propagation wavefront error after processing must be reduced from λ/20 of conventional process to λ/40.

1.3.1.3 The Functional Optoelectronic Devices

Functional optoelectronic devices are usually used to grow thin films with Molecular Beam Epitaxy (MBE) or Chemical Vapor Deposition (CVD), Physical Vapor Deposition (PVD), and other methods on the surface of the function crystal, such as SOS devices with silicon film grown on sapphire substrates. The surface roughness of the substrate crystal lattice integrity has a great impact on the film atomic arrangement directly. So the substrate surface requires excellent lattice integrity. On the other hand, many functional crystal materials, such as mercury cadmium telluride, indium antimonide, indium phosphide, and gallium arsenide, are of very low hardness, whereas only ultra-smooth processing technology of atomic-level can obtain high quality surface. For example, the Kalium Di-hydrogen Phosphate (KDP) crystal is a soft brittle material for the requirements of surface roughness of 1–2 nm.

1.3.1.4 Information and Microelectronics

In the case of the hard disk magnetic storage with recording technology and in order for the storage density to improve, the waviness and roughness of hard disk are required to be below 1 Å. In the very large scale integrated circuit manufacturing of 45–18 nm groove width, copper interconnect manufacturing requires very soft Low-k materials. Although the hardness of each polished material in silicon electronic chip surface varies widely, it also wants to achieve sub-nanometer level roughness on the whole surface.

Both at home and abroad, there is ultra thinning processing technology such as ultra-precision grinding, chemical mechanical polishing (CMP), wet etching (WE), and atmospheric pressure ion etching (ADPE). With the large size of the substrate (450 mm) and ultra thin (<40 μm), the machining accuracy and surface quality requirements are becoming increasingly high. The thinning processing of the silicon wafer substrate does not only require the surface roughness to reach nanometer scale, but also requires surface defects and metamorphic layer thickness close to zero. This requires advanced thinning processing technology for high efficiency, high-precision, high-quality, and pollution-free.

1.3.1.5 The Large-Scale Ultra-Smooth Surface with Complex Shape

As a typical example of a Large Scale Integrated circuit (LSI) lithography lens, Extreme Ultraviolet (EUV) lithography in microelectronics manufacturing of 32 nm groove width, the very technical projection lens manufacturing, using off-axis aspheric, requires the whole band to achieve sub-nanometer accuracy, surface form accuracy, waviness, and roughness at the same time achieving sub-nanometer. [30] Specific requirements are:

1. The form error: the error arises when space wavelength is greater than mm, which will produce a small angle scattering; associated with the aberration of the system, it determines the quality of the imaging system. Due to the diffraction limit imaging, with the system wave meeting with the RMS value of less than $\lambda/14$, the RMS assigned to each component is less than 0.2 nm.
2. The median frequency roughness (MSFR): for space wavelength in the micrometer region, its scattering in the field of view will increase the shine (Flare) level and reduce the image contrast, and requirements of the MSFR must be smaller than 0.1 nm RMS under its scattering and imaging of system.
3. The high frequency roughness (HSFR,): for space wavelength smaller than the micron region, its scattering is not in the field of view. The loss of energy does not affect the image quality. In order to improve the productivity of the lithography machine, HSFR must be smaller than 0.2 nm RMS.

The large-scale ultra-smooth surface manufacturing with complex form is carried out on the basis of the aspheric processing, meaning to accomplish more high-precision processing, by combination of mechanical pad CCOS (Computer Controlled Optical Surfacing), MRF and IBF (Ion Beam Figuring) methods.

1.3.2 Manufacturing Technology Overview of Super-Smooth Surface

The ultra-smooth surface processing technology is an important branch of the ultra-precision machining technology.

Firstly, surface roughness needs a measurement standard when measurement enters the sub-nanometer order of magnitude. When roughness is bigger than 0.5 nm, its measurement is used by a Zygo white light interferometer. When the sampling length is 0.14 mm, a 50 times optical lens is used, and when the sampling length is 0.7 mm, 10 times optical lens is used for this interferometer. When using the atomic force microscopy to measure, its sampling length is only a few microns, and measured roughness range should be less than 0.5 nm usually. [31]

Ultra-smooth surface processing technology has been developed very maturely. Some techniques are based on mechanical micro-cutting principle, such as Single Point Diamond Turning (SPDT), milling and boring, Ductile plastic Grinding (DG), and so on. Others have evolved from the traditional dissociate abrasive polishing techniques, such as CCOS; Fixed Abrasive Grinding (FAG); Elastic Emission Machining (EEM), Float Polishing (FP), MRF; Magnetic Field Assisted Fine Finishing (MFAFF), and so on. [32]

Some new technologies have developed from special processing, such as IBF, Reactive Ion Beam Figuring (RIBF), Plasma Assisted Chemical Etching (PACE) or PACE-Jet, Electrolytic Abrasive Mirror Figuring (EAFM), and Chemical Vapor machining (CVM), and so on.

The above-mentioned polishing methods can achieve the roughness requirements to 1 nm (except n to MFAFF), but owing to the processing differences characteristic of the workpiece material properties, size, shape, and processing conditions, the processing effects are different, too. We must take into account the polishing efficiency and surface roughness, economy, and practicability to employ these methods.

1.3.3 Manufacturing Technology of Ultra-Smooth Surface Based on the Mechanical Micro-Cutting Principles

1.3.3.1 Single-Point Diamond Turning

SPDT, boring and milling with diamond tools, is characterized by soft materials processing, such as the layer of aluminum, copper, tin, lead, electroless plating nickel, zinc, Jun, silver, gold, and other metal materials. And other semiconductors materials such as zinc selenide, lithium niobate, silicon, potassium bromide, and crystalline materials, also can be done. Diamond tools with extremly high hardness can be sharpended to the utmost extent, which enables removal of ultra-thin layer of materials and finnally realizes very smooth surface machining. For example, KDP crystal processing in the ignition of laser fusion test plan (LIF) in the United States is used by a single-edged diamond fly cutting, and it was reported that its surface roughness can reach 1.5 nm. Now, for the infrared detector crystal optical components, electronic products in the disk, the drums are also used by single-point diamond turning. Since ultra precision boring techniques commonly used in the hole processing for non-ferrous metals, multi-axis ultra-precision milling machine is mainly used for ultra-precision three-dimensional micro-structural processing. The fly cut way is more widely used for plate processing, whereas the milling of multi-blade cutter is still rarely used in ultra-smooth surface finishing.

1.3.3.2 *Ductile Grinding Technology* [33]

The fracture toughness of hard and brittle materials such as glass is very small: in general only 10^{-2} to 10^{-3} of the metal material is fracture toughness. Therefore, when machining hard and brittle materials, cracks appear easily. It is impossible to use an ordinary cutting or grinding method for smooth surfaces processing of hard and brittle materials. It is established that the ultra-precision machine with small feed rate and the appropriate process parameters for cutting or grinding of hard and brittle materials can also achieve ultra-precision mirror surface, as can metal materials plastic processing. This grinding of brittle materials is called ductile mode grinding or micro-grinding. Plastic grinding processing is used for hard and brittle materials such as glass and engineering ceramics; it is likely to achieve the required surface roughness only by grinding without polishing. It makes sense that only the sub-surface damage value (SSD) and modulus of rupture values (MOR) are small enough. According to the ductile mode grinding theory and experiment, the plastic grinding mode requirements of the machine are such that the feed of grinding wheel should be controlled within a 10–100 nm range, for example, for the BKT glass about 45 nm and for the Zerodur materials about 55 nm. [34] The feed accuracy or resolution of the machine tool is usually required about 10 nm. In addition, as the hardness of the materials such as glass is bigger than 10-100 times of general metal materials, the grinding wheel cutting can withstand great resistance, and hence the machine must have sufficient rigidity in order to ensure the accuracy for very thin processing.

In recent decades, many scholars have studied and developed new grinding processing methods, which can accomplish a high-precision smoothing surface, including for the high-precision plane, spherical and aspheric optical components. Professor Yoshiharu Namba of the Central University of Japan [35] developed the ceramic ultra-precision grinding machine tool, which can achieve the 1 nm of grinding accuracy. The roughness value of BK7 glass is up to 0.074 nm RMS after plastic grinding and measured by atomic force microscope (AFM).

1.3.4 The Traditional Abrasive Polishing Technology for Ultra-Smooth Surface

Classical polishing principle is that the physiognomy negative from polishing die is used and moves relatively easy in the process, added with dissociative abrasive slurry. The polishing mold and workpiece surface contact each other through mechanical, chemical, and physical interactions between the polishing slurry and the workpiece surface.

1.3.4.1 The Dissociative Abrasive Polishing Mechanism

There are three basic theories to explain the polishing mechanism: mechanical micro-cutting, chemical reaction, and rheological theory.

In the mechanical micro-cutting theory, the polishing process is a continuous process of lapping. When the abrasive particle size is lessened, the cutting force is also reduced, which can cause chips to become smaller; therefore, roughness is reduced.

There are two modes of mechanical micro-cutting. One of them uses the pressure rupture theory to explain the removal action of the optical surface by polishing abrasive, as shown in Figure 1.1a. The abrasive particle is engraved on the workpiece surface in the continuous positive pressure, so the workpiece surface breaks to achieve material removal. The removal efficiency of this mode depends on the polishing abrasive particle shape and workpiece material properties (elastic modulus, hardness, and fracture toughness), so the classical polishing method can be used to explain it.

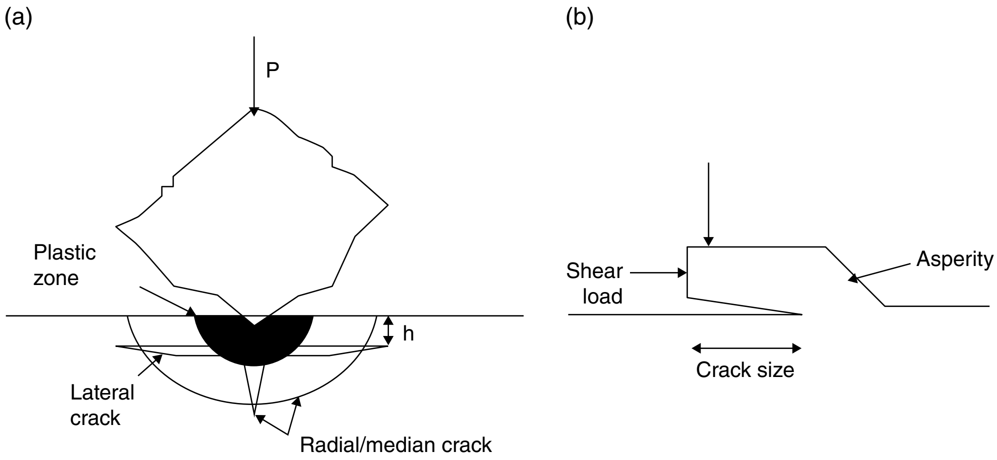

Figure 1.1 The mechanical fracture mechanism of the two polishing modes. (a) Pressure rupture mode. (b) Shearing action mode.

Another mode of material removal attributes to the shearing action of the polishing abrasive in rough surface, as shown in Figure 1.1b.

According to this mode, the rough surface on the optical parts is caused by nanometer scale cracks. The polishing abrasive grain contacts the rough surface by the vertical load. The shear force is to promote the crack to expand, whereas the vertical load is to sew the crack. If the shear force is large enough to the vertical load, then the material shear fracture and material removal come into being. In the actual polishing process, material removal may be a combined effect of the mechanism of the two modes.

In terms of chemical reaction, the water and the surface of the optical components play a role in a hydrated layer, especially the glass material. The hydrolytic reaction in the water and the silicate of glass surface form silicic acid gel film on the glass surface, and thereby the erosion of the water will slow down. But due to the silicone layer, often the surface is porous or cracked. In this case, the solution of alkaline ionized OH− will further erode the glass within body, so the glass body is stricken and destroyed, making more SiO_2 transferred to the slurry, and the polishing particles scrape colloidal silicate protective layer is exposed to the glass surface but also continues to be hydrolyzed, and so on. At the same time, the polishing mold and polishing slurry will generate the chemical reaction to the surface, resulting in material removal. According to the classic polished theory that the pH value of slurry is 3–9, the polishing efficiency is the most favorable.

The essence of the rheological theory in the polishing process is that there are flowing or re-distribution phenomena of molecules on the polished surface. Flowing will move the protruding to fill in and raise concave place, so the polishing process is the surface molecule redistribution to form a smooth surface. The current main reasons are the thermoplastic flow and melt flow due to friction heat and molecular flow due to chemical reaction.

The polishing process is an extremely complex process; therefore, it is difficult to explain in detail only one theory for the entire polishing process fully. Only depending on the polishing conditions, it is more likely to tell what theory plays a major role and which one plays a minor role in this polishing process. In the super-smooth polishing, the surface material removal is caused by action of mechanical and chemical effects, which is the outcome of the workpiece, polishing grain, polishing mold, and its slurry. The mechanical effects refer to cutting acting with sharp polishing particle edges to the workpiece material and workpiece surface friction. The chemical effects refer to the dissolution or the formation of the film in the surface layer for an easy removal.

1.3.4.2 The Traditional Ultra-Smooth Polishing Method

Traditional ultra-smooth surface polishing uses the swing polishing machine with the simple structure; in order to achieve ultra-smooth surface, it must be improved for materials of polishing film, polishing grain, as well as the polishing slurry and its supply method, and so on.

1. The improvements of polishing film material [36]
   Bitumen, rosin, and PTFE (Teflon) are used as polishing films in the classical polishing method. When the flatness is about λ/200 and roughness is less than of 0.4 nm RMS for many materials, using these polishing films can lead to success. It must be conducive to keep the surface, and also inhibit the waviness of the surface and sub-surface damage effectively. The fluorocarbons foam material or pure tin made of the polished mold to polish fused silica, sapphire, and the like also can get a sub-nanometer smooth surface.
2. The improvements of the polishing liquid supply
   In the classical method, for the operator from time to time to add a small amount of slurry to the polished mold, the polishing liquid supply mode is usually referred to as the "fresh feed" way. The disadvantage of this approach is that the flatness and the sub-nanometer roughness requirements often cannot be met at one time. For example, R. Dietz [37] changed the polishing liquid supply by means of polishing immersion supply: by the way of bowl feeds, the asphalt polishing mold is immersed in the slurry to obtain a surface roughness less than 0.3 nm RMS. The bowl feed polishing is one of the super-smooth surface processing technologies in which the equipment required is relatively simple. Compared with traditional polishing equipment, it is added with a sump and a blender in bath-polishing equipment. The polishing sump is used for the polishing mold and workpiece immersed in the slurry. The workpiece is submerged about 10–15 mm deep in the resting state. The action of the agitator is to remove abrasives by centrifugal force and to keep it from sinking to the bottom; consequently, it is always in a suspended state.
3. The improvement of the polishing grain
   Fine polishing grain in super-smooth polishing is extremely important. As the atomic scale of removal material, the role of chemical acting of the polishing grain cannot be overlooked. According to McIntosh, [38] who used the immersion polishing colloidal oxide silicon slurry and the asphalt polishing mold, the silicon surface roughness is of 0.6 nm, RMS. The ultrafine diamond (UFD) powder whose size is as tiny as some micrometer is a new type of nano-materials made by explosive synthesis method recently. N. Chkhalo [39] used the UFD powder to polish x-ray optical elements in a conventional polishing machine: its roughness is reduced from 1 to 0.3 nm.

1.3.5 The Principles and Methods of Non-contact Ultra-Smooth Polishing

In recent years, the application requirements of the crystal have grown rapidly, and there are many new features of crystal. Most of the crystal hardness is lower than the optical glass, but there are special requirements of its surface integrity. In the conventional polishing, polishing mold and polishing grain putting force onto the workpiece surface will cause surface damage and the destruction of the film lattice integrity of the crystal. In order to reduce the polishing force applied to the workpiece, in the non-contact polishing method, the workpiece to be polished is not in contact with the polishing mold directly.

According to the hydroplane polishing method proposed by J. Gormley, [40] the workpiece in the chemical erosion of the liquid on high-speed rotation by means of dynamic pressure is floating on the liquid surface, like skateboarding on the water, to achieve the purpose of uniform erosion in the workpiece surface. This method has achieved a good integrity of the crystal surface of InP and HgCgTe.

Kasai and Kobayashi [41] proposed the P-MAC polishing. Two workpieces with different hardness are polished on the same polishing pad using a special fixture. The material removal rates are different due to the different hardness of their materials. With the continuation of the polishing time, the workpiece of low hardness is removed of a large amount; with the state between the surface and the polishing mold changing from direct contact to sub-direct contact and to non-contact gradually, the polishing contacting force is going to zero; thus, the low hardness workpiece free of damage is available finally.

Watanabe [42] designed fan-shaped grooves with a certain angle in a polishing mold by using the principle of dynamic pressure bearing. In the polishing process, the polishing liquid filled with fan-shaped grooves makes a relative movement between the wedge angle and the workpiece so that the dynamic pressure in the contact surface is produced, so a layer of liquid film between two surfaces can achieve non-destructive non-contact polishing in a flat substrate of the large diameter.

Professor Namba Yoshiharu [43] of Central University of the Japan developed the FP technique that is a non-contact CMP method. It uses a bath polishing processing method, and an FP tin plate works as a polishing pad. The rotation accuracy of spindle is very high and its rotation speed is 60–200 rpm. Under the united acting with centrifugal force, the sump wall, ring, and fine threads on the tin plate, a thin layer of liquid is produced between the pad and the workpiece, making the workpiece float on the liquid in the polishing process. The abrasive grain suspended in the slurry under action of centrifugal force is continuously collided with the surface along the radial direction. The material of the local high points is continuously removed by the amount of atomic or molecular scale to achieve ultra-smooth surface finishing.

The super-smooth surface with a regular edge, damage-free sub-surface, and crystal lattice integrality can be acquired by this technology. The machining of tin polishing pads is a key technology in FP. Polishing machine with device of ultra-precision turning function, the concentric rings, which are 12 mm wide and 1 mm deep, can be cutting by diamond tools in the fine texture on the surface of tin plate, and then the disk form can be figured by a diamond tool to ensure the flatness of disk. Due to the role of the diamond tool tip, a lot of fine thread structure is on the disk surface, and this thread is very important for the FP. The soft abrasive and hard abrasive can be used for FP—the key is the abrasive particle size and uniformity. In order to increase the contact area and collision probability of the workpiece for a higher polishing efficiency, the smaller abrasive particle size is used, best for nanometer scale, as less than 20 nm typically. FP is one polishing method of the smaller amount of removal. A workpiece with traditional polishing method is processed to a certain surface accuracy, 2–4 Newton's ring firstly. The roughness on monocrystalline samples measured by SPM is up to 0.079 nm RMS.

Changchun Institute of Optics and Fine Mechanics and Physics Institute have used immersion ultra-smooth polishing to polish a workpiece of the synchrotron radiation components, and this FP method can obtain ultra-smooth surface with roughness less than 0.3 nm RMS. China's Beijing Aviation Precision Machinery Research Institute has also developed a similar FP machine tool CJY-500. An experiment of glass-ceramic polishing shows its roughness of 0.3 nm. [44]

1.3.6 The Non-contact Chemical Mechanical Polishing (CMP)

Glass is soluble in some solution, such as acidic solution. Such chemical properties can be used to improve the surface smoothness. Some corrosion pits in the surface will leave under pure chemical corrosion; therefore, on the basis of the existing CMP, a variety of new technologies have sprung up, and these methods are used in combination with fluid lubrication and polishing, making atomic class material removed to obtain high-precision surface generally. [45]

New technology is such as electrochemical mechanical polishing (ECMP), Abrasive-free chemical mechanical polishing (AF-CMP), and plasma-assisted chemical etching planarization, and so on. New technology is proposed for chip cleaning, such as supercritical fluid cleaning, spray cleaning, laser cleaning, and so on.

1. The electrochemical mechanical polishing

   This method is to improve the oxidation dissolution rate of Cu by the electrochemical action, using the mechanical polishing pole to remove the oxides of Cu generated by electrochemical reaction to achieve the global planarization of the wafer surface. Compared with CMP, it can also obtain a higher polishing efficiency in the ultra-low-pressure polishing conditions, because the electrochemical action is dominated in the ECMP. But this method also has its defects for ultra-low low-k/Cu structure surface.
2. The abrasive-free chemical mechanical polishing

   The liquid in AF-CMP has strong corrosion ability. The friction between the polishing pad and the processed material is used to remove the reaction film of chemical corrosion and to achieve the global planarization of the wafer surface. Because slurry does not contain any abrasive grain, chemical corrosion is dominate in the process, so surface scratches and other defects may be reduced significantly, but among the current main problems is such that the removal rate is too low, whereas flatness is not too high.

1.3.7 The Magnetic Field Effect Auxiliary Processing Technology

Shinmura *et al.* [46] developed the magnetic abrasive finishing (MAF), in which polishing grains consist of magnetic ferromagnetic material and alumina. In the magnetic field, magnetic polishing grains form a brush between the magnetic poles and the workpiece surface. The force the polishing brush exerts on the workpiece can be changed by controlling the magnetic field strength. This method can be used for processing various shapes, including flat, hollow, and cylindrical surfaces.

Umehara [47] developed the magnetic fluid polishing (MFP). MFP uses ordinary polishing grains as a magnetic flow, and the workpiece, and a non-magnetic plate are immersed in magnetic slurry. According to the principle of magnetic fluid dynamics, the ferromagnetic particles in the slurry are attracted and move to the strong magnetic zone in this magnetic field. The buoyancy produced pushes all of non-magnetic material (such as polishing grains, floating flat) to the low magnetic zone and contacted with the workpiece. In this way, the workpiece is polished by floating flat and polishing grains under the pole of the magnetic fluid. The polishing force of the workpiece can be controlled precisely and thus the damage-free and subnanometer scale smooth surface can be accomplished.

In recent years, MRT technology has been developed quickly. The physical and mechanical properties of this magnetic fluid, such as its liquid–solid state, hardness, and geometry, can be changed quickly by controlling the magnetic field, and the different removal functions can be obtained easily. Just like a flexible and wear-less grinding wheel, it can polish the complex shape workpiece and implement the ultra-smooth processing efficiently. The National University of Defense Technology (NUDT) used the MRF for SiC mirror processing, and the roughness can achieve better than 0.55 nm RMS.

1.3.8 The Particle Flowing Machining Technology

Mori *et al.* [48] proposed the EEM processing method, the basic point of which is that a small polyurethane ball with high-speed rotation is used to polish a workpiece under polishing liquid immersion. Between the ball and the workpiece surface is only a liquid film about 1 μm thick. The particles of about tens of nanometers in slurry are driven by polyurethane ball to collide with the surface at a high speed so that the elastic removal of atomic level from workpiece surface can be produced The EEM method can be used to process the soft X-ray mirrors, whose surface roughness is up to 0.1 nm RMS.

For the collision using particle flows on the surface, Baker [49] developed flow jet machining method for processing early. Fine polishing particles are mixed in water with the high-speed shooting at the workpiece; the thin materials can be removed off. Through precise control of the jet velocity and spray angle, the super-smooth polishing surface of a variety of materials can be obtained, with the surface roughness up to 0.1 nm RMS, too.

The other particle polishing methods of high precision and high efficiency are:

1. The ion beam milling (IBM) and IBF

   Ion beam processing is in vacuum. With argon (Ar), krypton (Kr), xenon (Xe), and other inert gas through the ion source, ion beam is made and then accelerated, focused, bombarded to the target to achieve a variety of processing. These physical effects can be used for different purposes. It can be divided into ion beam sputtering removal processing, ion beam sputtering coating processing, ion beam implantation processing, and ion beam lithography.

   In the ion beam sputtering removal processing, neutral ion flow is in collision on the surface, the atomic scale material is removed, high machining accuracy can be acquired, but the removal efficiency is very low. In the late 1980s, a Kaufman ion source was developed to produce low-energy and large current flow of ion flux so that high ion beam polishing removal rate has been reached.

   Ion beam sputtering removal processing can be divided into ion beam milling (IBM) for sub-surface damage layer removal to clean up the hydration and pollution layer. The processing of the IBF is carried out for the removal of high-precision surface form error in order to achieve a high surface accuracy.
2. The plasma-assisted polishing (PACE)

   Bollinger and Zarowin [50] proposed the PACE technology. The active plasma is generated by certain gases in the RF. Due to the activity of plasma and the surface chemical

Table 1.2 Several materials, their polishing gas and chemical reaction.

Material	Gas	Reaction equation
Quartz (SiO_2)	CF_4	$SiO_2 + CF_4 = SiF_4 + CO_2$
SiC	NF_3	$SiC + NF_3 = SiF_X + CF_Y$
Be	Cl_2	$Be + Cl_2 = BeCl_2$

reaction to generate volatile mixture gases, the surface material can be removed, so it is a chemical reaction to remove the surface material to achieve polishing. The material removal rate can be put under control by controlling the RF power, gas pressure, gas flow rate, and other factors. There are several materials with their polishing gas and chemical reaction shown in Table 1.2.

The collision of the ion beam on the surface to increase the material removal rate is similar to IBF principle. The PACE works in vacuum environment with 1–10 Torr. (1 Torr = 1.33322 × 102 Pa). The polishing head is located above the workpiece a few millimeters, perpendicular to the machined surface and controlled by a 5-axis CNC usually. The material removal rate can be controlled by RF power, gas pressure, gas flow rate, and other factors. The equipment can undergo the real-time monitoring of the removal of the surface for closed-loop control. The processing technology of Perkin-Elmer company has been machining for the aspheric surface of Φ0.5–1 m whose accuracy is to λ/50 RMS and whose roughness is to 0.5 nm RMS.

The principle of the Plasma Chemical Vaporization Machining (PCVM) is that it is operated in the atmospheric environment, with the gas-solid surface reaction to get atomic-scale planarization processing. This new method has both a high machining accuracy and a high processing efficiency. Fr example, plasma processing efficiency is up to several hundred microns/min, and the surface accuracy of PV reaches more than a dozen nanometers.

1.4 The Advanced Aspheric Optical Polishing Technology

1.4.1 The Classic Polishing for Aspheric Optical Parts

In classical polishing, the polishing tool and the workpiece surface have contact in relative motion. The convergence of the surface shape is a self-trimming process in plane or spherical workpiece polishing process. A polishing tool in general has a metal pad with the polishing film posted on the pad. The metal pad can be a choice from aluminum, copper, or cast iron. The polishing film can be a choice from polishing cloth, polyurethane, or bitumen. According to the hardness and characteristics of the polishing tool material, a polishing tool can make certain flexibility and a certain degree of deformation, but its deformation only can adapt to the slight shape change of the workpiece surface. Therefore, for polishing aspheric, polishing pads must be small enough or use a special shape of the polishing film.

Compared with the plane and spherical mirrors, processing and testing of aspheric are more difficult in that most of the asphere has only one symmetry axis, whereas the sphere has numerous axis of symmetry; as a result, aspheric surface processing is not like sphere by the same mold to lap each other. The aspheric has different radius of curvature at the different points, while the sphere's is the same at any point, so the aspheric surface shape is not easy to amend. The edge machined because of its deflection between two sides of aspheric mirror cannot be done by spherical centering edge milling machine tool. As the aspheric generally cannot use the Newton's ring optical model to test, the test method is more complex and time-consuming.

Traditional abrasive polishing and hand-processing methods for aspheric process are:

1. Using traditional abrasive polishing to get the closest sphere surface according to this aspheric surface.
2. According to the removed amount located of the mirror center or edge to design polishing film shape and its trench width.

   For example, the polishing film shape can be carved as some axisymmetrical spindle rods. If the removed amount of mirror center is more, the wide ends of spindle rods are located in the central place, whereas the narrow ends of spindle rods are located in the edge of the pad. If the edge needs to be removed more, the polishing film can be carved inversely: the narrow ends and tip of width film are in the central place, whereas wide and strong of width film is in the edge. In the polishing process, it must have many programs to measure, to replace the polishing mold, and to approach the desired shape gradually.
3. Using hand polishing to get the modification for the local high point.

   In traditional and hand-polishing methods, there is a lot of blindness and more human factors. Because a variety of process parameters easily can be changed by many uncontrolled factors, there are not only the high cost, low efficiency, labor intensive, but also machining accuracy that can not be guaranteed in this polishing process. It cannot meet the needs of a wide demand of aspheric optical components.

   Classical polishing technique has been developed more than 200 years, whose processing relies heavily on human experience, but the requirements of the equipment is low so that it is still widely used in China's optical factory so far, especially for lower accuracy of civilian small aspherical mirror processing. For a large mirror, the traditional method processing time is too long; for example, the 2.5 m Hooke telescope optical processing was carried out for 6 years presided over by Lucky of the United States; it took 14 years to process the Palomar 5 m telescope; the processing of 2.16 m telescope of China was done from October 1976 to 1983, 7 years in all, but the light concentration index concentrated in the 1.19″ only reached to 80%. [51] The classic processing of a primary mirror about 1 m of *F/2* to *F/3.5* took about 1–2 years. Therefore, the classical polishing technique of aspheric optical parts is called the first generation of optical aspheric surface processing technology.

1.4.2 The Modern CNC Polishing Method of Aspheric Optical Parts

1. The concepts of non-deterministic and deterministic polishing techniques

   The traditional polishing is a non-deterministic technology essentially. It is difficult to use an accurate mathematical model to describe the material removal, only by qualitative guesses or order of magnitude estimate. For the plane and spherical polishing, with the curvature of the spherical (the plane can be regarded as an infinitely large diameter spherical surface) being the same everywhere, the polishing model surface shape can be easily consistent with a workpiece everywhere; after a long processing, the surface shape will be convergent.

Mechanical cutting process is a kind of method to use a single-edged blade or cutting tool to remove material, so this removal can be determined. For the traditional optical process with the dissociative abrasive polishing to achieve the end of result, its convergence is a random probability event; in this sense, the removal amount and processing effects on the each point and each moment are non-determined. In general, for the small parts, the size of the polishing tool should be large enough to ensure that the workpiece does not leak edges, rendering the edge declining or uprising, which is the edge effect. A large high-precision flat or spherical mirror uses the greater polishing machine (e.g., 4 m ring processing machine for 1 m diameter plane mirror processing), so its difficulty is not less than the processing of the aspheric surface.

The deterministic technology, a new technology with the aspheric processing relative to the traditional one, is that its amount of polishing is to determine compared with non-deterministic. The aspheric radius everywhere is different, so the polishing tool fails to be as consistent as in classical methods. In the deterministic polishing technology of the aspheric processing, the accurate quantification of the material removal can be controlled by computer; hence, all or part of the manual process can be replaced, machining efficiency and surface quality of optical parts can be improved, and scrap rates can be reduced.

The CCOS technology is the core content to the deterministic polishing. Modern polishing of aspheric is built on the basis of CCOS.

2. The CCOS technology

The CCOS technology uses a small pad with a specific path and speed of movement controlled by computer. In this way, all of its polishing dwell time within each region, the amount of material removal and surface accuracy can be controlled accurately. Different from the traditional CNC machining, the CCOS technology is built on the basis of the three-dimensional space control of the traditional (four-axis or five-axis CNC machine tools) NC, and is added with the time dimension control. The time dimension control is employed for the removal amount to convert to dwell time or processing speed; in this respect, we call it as the four-dimensional (4D) CNC.

The CCOS technology is developed on the basis of the traditional polishing, and its lapping or polishing pad still uses a rigid one, which is posted with polyurethane, asphalt, polishing cloth, and other film. If the pad is too small, it will be more likely to reduce its processing efficiency and increase the high and medium frequency error of surface. An increase in the tool diameter is limited by the adaptation ability of the changed aspheric curvature. The method to solve the above problem is to alternate small and large diameter tools: a large-diameter tool is to eliminate the medium and high frequency error, and a small-diameter tool is to improve the low and the local shape error, sometimes assisting in the artificial to achieve the final accuracy.

The polishing mold has certain elasticity or flexibility, but it is not controllable by computer. The polishing film is changed due to wear, in order to maintain long-term stability of the removal function, which is also difficult. In addition, when the tool moves into the edge, the polishing conditions change, and the edge effect cannot be avoided; as a result, some special steps should be taken. We can classify this technology as the second-generation processing technology for aspheric. This generation technology is a mature technology now, and it has been gradually replacing the first generation technology to become the mainstream technology of the processing of aspherics in China.

1.4.3 The Controllable Compliant Tool (CTT) Manufacturing Technology for Aspheric Optical Components

1.4.3.1 The Classification of the CCT

The words of "compliant tool" have been used in some cases. [52,53] A number of new technologies have been emerging in recent years, and we call such technology as the controllable compliant tools (CCT) technology: the word "controllable" is added in that it better reflects the nature and characteristics of the latest modern polishing techniques. We propose that the concept of CCT technology can be used as a new classification method, and that the CCT polishing technology can be called the third-generation processing technology for aspherics in order to guide new research means and goals.

The technical features of CCT are that lapping and polishing tools are "soft" and the compliant can be controlled by computer so that the ability adapted to the aspheric curvature change is reinforced with the long-term stability of removal function to be maintained, and that the tool "flexibility" can be changed easily to adapt the different needs of lapping and polishing process.

The methods of CCT realization are of two categories: the lapping and polishing pad with elastic deformation and the lapping and polishing film flexibility with changes under the computer controlling.

Such a stressed-lap polishing technique is based on the controllability of the elasticity theory. The elastic deformation of the pad is continuously caused in the process by a group of computer-controlled motors as executors to achieve the polishing tool control.

The MRF, IBF, and jet polishing techniques can control the processing through the computer-controlled magnetic field, electric field, and flow field; in a broad sense, the polishing film flexibility in this type of processing technology is changed to achieve processing control. More complex control of polishing film flexibility of CCT is added on the aspheric four-dimensional numerical control technology, and it forms the five-dimensional or multidimensional control, so that the control margin of the removal function model is increased. This book will present and analyze MRF, IBF, and jet polishing technology in detail. From the perspective of the aspheric processing, these three kinds of technology belong to the sub-aperture processing technology. From the viewpoint of the processing principle, they are characteristic of the CCT technology based on the multi-energy fields.

1. The MRF technology

   The center for optical manufacturing (COM) of the University of Rochester has developed a new principle of controlled magnetic fluid to remove the optical surface material, and has made a long period of basic research for magnetic theories and methods of rheological polishing techniques since the 1990s.

   The MR fluid is mixed with magnetic particles, base fluid, surfactant-based fluid, and polishing grain. Under the action of controllable magnetic field, the chain structure of the magnetic flux liquid changes and its viscosity can be controllable. As the MRF's "polishing head" is not dull or do not wear, the liquid flow can adapt to the complex shaped surface, and there is high processing efficiency. The processing of small-diameter optical components is a great success. And developed by QED company, the Q22–750 MRF machine tools will also have important applications in large-diameter optical parts processing. The viscosity of magnetic fluid and polishing film flexibility can be controlled by computer. Their removal function is stable in long-term processing, so it is a suitable method for efficient and precise modification.

Jet polishing (JP) is a polished molding technology for processing the complex shaped surface of optical components. The MR fluid jet polishing (MJP) technology is a new one combined with the JP and MRF for optical complex surface polishing. Through the computer's real-time control, in principle, it can polish any shaped surface and size of the optical components, and in that there may be a fundamental solution to the edge effect and subsurface damage problems.

2. The IBF technology

The IBF is used for workpiece form error modification with high-energy ion bombardment in a vacuum. The accuracy can reach the atomic level. For example, NUDT developed the IBF machine, and the IBF machine can be used for high-precision flat, spherical and aspheric mirror machining, with the surface error achieving $\lambda/600$ RMS.

Since the ion beam intensity in the cross section is viewed as a Gaussian distribution, there is no gravity pressure in the vacuum chamber work, no deformation by processing pressure in mechanical polishing, or no headache edge effect, and it is much better for thin and light mirror processing especially. The technology is used successfully in the Keck telescope of 10 m primary mirror processing. For the primary mirror by the multilateral type of splicing sub-mirror, the IBF method is used for the second upgrade of the aspheric accuracy mainly.

In addition, the IBF can remove micro-defects, keeping trace of prophase processing, surface residues of chemical pollution, and stress, and also can improve the high-energy laser mirror coating firmness and mirror anti-damage threshold. For example, the Hughes Research Laboratory used low energy IBF of 7 keV and 300 $\mu A/cm^2$ for sapphire and ruby laser material polishing, which could improve their anti-laser damage threshold. The anti-destructive testing is of the laser power density 7–9 GW/cm^2. Compared with the ordinary polishing, the workpiece anti-laser damage threshold increases 26 times after IBF processing. The International representative IBF equipments are the IBF machine of the 2 m of Kodak, 2.5 m of the French REOSC optical laboratory, the products of German the NTGL company, and so on.

Table 1.3 is a comparison of advantages and disadvantages of the methods for a variety of deterministic processing features.

1.4.3.2 The Concept of Flexibility in CCT

1. The concept of flexibility and influence of traditional polishing tool rigidity for lapping and polishing processing

The concept of flexibility of a polishing tool is the deformation of the tool in the unit force applied, and its inverse is stiffness. The stiffness and flexibility matrix are such as Equations 1.3 and 1.4

Table 1.3 Different polishing methods.

Methods	Small tool, CCOS	SLP	MRF	IBF
Characteristics	Small size traditional polishing tool Depending on the time, pressure, relative velocity, deterministic polishing.	Large-size tools; tool and workpiece surface shape is adapting, for high-efficient, automated processing of large area.	Magnetic fluid in the magnetic field can change the flexibility to achieve deterministic polishing; for high-efficient and high-precision, automated modification.	The process is use of ion beam bombardment and the sputtering, atomic class removed for high-precision and ultra-high precision modification.
Advantages	There are various diameter tools can be replaced, low investment, for large gradient error can be smoothed by replaced bigger tools	The high efficiency for a large mirror, and to reduce small-scale processing errors, reduce dependence on artificial.	Removal function is stable and controllable, high efficiency, material removal by shear, can be achieved sub-surface damage-free processing.	The removal function is stable and controllable; no mechanical contact between the tool and optical parts, sub-surface damage-free and no edge effects.
Disadvantages	Removal function can not be a long time stability; low efficiency; There are sub-surface damage layer; Easy to produce small-scale error and edge effects.	Cannot well control precision modification for small local-shaped, no capacity for thin mirror processing, there are edge effects, high investment. Certain restrictions on the workpiece.	There are some limits for size and curvature of parts, processing spots is small, limited the ability of smoothing for large gradients and small-scale error, high investment.	Work in vacuum, processed optical materials are limited, material removal efficiency is low, high investment.

$$[K] = [S]/[\mathrm{F}] \tag{1.3}$$

$$[\Delta] = 1/[K] \tag{1.4}$$

where, $[K]$, $[S]$, $[F]$, and $[\Delta]$ are the matrix of tool stiffness, deformation, stress, and flexibility respectively.

We can use Figure 1.2 to show the distribution of rigidity and flexibility of the polishing mold.

The polishing tools can consist of the polishing pad and the film, and also the so-called polishing mold together. In order to facilitate the description, we divide polishing mold mass up in one line as a one-dimensional distribution, and define the centralized mass of the polishing mold as (m_1, m_2,…m_n), and (k_1, k_2,…k_n) its vertical stiffness. Using k_{12} to present the lateral

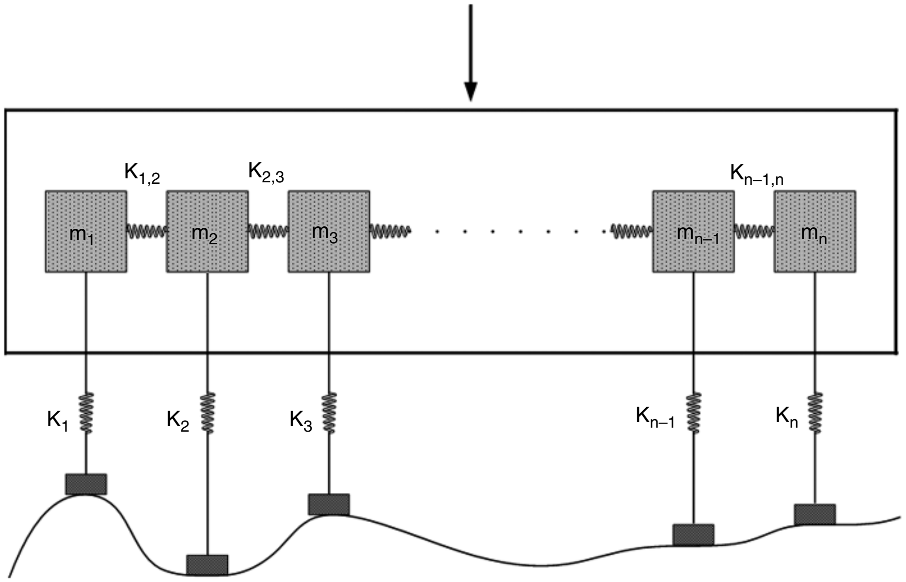

Figure 1.2 The relationship of rigidity and flexibility distribution of polishing mold.

joint stiffness between m_1 and m_2, and ($k_{1,2}$, $k_{2,3}$,…$k_{n-1,n}$) is defined as the lateral joint stiffness between the one-dimensional distribution of mass ($m_{1,2}$, $m_{2,3}$,…$m_{n-1,n}$). The polishing mold is divided into $n'l$ units of two-dimensional, the $K_{n'l}$ and $D_{n'l}$ are matrix of vertical stiffness and vertical flexibility respectively, and the $K_{n'l}$ and $D_{n'l}$ are matrix of lateral joint stiffness and lateral joint flexibility respectively. If the vertical flexibility $D_{n'l}$ is the greater or the vertical stiffness $[K_{n'l}]$ is the smaller, the polishing mold is more able to adapt to an aspheric surface shape; the robustness of positioning accuracy between polishing mold and the workpiece surface is stronger, which means the positioning accuracy is not too rigorous or intense.

Although it can adapt to the aspheric surface well, it can no longer meet the principle of priority to remove at the higher point automatically, for smoothing of medium and high frequency error is not good. If the lateral joint flexibility $[D_{n'l}]$ is the greater or the lateral joint stiffness $[K_{n'l}]$ is the smaller, the ability is the stronger to inhibition of medium and high frequency errors.

The processing affect of the lapping and polishing pad rigidity has been studied by many people, using the different metals with different modulus of elasticity to change the flexibility usually. For example, Kang Nianhui [54] of the NUDT did simulation and experiments of lapping effects with different hardness of the copper, cast aluminum, and the cast iron. The hardness of copper, aluminum, and cast iron plate is for 370, 700 and 2000 MPa respectively. The basic technical parameters of the simulation and test by CCOS are Ø25 mm of the lapping pad, W14 of diamond grain, 5 wt.% of slurry concentration, 36.9 kPa of pressure, 10 mm of eccentricity, rotation and revolution speed ratio of −2, rotation speed of 90 rpm on a flat workpiece machining.

The simulation results show that when the rigidity of the lapping pad ranged from 370 to 2000 MPa, the normalized material removal rate increased about 70%. He used these three

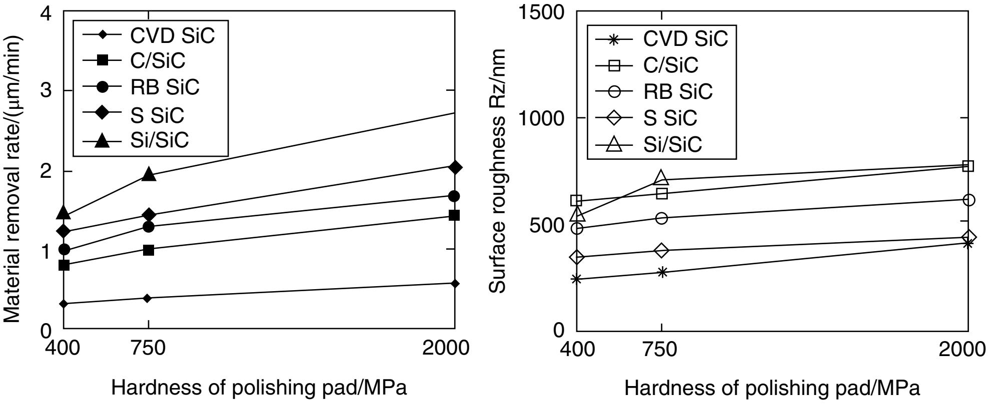

Figure 1.3 The effects of lapping pad rigidity on lapping efficiency and surface roughness of typical silicon carbide optical materials.

lapping pads to process five kinds of silicon carbide material plane workpieces. The effects of lapping pad rigidity on the material removal rate and surface roughness are shown in Figure 1.3. When the lapping pad rigidity is increased, it leads to the increase in single grain load and lapping pressure; therefore, the material removal rate and surface roughness have a corresponding growth.

The flexibility of the polishing film is commonly dependent on material itself, such as polyurethane, asphalt, canvas, and so on. The asphalt has good flexibility and mobility, so it is the first choice for the high-precision and ultra-smooth surface processing currently. However, in the polishing processing, the polishing film wear can cause instability in removal function, thereby affecting the convergence rate of the polishing surface error.

Our experiment has found the effect between polished film material and removal function stability. As shown in Figure 3.6, it can be seen that the removal function stability deteriorates one by one, with such three materials as polyurethane, resistance cloth, and asphalt, respectively.

The above simulation and experiment are in the plane processing conditions. The intensity of pressure of plane processing is distributed uniformly. In the aspheric processing, the polishing pad with the workpiece surface is not consistent; its intensity of pressure distribution will vary with the curvature change. As the intensity of pressure at the place of big curvature is bigger, the local material removal will increase, thereby undermining the aspheric surface shape. In the processing of aspheric, there is limited flexibility of polishing film, simultaneously with the local wear of polishing film intensified, so that its lifespan declines and the removal function deteriorates. Furthermore, the flexibility of polishing mold cannot be controlled by computer, so the first- and second-generation technology has significant limitations.

The task of CCT technology is designated for aspheric or more complex free-form surface process. Compared to the rigid pad, the basic properties of the CCT flexible polishing tool can be expressed as follows: its ability to adapt the aspheric surface is good, with the required relative position accuracy between the tool and the workpiece being robust. We look forward to a large vertical flexibility of polishing mold and high robustness of positioning accuracy, and that it has a strong ability to adapt to the machined surface. We also hope that there is large lateral joint flexibility of polishing mold so that it can maintain the principle of high priority to remove higher point in the processing zones as a rigid plate in order to obtain good suppression capacity of high and medial frequency error, but these two requirements are often a contradiction.

2. The flexibility of SLP

The stressed-lap polishing technology is based on the elastic deformation, which uses an aluminum polishing pad, and its deformation is driven by sovo-motor to adapt the shape of the aspheric. The active deformation of the stressed-lap can be controlled by computer rather than the passive formation. Through the elastic deformation of stressed lap, it can match and coincide to the aspheric everywhere; therefore, it is can be a large vertical flexibility $[\Delta_{n\times l}]$.

For additional constraints on aluminum bending strength, the lateral joint flexibility $[\Delta_{n,l}]$ of the polishing mold is small, the polishing area still observes the principle of the priority removal of higher point, and it is capable of inhibiting high and midial frequency errors. So these two contradictory requirements can be well unified.

As the diameter of the stressed lap is one-third of the processing mirror, its biggest advantage is that it has high efficiency for large aspheric processing and the dampening effect for high and midal frequency error. But if the size of stressed lap is too big, it cannot do precision figuring for a small aperture workpiece and small local area. And its material removal mechanism is still similar to the traditional polishing on the basis of the brittle fracture theory. Some problems still exist, such as the sub-surface damage, the long-term stability of removal function caused by the tool wear, edge effects, and so on. So generally the stressed-lap polishing technology is used for large mirror error converges to a certain extent firstly, then replaces the polishing pad by using the small diameter, and passes more iterative to get the processing target finally.

3. The flexibility of IBF

IBF is a sub-aperture processing method using a small-diameter tool. The polishing beam consists of many particles of ion and forms a stream as a united polishing mold. In comparison with the rigid polishing mold, its vertical flexibility $[\Delta_{n\times l}]$ is great, its ability to adapt the shape of the aspheric is very good, and its position robustness is very strong. But since the lateral joint flexibility $[\Delta_{n,l}]$ is also great, there is a little contributing to the improvement of a high-frequency error.

Take the IBF machine tool developed by our lab for example. When ion energy is about 500 eV and 10 mA/cm^2, under the simulation of argon ion beam processing conditions, the impulse pressure is only available about 0.2 mN/cm^2 on the material surface. Processing positive pressure of the workpiece almost is zero, and it will not introduce surface mechanical damage, suitable for processing a lightweight and thin mirror. The Ion beam works in vacuum, and the resistance is so small that its kinetic energy is almost without wasting to bomb to the target. Thus, the robustness of the polishing mold positioning is strong and its allowance is up to several millimeters, so its vertical flexibility $[\Delta_{n\times l}]$ is almost infinite in the macro effect. Another advantage is that the ion beam can focus on a small aperture and can be used to do accurate figuring for a workpiece of a small area.

The macro effect of IBF is the sum of numerous ions in the wide-focused beam in that the lateral joint stiffness between each ion is almost zero, which explains that the removal priority of higher point does not exist so that the IBF does not change the roughness basically. When the incident angle of the beam decreases, the collision probability of the higher point at the surface also increases, with the sputtering effect increasing and the roughness reducing lightly. Compared with the atomic weight of Ar, Kr atomic weight is 83.80, and the Xe atomic weight is 131.2, which is three and four times larger than Ar respectively. Using Kr or Xe ion beam polishing and small angle of incidence, it can improve the roughness situation lightly.

4. The flexibility of MRF

Either vertical stiffness $[K_{n\times l}]$ or lateral joint stiffness $[K_{n,l}]$ of MRF is not large, and it is located between the traditional hard pad and IBF. An MRF rigid wheel does not contact the workpiece surface directly, and the gap between them is about 1 mm. The magnetized ribbon of MR fluid is pressed down about 0.3 mm thickness by workpiece. Between the polishing wheel and the workpiece surface, the ribbon consists of the solid-state core layer of the MR fluid, MR shear flowing layer, and the abrasive grain layer. In the polishing region, due to the MR fluid flowing through the wedge, the hydrodynamic pressure will exist, with the thickness of shear flowing layer about 100–150 μm. Since MR film consists of a flexible Bingham fluid and the nucleation zone of the MR, both its vertical flexibility $[\Delta_{n\times l}]$ and lateral joint flexibility $[\Delta_{n,l}]$ are great. The experiments show that the MR flow fluid pressure in the wedge is about 200 kPa, whereas the positive pressure of a single abrasive grain put on the surface is only 10^{-7} N; the value is far less than a single abrasive's in classical polishing, which is about 0.007–0.65 N. It is much smaller than the critical value of the fracture, so only plastic removal exists in MRF processing.

MR fluid is flexible, and its positioning accuracy has a certain degree of robustness compared to the rigid tool (such as turning, milling, grinding).

Shi Feng of the NUDT did some theoretical simulation and experimental tests. [55] The quantitative relationship between the positioning accuracy of the MRF wheel and processing residuals is found. For example, if it is defined that the residual error rate is the ratio between the RMS value of before and after process, the residual error rate caused by the tangential positioning error of 0.1 mm is about 1.484%, the residual error rate caused by angular positioning errors of 10 is about 0.719%, and the residual error rate caused by the sensitive direction positioning error of 10 μm is about 7.446%. Although the vertical positioning error is identical to the sensitive direction error, it has a certain margin of positioning accuracy requirements compared to the rigid processing tool.

5. The flexibility of jet polishing processing

According to the experimental results, [56] the optimal spray distance range is about 8–15 mm with the nozzle diameter being 2 mm of JP. When the spray distance is of 12 mm, the material removal is maximal; whether the spray distance increases or decreases, the amount of material removal are reduced gradually. And if the distance deviation is about 0.2 mm, the change of material removal rate is very small, which is a strong robustness. The robustness of the sensitive direction shows that there is a greater flexibility in the equivalent polishing mold.

1.5 The CCT Based on Elasticity Theory

With the method based on the principle of stress and elastic deformation to form aspheric under appropriate controllable force, the circular sheet surface has to be close enough to quadric, off-axis quadric or even higher order surface by elastic deformation. The desired surface anywhere also can be generated by the required local deformation under the controllable force. There are two technical approaches to achieve this CCT process.

1.5.1 The Controlled Elastic Deformation Pad Polishing—Stressed-Lap Polishing (SLP) [57–60]

In the early 1990s, the rigid elastic deformation, based on mathematics and mechanics, was used in the large size abrasive pad control by the Steward Observatory Mirror Lab of University of Arizona. This polishing tool can be real-time adapted to an aspheric surface dynamically and continuously in the radial translation and rotation movement of polishing process, the diameter of the polishing tool is one-third of the processed primary mirror. The method was used for the sub-mirror of 10 m diameter Keck telescope successfully.

Using SLP in Observatory Mirror Laboratory has processed seven large mirrors in diameter from 1.2 to 3.5 m initially, including 1.2 m and F/1.9 of SAO primary mirror, 1.8 m and F/1.0 of Lennon primary mirror, the 3.5 m and F/1.75 of ARC primary mirror, 3.5 m and F/1.75 of WIYN primary mirror, 3.5 m and F/1.5 primary mirror in Philips Laboratory, their accuracy reaching 20 nm. Later, the 6.5 m and F/1.25 large aspheric mirror and the 8.4 m and F/1.25 LBT large mirror have been processed successfully.

The 1.2 m lap has been used to polish 3.5 m mirrors, and will be the primary tool to polish all the 6.5 and 8.4 m primary mirrors. The 300 mm and 600 m tools will be used in secondary mirror polishing program.

The SLP can solve the efficiency problem in a large mirror processing, and can get good inhibition for the high frequency error. For example, the SLP technology was used to process a 8.3 m aspheric primary mirror, whose surface accuracy was up $\lambda/6$ PV ($\lambda = 0.6328$ μm) by the end of 1996 at the Mirror Lab laboratory of optical center of the University of Arizona. Another primary mirror of 6.5 m and F/1.25 of the UOA large mirror Laboratory used SLP processing, and the surface error was 23 nm RMS.

1.5.2 The Controlled Mirror Body Elastic Deformation Polishing by Active Support

Another example is a method based on controllable mirror body deformation by active support technology.

The elastic deformation of the mirror itself is controlled by active support system in aspheric mirror process, so it can be similar to the spherical process. After this processing, the stress of the mirror is released and then aspheric surface is produced. Germany and France have developed this dynamic support technology for optical aspheric manufacturing; some large thin primary mirrors and a flexible dynamic active optical primary mirrors were processed successfully with this technology. For example, the deformation theory based on the active support was used for an 8.4 m thin soft primary mirror of the VLT (Very Large Telescope), whose ratio of its thickness and diameter is 1 to 47 by REOSC of France. As an assisted polishing technology, the required face accuracy is adjusted and satisfied by a set of active actuators eventually.

The CCT based on elastic deformation technology helps to simplify the complex process of manufacturing large, steep aspheric mirrors to that of manufacturing approximately spherical mirrors. The Institute of Optoelectronic Technology of Chinese Academy of Sciences in Chengdu City, which has developed SLP machine tool and its technology with 12 actuators, has carried out SLP and active support processing technology, and has applied to the large and deep primary mirror processing of 1.3 and 1.8 m successfully.

1.5.3 Bonnet Polishing with Precession Process [61,62]

Bonnet polishing technology was developed by London optical laboratory of the UK in the 1990s, and it is a flexible polishing tool to replace the traditional polishing pad.

In the bonnet polishing technology, the bonnet as a polishing tool uses a pre-shaped spherical and flexible thin membrane mold so that the internal gas pressure of the bonnet can be controlled. The bonnet surface covers the polishing film with a special polishing cloth (proprietary cloth), together with the appropriate polishing slurry to lapping and polishing the optical surface. It also can use flexible material with a bonded fix abrasive to replace the polishing cloth, when water is available to substitute for polishing liquid.

The polishing pressure (tool hardness) and the contact area (polishing spot size) can be changed independently by varying the air pressure and the axial position of the tool with respect to which part is in use. The bonnet internal pressure is distributed evenly and it will do not change with the workpiece surface shape, so the bonnet polishing can adapt to the aspheric surface.

The rotation axis of polishing tool is parallel with the local surface normal of workpiece in traditional polishing process. It is different in that the rotation-axis of the bonnet is inclined to the surface's local normal with an angle of 10–25° typically. The tool polishes on the side of the bulged membrane, and the zero-point of surface-speed is shifted outside the contact spot. So it can avoid a "W"-shaped removal function caused by zero speed generated at the center profile in the traditional polishing methods. It is good for the convolution error control.

On the other hand, in the polishing process, the bonnet cannot only rotate at any position, but also can add swings by 7-axis CNC. Around the local normal axis with the center of polishing spot, the tool-axis swings are similar to gyro precession movement, which retains a precession angle. It is called the "precession of the process."

The advantage of the bonnet polishing technique is that the polishing tool flexibility can better adapt to the aspheric surface, and with the high polishing line speed the processing efficiency can be increased. Although the precession can get a better line of chaos and Gaussian removal function, it reduces the dynamic response time of the figuring and processing efficiency.

1.6 The Key Basic Theory of CCT Technology Based on the Multi-Energy Field

A new challenge of the CCT for our research is how to summarize the common law from single specific processing method and render it a synthesis theoretical system for large optical aspheric manufacturing. This theory will make our research more general and extensible. It also can give new technology a more sustainable development and strengthening capabilities to application. The theoretical system of the CCT can be divided into the following five aspects.

1.6.1 The Material Removal Mechanism and Mathematical Model

As different physical and chemical principles are used in different types of CCT, the different material removal mechanisms also cause the different removal function, which determines the basic mathematical model of the CCT. Undoubtedly, how to reveal the different mechanisms under different mechanism conditions to develop manufacturing means is the core of the basic theory of CCT.

1.6.1.1 The Material Removal Mechanism and Mathematical Model of IBF

The ion beam polishing uses a low-energy and large-current beam mode. The low energy ion sputtering phenomenon is one kind of elastic collision process, and it is called impact sputtering. It can be divided into three categories: single collision impact sputtering, the linear cascading collision impact sputtering, and non-linear cascading collision impact sputtering. [63,64]

The single collision impact sputtering occurs in the collision process between the surface atoms and lower energy ion mainly, for the impulse energy and direction are insufficient to cause surface atom to be sputtered out directly.

When the ion energy is greater than nuclear stopping energy of the surface atoms, the ion will enter the material to a certain shallow depth, and the energy is viewed as a Gauss scattering distribution. This energy along the ion path making the atoms with the initial recoil energy and colliding with other stationary atoms further causes a new series of cascading movement. When the cascading collision energy is greater than the binding energy of the surface atoms, these atoms will be sputtered out from the material body. It is the linear cascading collision impact sputtering.

In other certain areas, collision of most moving atoms with one another is non-linear collision cascade; it exacerbates the vibration of these atoms, and its energy decays into the form of heat.

This shows that the mechanism of IBF is surface atomic bomb sputtering to remove mainly and relocate surface atoms by the thermoplastic flow secondly. It is to be described in detail in Chapter 4.

1.6.1.2 The Material Removal Mechanism and Mathematical Model of MRF

The removal mechanism of MRF is based on Bingham non-Newtonian fluid dynamics and the material removal theoretical model of abrasive double-blade radius. It is to be described in detail in Chapter 5. The MR fluid nucleation theory and experiments show that the MRF removal mechanism is one in which the material brittle fracture can be avoided and plastic shear can be achieved completely. Furthermore, the MRF process has more margins in the plastic zone, which means that it is easy to control and get high accuracy and efficiency of processing.

The MRF can eliminate the subsurface damage by traditional polishing, and effectively obtain near-zero sub-surface damage of ultra-smooth surface. But there are plastic scratches in a single direction on surface. For example, the surface roughness on the specimen is the 1.028 nm RMS and 0.810 nm Ra by traditional polishing, and it is upgraded to the 0.622 nm RMS and 0.495 nm Ra after the MRF finishing in our experiment. [55] Some dislocation and migration of lattice or the molecular will turn up in the plastic removal processing. Also, there remain certain residual processing stresses. Elastic removal is often accompanied by chemical phenomena. If proper MRF parameters and special MRF fluid are selected rightly and the material mechanical removal is very small, the processing can enter the elastic removal area. In our experiment, when processing is of lower efficiency, and the decreased rate of roughness reaches about 0.2 nm/h, the roughness of 0.812 nm Rq and 1.020 nm RMS before processing have been reduced to final results of 0.216 nm Rq and 0.160 nm Ra, bringing about the disappearance of the plastic scratches.

1.6.1.3 The Material Removal Mechanism and Mathematical Model of JP

Abrasive water jet polishing is a non-contact sub-aperture processing technology that uses low-pressure continuous liquid–solid two-phase fluid to jet onto a non-submerged workpiece surface. Based on the flow characteristics, it can be divided into three regions: the free jet region, the impact area, and the wall jet region, as is will be shown in Chapter 5. In the free jet region, the impact of the wall is so small that its characteristics are the same as free flow. The flow direction rapidly changes in the impact area region, and there is high pressure gradient, with the axial direction of flow changing to radial direction rapidly. So, the elastic and plastic deformation of the wall occurs, resulting in the further occurrence of the plastic and brittleness material removal in the wall jet region.

The abrasive water jet polishing process is a complex material removal process, which includes the role of abrasive particle collisions and micro-shear to workpiece material. Brittle removal is generated by the larger impact energy, and water jet cutting is such a case in point. Generally, elastic deformation and removal result from the low-speed collision, usually accompanied by the surface chemical reaction; in this case, the micro salient points of materials on the surface are changed by chemical reaction performance, mechanical collision of grains, and micro-shear, which play the role in removing. Jet EEM technology is a typical representative one that generates both the very small material removal and tiny elastic deformation without producing damage and residual stress for the ultra-smooth processing.

There is a critical depth of cut of the brittle issue based on the theory of fracture mechanics. The energy of a single impacting grain can be converted into a depth of cut. If the penetration depth of the material by the grain is above the critical depth, brittle removal arises; otherwise the plastic removal will be in place.

1.6.2 The Multi-Parameter Control Strategy

The flexibility of the traditional polishing tool can be controlled by composition and performance of abrasive media, but it is difficult to change in the process. The CCT technology can control the parameters of stress field, electric field, magnetic field, and flow field by computer to change the flexibility of the polishing tool.

Therefore, some of the passive and active control parameters must be selected from the redundant parameters, for this multi-parameter conditions can help get optimization of control strategy for long-term stability of the removal function or for different process goals. Compared with traditional CNC polishing processing, the control margin of the CCT is increased. How is the cross-coupling influence with various parameters? And what about controllability, selection, and optimization, which are control targets of these parameters? All of them bring new research opportunities, which is the key technology for optical polishing processing from uncertainty to a fully deterministic processing.

For example, with the very complex influencing factors of the MRF process, it can be divided into three categories:

1. The polished material factors of workpiece

   Its composition, crystalline structure, mechanical properties (hardness, elastic modulus, fracture strength, and so on), chemical stability, materials relative binding strength, and other properties are very different.
2. The MR fluid factors

   The type and content of carbonyl iron powder, abrasive, and its stability are different. So are the performance indicators such as shear yield strength, the viscosity of zero magnetic field, and pH value of MR fluid.
3. The factors of process parameters

   The process parameters are such as polishing wheel speed, compress depth, flow, and magnetic field, which will exert a great impact on the size and distribution of the field of magnetic, pressure, and shear stress in the MRF finishing region, and then finally on the removal function of MRF. Furthermore, various factors can be mutual influencing and coupling. For example, the MR fluid will influence the chemical stability of the mechanical properties of the workpiece, and the magnetic field will affect the shear yield strength and apparent viscosity of the MR fluid.

We must, through theoretical analysis and experimental data, optimize the selected parameters and realize process goals by the multi-parameter control strategy.

There are many process parameters of materials and MR fluid. We can adopt the orthogonal experimental methods to do trial and classification research. The first category of experiments is fixed workpiece material and the MR fluid parameters, focusing on the process parameters (speed, flow, magnetic field compress depth, and so on) to optimize the influence factors of the removal function. The second class of experiments is fixed processing parameter, focusing on the workpiece materials and MR fluid to optimize the factors too. Based on the multi-parameter model of removal function, the performance optimization is to ensure the performance of removal function (the stability, removal efficiency, shape, and surface quality); for example, its long-term stability deviation must be less than 3–5% during the 12 days it runs.

On the other hand, the art goals of MRF process can be selected through changing the parameters by computer control in the process; for example, a rough removal function is used to increase the cutting margin to quickly remove damage layer in lapping process firstly, and then a precision removal function is used for final figuring and polishing process without replacing the tools. Among a variety of material being processed, super-hard materials of SiC, soft and brittle and easy deliquescence materials of KDP, anisotropic materials of magnesium fluoride, and calcium fluoride must be of different process parameters and control strategies.

Through the multi-parameter control strategy, we can get the series of removal function of the MRF and IBF respectively as shown in Figures 1.4 and 1.5. [55,64] Firstly, the subnanometer scale resolution of material removal can be achieved to guarantee nanometer accuracy machining. Secondly, the different removal functions can be selected by computer for

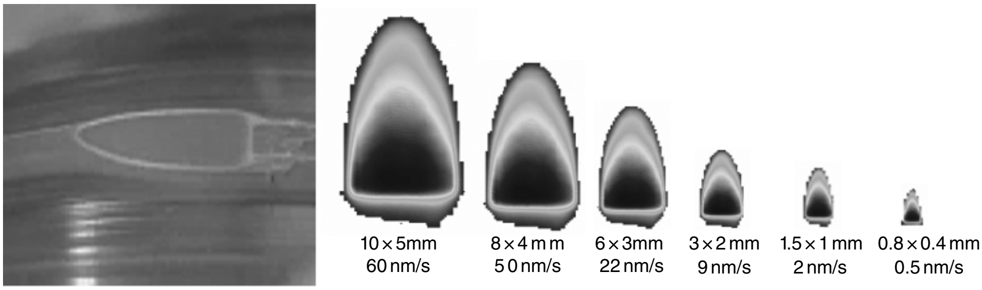

Figure 1.4 The series of removal function of the MRF.

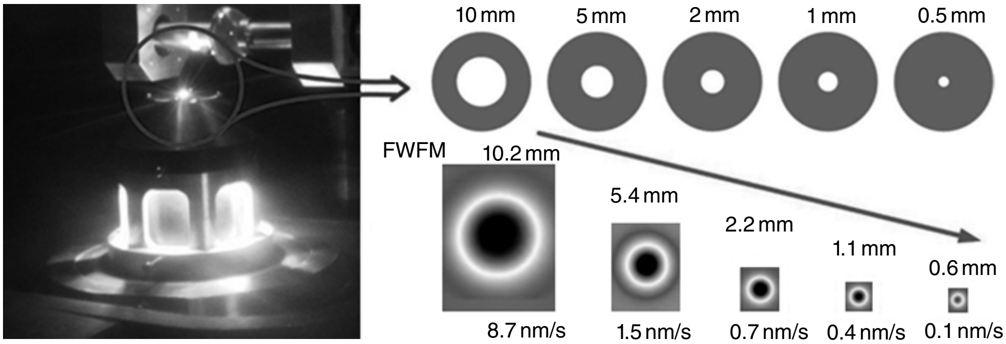

Figure 1.5 The series of removal function of the IBF.

different art goals expediently. Finally, the removal function should be stable in the whole processing.

1.6.3 4D CNC Technology

General CNC is used to control the position relationship of three-dimensional space between the tool and the workpiece for the purpose of maintaining a constant cutting speed. The 4D CNC technology is a three-dimensional space position control and an added dwell time control of each processing point, which is a time dimension control. The basic idea is that the three-dimensional surface error distribution of the workpiece surface is to transform the dwell time distribution, and then convert to velocity and acceleration distribution of machine tools. 4D CNC will be combined into dynamic characteristics of machine tool to obtain optimized control results. Since it is different from the low-speed mechanical CCOS polishing method, CCT can achieve high-speed polishing, high efficiency, high precision, and fully automated processing, and it also brings about new research projects.

Because the amount of materiel removal is equal to the convolution of removal function and dwell time, the dwell time can be a solution of deconvolution. The 4D CNC technology has high requirements for higher accuracy and dynamic performance of the machine tool. The key point of the 4D CNC software is precision control for the dwell time and the balance of the realization ability between process path and dwell time. The kernel software is designed for/from the accelerate iterative algorithm of the dwell time distribution, the dwell time extension of the edge and the optimized smoothing, the approximation of planarization of low steepness aspheric, non-linear compensation algorithm of high steepness aspheric, magnanimity data efficient algorithms of large diameter workpiece, and so on. For the realization of optical ultra-precision machining automation, CAM/CNC process software and equipment supporting the software must also be developed, including the path planning, NC code generation, forecast and prediction of the processing results and others for complex optical surface shape digital processing. It will be described in great detail in Chapter 2.

For the lack of machine dynamic performance, the optimal processing parameters and the machining path planning method can be used.

When Zhou Lin [64] established the linear equations (CEH) model and used truncated singular value decomposition (TSVD) algorithm to solve the dwell time, he discovered that processing time (or material removal amount) and residuals RMS value after processing related to the truncation parameter *K*. TSVD algorithm is described in Section 2.4.3. We connected altogether the value *K* to a curve. This curve can predict the truncation parameter (i.e., the processing time) and accuracy of processing (i.e., processing residuals value), so we call it "processing predicted curves." We have found that in logarithm coordinate system the curve usually has the letter "L" shapes, which we call the "L-curve." The optimum K is located at the corner of the "L-curve."

In the MRF and IBF process, it is essential to add some additional removal layer to ensure that dwell is non-negative, and another additional removal layer can also reduce the requirements of machine tool dynamics. The thickness of additional removal layer can be determined by the above optimum K.

The following comparative experiment of MRF shows an example, in which the # 1 and # 2 of the two Φ100 mm k9 glass plate mirrors are polished, respectively. The thickness H_{extra} of additional removal layer is zero for # 1 and is 0.1 mm for # 2. Table 1.4 shows the results of this processing. From this table we can see that the additional removal layer is useful to fetch up the lack of machine dynamical performance. [55]

Another method used is the re-planning of the regional processing path to reduce the requirements of the machine dynamic performance.

For example, the tool path is/serves as a helical line in the rotation scan processing methods. When the rotation speed of workpiece table remains the same, and the tool is nearer to the center, its relative line velocity will become smaller/lower until it reaches zero at the center. In order to meet the requirement of control dwell time distribution, the nearer the tool is to the

Table 1.4 The results of # 1 and # 2 processing.

Sample	1#: $H_{extra} = 0$	2#: $H_{extra} = 0.1$ mm
The initial surface form error	145.01 nm PV, 26.342 nm RMS	120.60 nm PV, 27.898 nm RMS
The form error after processing	82.924 nm PV, 12.244 nm RMS	52.305 nm PV, 2.754 nm RMS
The convergence ratio of form error	2.15	10.12

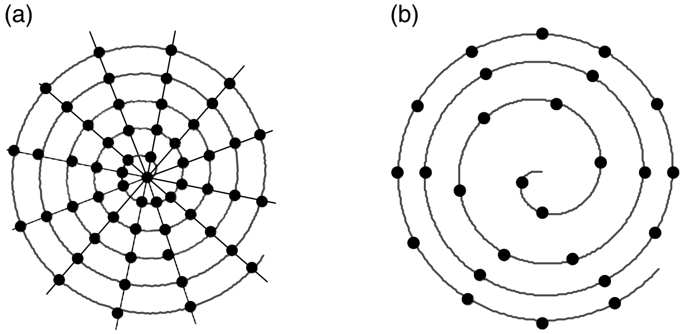

Figure 1.6 The central area speed control schematic diagrams. (a) The original path and its dwell points; (b) improved path and its dwell points.

center, the greater the rotation speed of workpiece table is required: it is impossible to achieve the rotation speed, which should be infinite at the center point in theory. When the table rotation is up to the highest possible rotation speed, the central area has been overcut, caused by the truncated speed and longer dwell time.

This problem can be tackled by the path re-planning control. The dwell time can be calculated/adjusted/set for re-planning to make sure that the sum of the removal of the speed truncated region is constant. For example, Hu Hao [65] of the NUDT proposes that using one kind of spiral path, which retains equal growth area in the polishing, rotation speed, and pitch of the spiral scan that increases gradually, but area growth rate of removal function is constant. He referred to this method as a non-equal spiral pitch for speed turntable compensation method. In this respect, the requirements of rotation speed for center area can be reduced, and thereby the requirements of the dynamics of workpiece table are reduced, too. The central area speed control schematic diagram for speed turntable compensation is as shown in Figure 1.6.

1.6.4 The Evolution Theory and Control Technology of the Errors

The CCT technology based on sub-aperture processing aims to make optical surface form error figuring and, at the same time, to obtain the best surface and sub-surface quality. The processing response of the acting between polishing tool, machined material, and micro structure of workpiece surface is composed of their own rules and characters. The rules of generating, converging, and controlling of the medium and high frequency error, the constraints condition and nonlinear control method of the edge and curvature effects, the optimization of parameters and machining path of polishing process, the sub-surface quality and integrity and the like can be all included in error evolution theory and control technology.

The causes of the low, medium, and high frequency error are complex. Based on sub-aperture processing methods, the main reasons are given as follows:

1. The errors caused by the convolution effect

   Considering the sub-aperture processing methods, the solution of the dwell time is obtained based on the convolution calculation of the removal function and dwell time in the direction of the moving trajectory. The periodical residual errors based on the role of the convolution are inevitable, so the errors caused by convolution effect are one kind of principal errors.

2. The errors caused by the path planning

   Some certain residual errors are caused by the renew line of process scanning. The regularity for renew line spacing to bring the regular error trace will form a grating effect resulting from light modulation, which must be avoided.

3. The error caused by a lack of the amendment ability

   The relationship between removal function and error frequency components of surface is discussed in Section 2.3.2. The size of removal function determines its modification capabilities and its theoretical description and definition are discussed in Section 2.3.2, too. The higher the surface error frequency is, the greater the solution number of dwell function is; thus, it is compulsory to remove the extra material in order to remove the surface error. In addition, the position and movement error and dynamics of the machine tool can also determine its modification ability.

4. The error caused by the fluctuations of process parameters

   The parameter errors of polishing tool, processing art, the factors of optical materials, measurement, and environment can lead to final machining errors. The characteristics of the workpiece surface, such as the microstructure, edge, curvature rate and local singular point, can also produce final machining errors, respectively.

Facing the above problems, we did some research/experiments as follows.

1.6.4.1 The Local Random Processing Path Planning Based on the Theory of Entropy Increasing

The goal of polishing is to reduce the form error and roughness of machined surface to a minimum and to achieve convergence consistently. The convergence process for disperse abrasive polishing is a typical multi-parameter random process, which is an alternate processing and should be consistent with the statistical laws. Under the different conditions, the polishing process varies widely. The maximum entropy principle is a universal concept and description. Originally stemming from the thermodynamics, it reflects the status of how to close thermal equilibrium. We use the concept of entropy to/for the polishing effect to describe the ability of error convergence and self-correction capability.

Traditional polishing process for plane and spherical processing, a tamper chaos track of the relative motion between the polishing pad and the workpiece, is easy to achieve relatively. The chaos trajectory of the whole domain in aspheric processing is difficult due to the mechanical structure constraints. The certain ingredient error of frequency distribution is caused by the processing path. The experiment of the entropy growth theory for the small area is described in Section 2.7; it is used in a linear raster scanning trajectory of aspheric processing by the MRF. The local random processing path is based on design of the entropy increase theory, and the information entropy is used as the measure of random distribution of the removal function dwell points. The experiments have confirmed that the high-frequency error by this local random path is obviously less than of the equidistant raster scan path, and the peak value of the frequency components of the path wrap is significantly inhibited in the PSD curve.

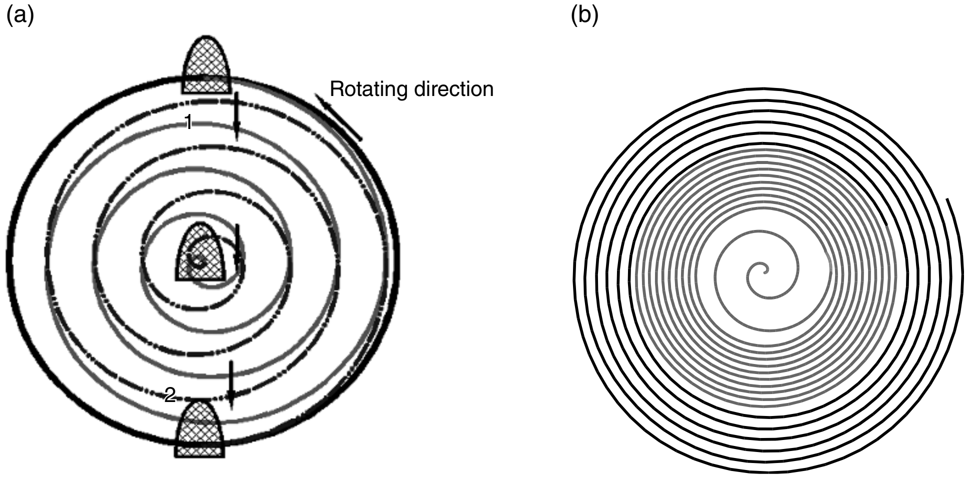

Figure 1.7 The schematic diagram of optimized spiral path. (a) The processing pitch along the diameter trajectory; (b) the random pitch trajectories (only draw along the radius of the processing). Reproduced from Hao Hu (2011), with permission.

The processing effect of equal pitch spiral scanning mode for the circular symmetry workpiece is better than the linear raster scan mode. The processing of the removal function is along the diameter and out of the entire surface, the process will sweep the entire processing surface twice, and these twice helix does not repeat, see Figure 1.7a. This method is better than only along the radius of the processing. We use the pitch path is on pseudo-random distribution along the diameter. Its pitch size of the helix is changed based on surface error distribution and randomly, as shown in Figure 1.7b proposed by Hu Hao of NUDT. [65]

In the case of the MRF process, a Φ100 mm fused silica material plane mirror is processed by a helical path of 1 mm pitch and is along the radius direction. The surface accuracy is 0.386λ PV and 0.059λ RMS after processing. There are obvious traces of the spiral and periodic ripples that can be found at the machined surface, and there is an obvious spike at 1 mm wavelength of PSD curve. Using the random pitch spiral path for processing along the diameter of the entire surface, the accuracy of the surface is improved up to 0.072λ PV and 0.005λ RMS, no significant spike is protruded at 1 mm wavelength of PSD curve. The experimental results show that the error value of all spectrum is decreased, so it does not only verify that the high-frequency processing error can be suppressed by the random pitch spiral path effectively, but also proves that the accuracy has been improved so much. [65]

1.6.4.2 The Nonlinear Compensation Control for the Curvature Effect of Aspheric Process

For nonlinear effects of the high steepness surface, the calculation of the surface convolution will be tend to more complex and will bring instability of the algorithm. For IBF, the surface geometry correction based on compensation control strategy can be easy and effective. In the MRF processing, due to changes of the three-dimensional body of fluid ribbon involving non-Newtonian fluid dynamics, the compensation control strategy is more complicated.

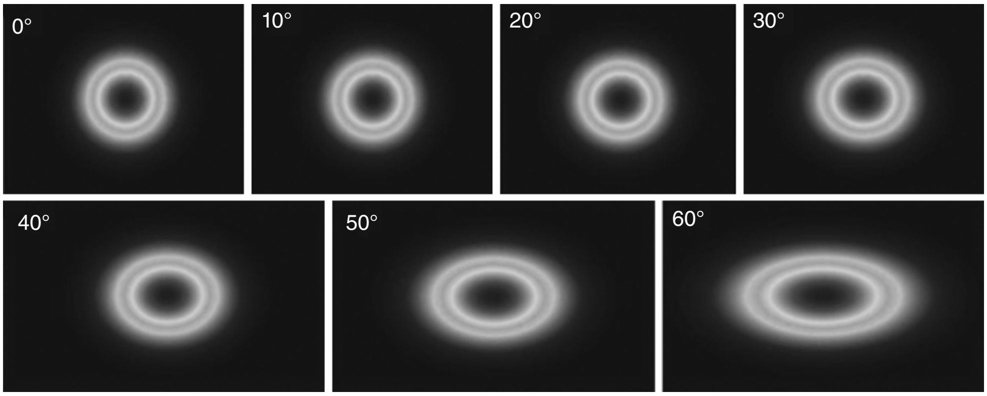

Figure 1.8 The nonlinear variation of the shape and peak removal rate of removal function with the different incident angles.

With incident condition along the optical axis, the removal functions of the IBF change as a non-linear rule. Figure 1.8 shows that the removal function shapes change with the different incident angles of IBF. The peak removal rate (MRR) has a significant nonlinear variation and there is a clear inflexion point at about 70° angle of incidence. This nonlinear change of removal function shape and the removal efficiency will also bring uncertainty for nanometer accuracy processing. Therefore, it is necessary to establish a nonlinear model of change, using the way of compensation for high accuracy processing. [64]

1.6.4.3 The Edge Effect of the Nonlinear Compensation Control

The edge effect of the MRF is similar to that of the traditional small lap process. The edge effect is a common problem of contact polishing methods, and MRF is not an exception. The status of removal function is changed at the edge processing region of MRF and error is produced, because the material removal amount is dependent on acting together with the hydrodynamic pressure and its shear forces of the MR ribbon at the processing area. At the edge of the workpiece, the closure current status of the MR fluid is obviously different with inside of workpiece, as shown in Figure 1.9.

Figure 1.9b shows the polishing status inside of workpiece; Figure 1.9a and c show the polishing status of the MR fluid ribbon that moves into and left out from the edge of workpiece respectively.

The peak removal rate (MRR) and volume removal efficiency (VRR) are different compared with the ideal and actual removal function. It can be seen that the value of MRR and VRR, which is moved into the edge, is smaller than inside one but is bigger than one that is left out from the edge. With the polishing spot farther and farther from the edge of the workpiece, the actual peak removal efficiency and size of polishing spot are decreased too much, which is the main cause of the edge effect, and hence the error at the edges is often "raising."

For example, as a processing experiment for Φ100 mm circular plane mirror, the compensation control for the edge effect is used by us. The initial surface error of workpiece is 0.201λ PV and 0.050λ RMS. After the compensation controlled process, with its convergence to

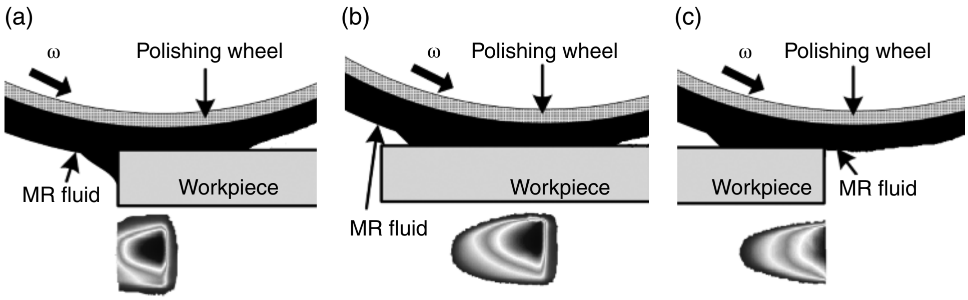

Figure 1.9 The diagram of the edge effect of the MRF removal function. The MR fluid ribbon moves (a) move into; (b) inside; (c) move out.

0.059λ PV and 0.007λ RMS of the full aperture, the error convergence ratio is up to 7.1, at one processing time only. The experiment results verify the validity of this method to control the edge effect. [65]

1.6.4.4 The Surface Roughness and Sub-Surface Integrity Control [66,67]

For the surface roughness and sub-surface integrity based on ductile shear characteristics of the MRF with matching of suit parameters, the surface quality can improve greatly. It can be used to remove surface flaws and the surface hydrolysis layer, and can eventually reach near to the subsurface damage-free. The surface roughness can be achieved less than 0.5–0.3 nm level of the MRF processing. MRF is a low-damage polishing technology, so it can be used as a sub-surface damage detection means, and thus can establish the relationship between surface roughness and subsurface damage of grinding and lapping. The IBF is processed through bombardment of a small angle of incidence and using the sacrificial layer protection to reduce the surface roughness further; for example, the roughness is improved from 0.67 nm RMS by 90° incident to 0.38 nm RMS by 45° incident polishing. When a sacrificial layer of protection is used, the roughness is improved from 0.81 nm RMS to 0.28 nm RMS, and when IBF is processing in vacuum environment, its surface cleaning processing function is best. For example, for the 100 mm plane mirror specimen of CVD SiC, one of the MRF spots is used to measure the damage depth of sub-surface firstly, and then reasonable parameters are selected and optimized to remove the sub-surface damage layer, and another one is selected to improve its accuracy finally. The surface accuracy can be up to 0.1007λ RMS, and the surface roughness is to 0.1659 nm rms.

1.6.5 The Equipment and Technology of the CCT

The equipment and technology of the CCT include machine tool structure design, accuracy analysis, control systems, online measurement instruments and software, and so on.

Traditional precision machine tools are based on error copying principle that the error of the machine tool will be copied onto the workpiece. Through the ultra-precision, diamond machine tool is a typical representative one whose motion accuracy of machine tool can be up to 100 nm. Its machining precision also is about at 100 nm level.

For machine tools of high-precision polishing based on discrete abrasive processing, their error convergence is based on statistical laws. So it no longer follows the principle of the error copying. The motion accuracy of machine tools can be 0.1 mm, and workpiece accuracy can be nanometer scale. However, the error convergence processing of non-deterministic processing should be for a long time.

The CCT technology is based on the exact mathematical model; it follows neither error copying principle nor the non-deterministic statistical laws. The motion accuracy of machine tools has higher requirements about 10 μm, and the dynamic performance of machine tools has a higher time control accuracy about tens of milliseconds. [68] Therefore, the equipment and technology of the CCT are required to host a new processing mechanism; and to realize the process conditions of this mechanism, all of them pose a new challenge for CCT machine tools.

References

[1] Council, N.R. (1998) *Harnessing Light, Optical Science and Engineering, for 21st Century*, National Academy Press, Washington, DC.

[2] Bielke, A., Beckstette, K., Kübler, C. *et al.* (2004) Fabrication of aspheric optics: process challenges arising from a wide range of customer demands and diversity of machine technologies. *Proceedings of SPIE*, **5252**, 1–12.

[3] Zhang X.J. (2006) The technology of the aspherical processing and testing. *Optics and Precision Engineering*, **14** (4), 527 (in Chinese).

[4] Xin Q.M. (2005) *The Manufacturing Technology of Optical Plastic Aspheric*. Beijing: National Defence Industry Press (in Chinese).

[5] Lincoln, L. (1997) Endelman, Endelman Enterprises, San Jose. Hubble Space Telescope: now and then. *Proceedings of SPIE*, **2869**, 44–57.

[6] Crocker J.H. (1993) Commissioning of Hubble Space Telescope: the strategy for recovery. *Proceedings of SPIE*, **1945**, 2–10.

[7] Philip, S.H. (2003) Optic needs for future space telescopes. *Proceedings of SPIE*, **5180**, 1–5.

[8] Clampin, M. (2008) The James Webb Space Telescope (JWST). *Advances in Space Research*, **41**, 1983–1991.

[9] Yang L. (2001) *The Advanced Optical Manufacturing Technology*. Beijing: Science Press (in Chinese).

[10] Hao, Y.C. (2000) Research of optical system for space camera of detailed investigation. Doctoral thesis. Shanghai: Shanghai Institute of Medication, Chinese Academy of Sciences (in Chinese).

[11] Richard, B. (1971) The influence of random wavefront errors on the imaging characteristics of an optical system. *Optica Acta*, **18**, 683–694.

[12] Harvey, J.E. and Kotha, A. (1995) Scattering effects from residual optical fabrication errors. *Proceedings of SPIE*, **2576**, 155–174.

[13] Lawson, J.K., Auerbach, J.M., English, R.E. *et al*. (1998) NIF Optical Specifications: The Importance of the RMS Gradient. LLNL report UCRL-JC-130032, 7–12.

[14] Tricard, M. and Murphy, P.E. (2005) Subaperture stitching for large aspheric surfaces. Talk for NASA Technology Days. Aug. 16, 2005.

[15] Lyubarsky, S.V, Khimich Y.P. (1994) Optical mirrors made of nontraditional materials. *Journal of Optical Technology*, **61**, 61–67.

[16] Anapol, M. and Hadfield, P. (1992) SiC lightweight telescopes for space applications. *Proceedings of SPIE*, Surveillance Technologies, **1693**, 42–45.

[17] Eaton, D.C.G. and Bashfor, D.P. (1998) The materials challenges facing Europe. *ESA Bulletin*, **75** (9), 41–46.

[18] Robichaud, J., Anapol, M., Gardner, L. *et al*. (1995) Ultralightweight off-axis three mirror anastigmatic SiC visible telescope. *SPIE*, Symposium on Silicon Carbide Materials for Optics and Precision Structures, San Diego, California, USA, 74–78.

[19] Tobin, E., Magida, M., Krim, S. *et al*. (1995) Design, fabrication and test of a meter-class reaction bonded SiC mirror. *SPIE*, Symposium on Silicon Carbide Materials for Optics and Precision Structures, San Diego, California, USA, 57–63.

[20] Robb, P., Charpentier, R., Lyubarsky, S.V. *et al*. (1995) Three mirror anastigmatic telescope with a 60-cm aperture diameter and mirror made of silicon carbide. *SPIE*, Symposium on Silicon Carbide Materials for Optics and Precision Structures, San Diego, California, USA, 87–92.

[21] Pickering, M.A., Taylor, R.L., Keeley, J.T. *et al.* (1989) Chemically vapor deposited silicon carbide (SiC) for optical application. *SPIE*, Symposium on Space Optical Materials and Space Qualification of Optics, Orlando, Florida, USA, 50–54.

[22] Goela, J.S. and Taylor, R.L. (1989) Large scale fabrication of lightweight Si/SiC LIDAR mirrors. *SPIE*, Symposium on Space Optical Materials and Space Qualification of Optics, Orlando, Florida, USA, pp. 63–68.

[23] Tam, H.Y., Cheng, H.B. and Wang, Y.W. (2007) Removal rate and surface roughness in the lapping and polishing of RB-SiC optical components. *Journal of Materials Processing Technology*, **192–193**, 276–280.

[24] Foreman, J.W. (1986) Simple numerical measure of the manufacturability of aspheric optical surfaces. *Applied Optics*, **25** (6), 826–827.

[25] Kumler, J. (2005) Designing and specifying aspheres for manufacturability. *Proceedings of SPIE*, **5874**, 58740C–1–9.

[26] Yang, M.Y. and Lee, H. (1999) The PC-based numerically controlled polishing machine for aspheric surfaces with dwell time control. *Proceedings of the First International Euspen Conference*, **1**, 242–245.

[27] Yang, M.Y. and Lee, H.C. (2001) Local material removal mechanism considering curvature effect in the polishing process f the small aspheric lens die. *Materials, Processing Technology*, **116**, 298–304.

[28] du Jeu, C. (2004) Criterion to appreciate difficulties of aspheric polishing. *Proceedings of SPIE*, **5494**, 113–121.

[29] Louis, M. (2004) Fabrication and metrology of 10X Schwarzschild optics for EUV imaging. *Proceedings of SPIE*, **5193**, 1–10.

[30] Hans M.L., Vadim B., N. Hamed *et al.* (2005) Development of the ASML EUV alpha demo tool. *Proceedings of SPIE*, **5751**, 90–101.

[31] Wingerden, J.V. (1992) Production and measurement of superpolished surfaces. *Optical Engineering*, **31** (5), 1086–1092.

[32] Stowers, I.F. (1988) Review of precision surface generation process and their potential application to the fabrication of large optical components. *Proceedings of SPIE*, **996**, 6673.

[33] Bifano, T.G., Dow, T.A. and Scattergood, R.O. (1991) Ductile regime grinding: a new technology for machining britlle materials. *Transactions of the ASME*, **113**, 184–189.

[34] William, J., Wills, M., Keith, C. *et al.* (1990) Ductile regime grinding of glass and other brittle materials by the use of ultra-stiff machine tools. *Advanced Optical Manufacturing and Testing, Proceedings of SPIE*, **1333**, 10 p.

[35] Namba, Y., Wada, R., Unno, K. *et al.* (1989) Ultra-precision surface grinder having a glass-ceramic spindle of zero-thermal expansion. *Annals of the CIRP*, **38** (1), 331–334.

[36] Leistner, A.J. (1993) Teflon some new developments and results. *Applied Optics*, **32** (19), 3416–3424.

[37] Dietz, R. and Bennet, T.J. (1966) Bowl feed technique for producing supersmooth optical surfaces. *Applied Optics*, **5** (5), 881–882.

[38] Mclntosh, R.B. (1980) Chemical–mechanical polishing of low-scatter optical surfaces. *Applied Optics*, **19** (14), 2329–2331.

[39] Chkhalo, N.I. (1995) Ultradispersed diamond powders of detonation nature for polishing X-ray mirrors. *Nuclear Instruments and Methods in Physics Research Section A*, **359**, 155–156.

[40] Gormley, J. (1981) Hydroplane polishing of semiconductor crystals. *Review of Scientific Instruments*, **52** (8), 1256–1258.

[41] Kasai, T. and Kobayashi, A. (1984) Progressive mechanical and chemical polishing. The Science of Polishing, *Technical Digest*, *OSA*, Washington, DC, TuB–B4–1–TuB–B4–4.

[42] Watanabe J. (1983) The non-contact grinding technology for semiconductor substrate. *Journal of the Japan Society for Precision Engineering*, **49** (5), 655–660 (in Japanese).

[43] Namba, Y. and Tsuwa, H. (1987) Ultraprecision float finishing machine. *Annals of the CIRP*, **36**, 211–214.

[44] Yang Z.F., Yang H. Li C.G., Liu Y., and Fang J.G. (2008) Ultra-smooth surface polishing based HHT of glass-ceramic, *Optics and Precision Engineering*, **16** (1), 35–41 (in Chinese).

[45] Yongsik M. (1999) Mechanical aspects of the material removal mechanism in chemical mechanical polishing. Ph.D. dissertation. University of California, Berkeley.

[46] Shimura, T., Takazawa, K., Hatano, E. *et al.* (1984) Study on magnetic abrasive process finishing characteristics. *Bulletin of the Japan Society of Precision Engineering*, **18** (4), 347–348.

[47] Umehara, N. (1994) Magnetic fluid grinding a new technique for finishing advanced ceramics. *Annals of the CIRP*, **43**, 185–188.

[48] Mori, Y.K. and Endo, K. (1987) Elastic emission machining. *Bulletin of the Japan Society of Precision Engineering*, **9**, 123–128.

[49] Baker, P. (1989) Advanced flow-polishing of exotic optical materials. *Proceedings of SPIE*, **1160**, 263–270.

[50] Bollinger, L. and Zarowin, C. (1988) Rapid, nonmechanical, damage-free figuring of optical surfaces using plasma-assisted chemical etching (PACE): part I experimental results. *Proceedings of SPIE*, **966**, 82–90.

[51] Su, D.Q. (2001) *2.16 m Telescope Project Anthology*, China Science and Technology Press, Beijing.

[52] Burge, J.H., Anderson, B., Benjamin, S. *et al.* (2001) Development of optimal grinding and polishing tools for aspheric surfaces. *Proceedings of SPIE*, **4451**, 153–164.

[53] Dae, W.K. and James, H.B. (2010) Rigid conformal polishing tool using non-linear visco-elastic effect. *Optics Express*, **18** (3), 2242–2257.

[54] Kang, N.H. (2009) Research on material removal mechanism and process of silicon carbide mirror ultra-precision machining. Ph.D. thesis. National University of Defense Technology, Changsha (in Chinese).

[55] Shi, F. (2009) Research on key technologies of magnetorheological finishing for high-precision optical mirror. Ph.D. thesis. National University of Defense Technology, Changsha (in Chinese).

[56] Li, Z.Z. (2011) Study on Abrasive Jet Polishing Technology. Ph.D. thesis. National University of Defense Technology, Changsha (in Chinese).

[57] West, S.C., the Martin H.M, Nagel, R.H. *et al.* (1994) Practical design and performance of the stressed lap polishing tool. *Applied Optics*, **33** (34), 8094–8100.

[58] Anderson D.S, Angel J.R.P., Burge J.H., *et al.* (1991) Stressed-lap polishing of a 3.5-mf/1.5 and 1.8-mf/1.0 mirrors, in Advanced Optical Manufacturing and Testing II, VJ Doherty, ed, *Proceedings of SPIE* **1531**, 260–269.

[59] Martln, H.M., Alien, R.G., Burge, H. *et al.* (2002) Fabrication of mirror for the Magellan telescopes and large binocular telescope. *Proceedings of SPIE*, **4837**, 609–618.

[60] Martln, H.M., Alien, R.G., Burge, H. *et al.* (2002) Optics for 20/20 telescope. *Proceedings of SPIE*, **4840**, 1–12.

[61] David, D.W., David, B. and Andrew, K. (2003) The 'Precessions' tooling for polishing and figuring flat, spherical and aspheric surfaces. *Optics Express*, **11** (8), 958–964.

[62] Walker, D.D., Beaucamp, A.T.H., Bingham, R.G. *et al.* (2002) The Precessions process for efficient production of aspheric optics for large telescopes and their instrumentation. *Proceedings of SPIE*, **4842**, 73–84.

[63] Liu J. (1995) *Ion-Beam Technology and Applications*, National Defence Industry Press, Beijing (in Chinese).

[64] Zhou, L. (2008) Ion beam figuring modification theory and technology, the National University of Defense Technology. Ph.D. thesis. National University of Defense Technology, Changsha (in Chinese).

[65] Hu, H. (2011) The key technology of high-precision optical components MRF controllable compensation figuring, the National University of Defense Technology. Ph.D. thesis. National University of Defense Technology, Changsha (in Chinese).

[66] Liao W.L., Dai Y.F., Zhou L., Chen S.Y. (2010) Research on optical surface roughness evolving under the IBF processing. *Applied Optics* **31** (6), 59 (in Chinese).

[67] Kang N.H., Li S.Y., Zheng Z.W., Dai Y.F. (2009) The high-precision ultra-smooth processing for silicon carbide flat mirror of chemical vapor deposition. *China Mechanical Engineering*, **20** (1), 69–73 (in Chinese).

[68] Yuan, L. (2012) The MRF machine tool performance analysis and the influence of machining accuracy, the National University of Defense Technology. Master thesis. National University of Defense Technology, Changsha (in Chinese).