LARGE AND MIDDLE-SCALE APERTURE ASPHERIC SURFACES
LARGE AND MIDDLE-SCALE APERTURE ASPHERIC SURFACES LAPPING, POLISHING, AND MEASUREMENT

Shengyi Li
Yifan Dai
National University of Defense Technology
China
Contents

About the Author xiii
Foreword xv
Preface xvii

1 Foundation of the Aspheric Optical Polishing Technology 1
  1.1 Advantages and Application of Aspheric Optics 1
    1.1.1 Advantages of Optical Aspherics 1
    1.1.2 The Application of Aspheric Optical Components in Military Equipment 2
    1.1.3 The Aspheric Optical Components in the Civilian Equipment 2
  1.2 The Characteristics of Manufacturing Aspheric Mirror 3
    1.2.1 Requirements of Modern Optical System on Manufacturing Aspheric Parts 3
    1.2.2 The Processing Analysis of Aspheric Optical Parts 7
  1.3 The Manufacturing Technology for Ultra-Smooth Surface 9
    1.3.1 Super-Smooth Surface and Its Applications 9
    1.3.2 Manufacturing Technology Overview of Super-Smooth Surface 11
    1.3.3 Manufacturing Technology of Ultra-Smooth Surface Based on the Mechanical Micro-Cutting Principles 12
    1.3.4 The Traditional Abrasive Polishing Technology for Ultra-Smooth Surface 13
    1.3.5 The Principles and Methods of Non-contact Ultra-Smooth Polishing 15
    1.3.6 The Non-contact Chemical Mechanical Polishing (CMP) 17
    1.3.7 The Magnetic Field Effect Auxiliary Processing Technology 17
    1.3.8 The Particle Flowing Machining Technology 18
  1.4 The Advanced Aspheric Optical Polishing Technology 19
    1.4.1 The Classic Polishing for Aspheric Optical Parts 19
    1.4.2 The Modern CNC Polishing Method of Aspheric Optical Parts 20
    1.4.3 The Controllable Compliant Tool (CTT) Manufacturing Technology for Aspheric Optical Components 22
1.5 The CCT Based on Elasticity Theory

1.5.1 The Controlled Elastic Deformation Pad Polishing—Stressed-Lap Polishing (SLP)

1.5.2 The Controlled Mirror Body Elastic Deformation Polishing by Active Support

1.5.3 Bonnet Polishing with Precession Process

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

1.6.1 The Material Removal Mechanism and Mathematical Model

1.6.2 The Multi-Parameter Control Strategy

1.6.3 4D CNC Technology

1.6.4 The Evolution Theory and Control Technology of the Errors

1.6.5 The Equipment and Technology of the CCT

References

2 The Basic Theory of Aspheric Optical Lapping and Polishing Technology

2.1 The Preston Equation of Optical-Mechanical Polishing Technology and Its Application

2.1.1 The Preston Equation

2.1.2 The Application of Preston Equation in the Traditional Polishing

2.2 The Deterministic Processing Principle for Aspheric

2.3 The Molding Theory of Aspheric Surface Processing

2.3.1 The Dual-Series Model for the Aspheric Molding Process

2.3.2 The Influence of the Removal Function Size on the Processing

2.3.3 The Influence of Removal Function Disturbing

2.3.4 The Influence of the Positioning Errors

2.3.5 The Influence of Discrete Interval

2.4 The Figuring Theory of Linear Scanning Mode on Full-Aperture

2.4.1 The Iterative Algorithm Based on Bayesian

2.4.2 The Pulse Iterative Method

2.4.3 The Truncated Singular Value Decomposition

2.5 The Polar Scanning Mode of Surface Figuring

2.5.1 The Removal Function with Approximate Rotation Symmetry Property

2.5.2 The Removal Function without the Characteristics of Rotation Symmetry

2.6 The Frequency Domain Analysis of Forming

2.6.1 The Characteristics of the Spectrum Under the General Forming Conditions

2.6.2 The Figuring Ability of the Rotary Symmetric Removal Function in the Forming Process

2.7 Maximum Entropy Principle of Polishing

2.7.1 The Entropy Principle Expression for Polishing

2.7.2 An Application Example of the Principle of Maximum Entropy in the Fixed Eccentric Flat Polishing

2.7.3 The Example of Processing Parameter Choice Based on Maximum Entropy Principle for Dual-Rotor Pad

2.7.4 The Example of Inhibition Medium and High Frequency Errors Based on the Entropy Increase Principle for the MRF
3 CCOS Technology Based on Small Polishing Pad

3.1 Review of CCOS Technology Based on Small Polishing Pad
   3.1.1 Progress of Small Tool CCOS Technology
   3.1.2 Key Problems of Small Tool CCOS Technology

3.2 Aspheric Optical Compound Machining Tool Optical Aspherical Mirror Process Machine Tool

3.3 Modeling and Analysis of Removal Function
   3.3.1 Characteristics of Ideal Removal Function
   3.3.2 Theoretical Model
   3.3.3 Experimental Model
   3.3.4 Figuring Ability Analysis of Removal Function
   3.3.5 Modeling and Analysis of the Complex Shape Polishing Pad's Removal Function

3.4 Calculation and Analysis of Dwell Time in CCOS Technology
   3.4.1 Pulse Iterative Method Based on Process Time
   3.4.2 Influence of Convolution Effect on Residual Error

3.5 Removal Function Modeling Under the Edge Effect
   3.5.1 Pressure Distribution When the Polishing Pad Out of Edge
   3.5.2 Removal Function Modeling Under Edge Effect

3.6 Cause and Modification Method of Optical Surface Small-Scale Manufacturing Error
   3.6.1 Cause and Evaluation of Optical Surface Small-Scale Manufacturing Error
   3.6.2 Full Aperture Uniform Polishing Correction Method of Small-Scale Manufacturing Error
   3.6.3 Deterministic Local Modification Method of Small-Scale Manufacturing Error

References

4 Ion Beam Figuring Technology

4.1 Outline of Ion Beam Figuring Technology
   4.1.1 Application of Ion Beam Processing Technology
   4.1.2 The Basic Mechanism and Character for Optical Machining by IBF
   4.1.3 Development of IBF of Optical Mirror

4.2 Basic Principle of IBF for Optical Mirror
   4.2.1 Description of Ion Sputter Process
   4.2.2 Material Removal Rate of IBF

References
4.3 Analysis of Removal Function Model in IBF
   4.3.1 Theoretical Modeling of Removal Function in IBF
   4.3.2 Experiment Analysis of the Removal Function Character in IBF
   4.3.3 Experiment Modeling of Removal Function in IBF

4.4 IBF System Design and Analysis
   4.4.1 System Set-Up
   4.4.2 System Analysis

4.5 Micro-Scale Error Evolution During IBF
   4.5.1 Surface Roughness Evolution
   4.5.2 Microscopic Morphology Evolution

4.6 The Polishing Experiment of IBF
   4.6.1 Flat Optical Mirror Polishing Experiment
   4.6.2 Curved Surface Figuring Experiment

References

5 Magnetorheological Figuring
   5.1 Overview of Magnetorheological Figuring
   5.1.1 Applications of Magnetorheological Fluid
   5.1.2 Development of Magnetic-Effect-Assisted Polishing Techniques for Optics
   5.1.3 Development of Deterministic Magnetorheological Figuring
   5.2 Mechanism and Mathematical Model of MRF Material Removal
   5.2.1 Mechanism of MRF Material Removal
   5.2.2 Theoretical Calculation of Load on Single Abrasive and Indentation Depth
   5.2.3 Fluid Dynamics Analysis and Calculation in Polishing

5.3 MRF Machine Tools
   5.3.1 Basic Requirement on MRF Machine Structure
   5.3.2 Machine Structure of MRF Experimental Prototype
   5.3.3 Design of Upside Down MRF Polishing Devices
   5.3.4 MR Fluid Circulation and Control System

5.4 MR Fluid and Its Performance
   5.4.1 Current Situation of MR Fluid Research
   5.4.2 Components of MR Fluid and Its Performance
   5.4.3 Principles on Choosing MR Fluid Elements
   5.4.4 Preparation of MR Fluid

5.5 Optimization of MRF Processing Parameters
   5.5.1 Orthogonal Experiments on MRF Process Parameters
   5.5.2 Grey Correlation Analysis
   5.5.3 Parameter Optimization of Multiple Process Indexes
   5.5.4 Comprehensive Optimization of Machining Process

5.6 MRF Optical Surfacing Technique and Machining Experiment
   5.6.1 Algorithm of Dwell Time for Optical MRF Surfacing
   5.6.2 MRF Polishing Examples

5.7 Magnetorheological Jet Polishing
   5.7.1 Overview of Abrasive Jet Polishing
6 Evaluation of Deterministic Optical Machining Errors 307
   6.1 Introduction 307
   6.2 Usual Evaluation Method of Optical Machining Errors 308
      6.2.1 Evaluation Parameters of Geometrical Accuracy in Optical
              Machining Process 308
      6.2.2 Evaluation Method of Optical Machining Errors Based on
              PSD Character Curve 310
      6.2.3 Evaluation Method of Optical Machining Errors Based on
              Scattering Theory 311
      6.2.4 Evaluation Method of Optical Machining Errors Based on
              Statistical Optical Theory 311
   6.3 Analysis on Distribution Characteristics of Optical Machining Errors 312
      6.3.1 Evaluation and Analysis on Machining Errors of Any Direction on
              Optical Surface 312
      6.3.2 Evaluation and Analysis of Local Errors on Optical Surface 319
      6.3.3 Influence of Processing Method on Optical Machining Errors 323
   6.4 Scattering Evaluation of Optical Machining Errors 340
      6.4.1 Binary Separation of Frequency Band for Optical Machining Errors 341
      6.4.2 Evaluation Based on Harvey-Shack Scattering Theory 344
      6.4.3 Influence of Optical Machining Errors on Scattering Properties 348
   6.5 Evaluation of Frequency Band Errors Based on Optical Performance 353
      6.5.1 Influence Characteristic of Different Frequency Errors on
              Optical Performance 353
      6.5.2 Requirement of Frequency Band Errors in Different Optical
              Applications 356
      6.5.3 Evaluation of Φ200 mm Paraboloid Mirror Machined by IBF 365
References 370

7 Measurement Technology in Manufacturing of Large-Middle
Optical Surfaces 373
   7.1 Introduction 373
      7.1.1 Requirements of Large-Middle Optical Surfaces 373
      7.1.2 Overview of Measurement in Manufacturing of Large-Middle
              Optical Surfaces 375
   7.2 Principles of Coordinate Measurement Technology in Manufacturing
          of Large-Middle Optical Surfaces 376
   7.3 Interferometric Null Test in Manufacturing of Large-Middle
          Optical Surfaces 377
      7.3.1 Basic Principle of Interferometric Null Test 377
      7.3.2 Null Test of Large-Middle Planar and Spherical Surfaces 378
7.3.3 Null Test of Conic Surfaces Using Conjugates
7.3.4 Null Test of Aspheric Surfaces Using Compensators
7.3.5 Null Test with Computer Generated Holograms
7.4 Non-Null Test in Manufacturing of Large-Middle Optical Surfaces
7.4.1 Shear Interferometry
7.4.2 Interferometry with High Resolution CCD
7.4.3 Sub-Nyquist Interferometry
7.4.4 Long-Wavelength Interferometry
7.4.5 Subaperture Stitching Interferometry
7.5 Phase Retrieval Technology
7.6 Subsurface Quality Assessment
References

8 Coordinate Measuring Technology of Optical Aspheric Surface
8.1 State of the Art of the Coordinate Measuring Technology of Optical Aspheric Surface
8.1.1 Status and Characteristics of Coordinate Measuring Technology for Optical Aspheric Surface
8.1.2 State of the Art of Optical Aspheric Coordinate Measuring Technology and Development Tendency
8.2 Large Aperture Aspheric Coordinate Measuring Technology
8.2.1 The Design of Coordinate Measuring System
8.2.2 The Measurement Principle of Large Aspheric Coordinate Measuring
8.2.3 Analysis and Evaluation of Optical Aspheric Form Error Based on Multiple Section Line Measurement
8.2.4 Machining Case—Machining and Measuring of Ø500 mm Aspheric
8.3 The Swing Arm Measurement of Large Aspheric
8.3.1 The Analysis of Measuring Principle
8.3.2 The Structural Design of Measuring System
8.3.3 The Accuracy Analysis and Modeling of the Measuring System
8.3.4 The Optimization Algorithm for Swing Arm Profilometry Measuring Aspheric Vertex Curvature Radius
8.3.5 The Simulation of Measurement Algorithm and Measurement Experiments
References

9 Subaperture Stitching Interferometry
9.1 Introduction
9.1.1 Basic Principle of Subaperture Stitching Interferometry
9.1.2 Overview of Subaperture Stitching Interferometry
9.2 Fundamentals of Subaperture Stitching Algorithm
9.2.1 Mathematical Model of Two-Subaperture Stitching
9.2.2 Model and Algorithm for Simultaneous Stitching
9.3 Iterative Algorithm for Subaperture Stitching
9.3.1 Mathematical Model
9.3.2 Iterative Algorithm
9.3.3 Coarse-Fine Stitching Strategy for Large Optical Surfaces
9.4 Method for Subaperture Lattice Design 463
  9.4.1 Rough Design of Lattice 464
  9.4.2 Calculation of Best-Fit Spheres for Subapertures 467
  9.4.3 Simulation and Verification of Lattice Design 469
9.5 Subaperture Stitching Interferometer 472
  9.5.1 Mechanical Configurations of Subaperture Stitching Interferometer 472
  9.5.2 Kinematics of Subaperture Stitching Interferometer 474
9.6 Case Study 477
  9.6.1 Large Flats and Planar Wavefronts 477
  9.6.2 Spherical Surfaces 488
  9.6.3 Aspheric Surfaces 491
9.7 Future Development of Subaperture Stitching Interferometry 495
  9.7.1 Non-null Subaperture Stitching Test 496
  9.7.2 Null Subaperture Stitching Test 496
  9.7.3 Near-Null Subaperture Stitching Test 500
Appendix 9.A Derivation of the Linearized Configuration Optimization Subproblem 503
Appendix 9.B Block-Wise QR Decomposition Procedure for Linear LS Problem 506
References 507

10 Phase Retrieval In Situ Testing of Large-Middle Optical Surfaces 511
10.1 Introduction to Phase Retrieval Technology 511
  10.1.1 Significance of Phase Retrieval In Situ Testing 511
  10.1.2 Application of Phase Retrieval Method 512
  10.1.3 Theory of Phase Retrieval Algorithm 513
10.2 Basic Principle and Algorithm for Phase Retrieval Optical Testing 514
  10.2.1 Principle of Phase Retrieval Optical Testing 514
  10.2.2 Diffraction Computation for Optical Field Propagation 517
  10.2.3 Phase Retrieval Algorithm for Surface Figure Testing 519
10.3 Phase Retrieval Testing of Spherical Wavefronts 524
  10.3.1 Measurement Setup 524
  10.3.2 Measurement of Large Diameter Spherical Surface 524
10.4 Subpixel Phase Retrieval Testing 528
  10.4.1 Principle of Subpixel Phase Retrieval Testing 529
  10.4.2 Design of Subpixel Intensity Constraint Function 531
  10.4.3 Subpixel Phase Retrieval Testing Experiments 533
10.5 Aspheric Phase Retrieval 535
  10.5.1 Aspheric Departure 535
  10.5.2 Characteristic of Aspheric Defocused Field 536
  10.5.3 Measurement Plan for Aspheric Phase Retrieval 539
  10.5.4 Aspheric Phase Retrieval Algorithm Design 541
  10.5.5 Testing of a 170 mm Aperture Parabolic Surface 543
  10.5.6 Phase Retrieval Testing of Aspheres Using Paraxial Conjugates 547
10.6 High Dynamic Range Phase Retrieval 550
  10.6.1 High Dynamic Range Algorithm 550
  10.6.2 Parametric Conjugate Gradient Method 552
About the Author

Professor Li Shengyi was born in 1946. He received his BS and MS degrees in Mechanical Engineering from Central South University and Zhejiang University, China, in 1968 and 1981, respectively. He was the dean of the College of Mechatronic Engineering and Automation, and is currently a professor with the National University of Defense Technology (NUDT). He has been dedicated to research on ultra-precision machining technology for over three decades. He won second prize in the National Award for Technological Invention competition as the first contributor. He is the chief scientist of the National Basic Research Program of China (“973” Program). He has published more than 100 papers and 7 books. He holds more than 50 Chinese patents.

Professor Dai Yifan was born in 1966. He received his BS degree in Mechatronic Engineering from NUDT in 1988, and his PhD degree from Moscow State Aviation Institute, Russia, in 1995. He was the head of the Department of Mechatronic Engineering, and is currently a professor with NUDT. His research interests include ultra-precision machining, optical machining, and testing. He won the second prize in the National Award for Technological Invention as the second contributor. He is also the winner of the National Hundred, Thousand and Ten Thousand Talent Project. He has published more than 100 papers and 5 books. He holds about 40 Chinese patents.
Foreword

The precision engineering research team at the National University of Defense Technology under the leadership of Professor Li Shengyi has existed for 32 years. This team is one of the super top teams within the domestic precision machining area. As they put forward, “Reach the acme of perfection; Refine on; The pursuit of excellence” precision culture spirit, they devote to strive to build a ultra precision engineering research “dream team.”

Ultra precision machining is taking accuracy as a target and challenges the limit of manufacture accuracy. “Refine on” means to establish one kind of spirit with a never-ending challenge limit, not only in machining accuracy but also in all aspects of it. Since the beginning of 2000, their team has focused on basic research of ultra precision optical processing method and obtained the support of two National Key Basic Research Projects of the People’s Republic of China. This book summarizes their research achievements. The book received a warm welcome from domestic scholars. I sincerely hope that the English version will be welcomed from overseas colleagues, and also hope that our Western counterparts get better grades.

Shengyi Li
The optical aspheric mirror is realized by increasing the high-order curvature rate on the usual spherical mirror surface. It has many incomparable advantages to the spherical mirror, such as that spherical aberration in the light propagation process can be eliminated and that the accuracy of focus and calibration can be improved. By increasing the number of independent variables, aspheric lenses increase the freedom of aberration correction as well as the freedom of system design. The optical system that uses aspheric design can correct aberrations, improve image quality, expand the field of view, increase the role of distance, reduce the loss of light energy, thereby obtaining high-quality optical characteristics while staying small in small and design. The optical aspheric system has been widely used in aviation, aerospace, defense, and high-tech civilian areas.

The Precision Engineering Laboratory of National University of Defense Technology (NUDT) was established in 1981. For three decades, our research has focused on ultra-precision machine tools design, processing arts for ultra-precision turning, grinding and optical polishing, large and medium-sized and micro optical components manufacturing, MEMS and Microsystems, and so on. Since 2000, we have embarked on the new technology research of optical aspheric processing and measurement, especially on the basic theory research supported by two of National Important Foundation Research Project of the People’s Republic of China. A lot of progress has been made by our team, therefore we compiled the main content of our research results as the book, *New Technology for Manufacturing and Measurement of Large and Middle-scale Aspheric Surfaces*, which was published by the National Defense Industry Press (NDIP) in 2011 in Beijing, China. This book is an English version translated from the Chinese version, with a few amendments.

This book consists of two parts. The first part is concerned with new technology of manufacturing from Chapter 1 to Chapter 6, and the second part is for new technology of measurement from Chapter 7 to Chapter 11.

The main contents in the first part include:

The first chapter, a comprehensive description of the modern optical aspheric mirror processing technical is carried out, including the require of modern optical systems for aspheric lens; the aspheric optical elements manufacturing characteristics; their definitions, features, and
implementation methods of ultra-smooth surface processing, the classic polishing, the modern CNC polishing and the Controllable Compliant Tools (CCT) polishing methods.

The second chapter introduces the basic theory based on subaperture processing of optical aspheric lens, including mathematical analysis and modeling methods of aspheric processing, linear and polar axis scanning processing theory and technology, the spectral characteristics of optical aspheric figuring errors, based on maximum entropy polishing principle. This chapter’s theoretical basis of universal significance as a deterministic polishing processing, processing various types of optical aspheric lens will play a guiding role.

The third chapter introduces the Computer Controlled Optical Surfacing (CCOS) technology with small tool, which is as a bi-rotation polishing pad, including dwell time algorithms and analysis; the removal function modeling under the edge effect; the small-scale manufacturing error of the optical surface causes and correction method; and the CCOS processing experiment of a parabolic mirror as an example.

The fourth chapter introduces the ion beam figuring (IBF) technology, including its basic principles; the removal function theoretical modeling and experimental, small-scale error evolution during IBF processing; the theoretical and experimental research of IBF machine tools. Finally, CVD SiC plane mirror, glass spherical mirror, and a parabolic mirror as examples are introduced.

The fifth chapter introduces the magnetorheological finishing (MRF) technology. First, it introduces the MRF’s history and basic principles, including the material removal mechanism and mathematical model, and the design and analysis of MRF machine tool. Second, it introduces some of the theoretical and experimental research results and experience of MRF, such as MRF polishing fluid and its performance test, the processing parameter optimization method of MRF process, and the surface figuring technology by MRF for plane, spherical, and a parabolic mirror. Finally, the magnetic fluid jet polishing technology is also introduced.

The sixth chapter introduces the evaluation method for deterministic optical processing error. First introduced is the commonly used optical processing error evaluation method, and second, optical processing error evaluation research, including the use of wavelet transform combined with the characteristic curve of the power spectral density optical processing local error evaluation method, based on the Harvey-Shack method. Finally, we present the optical scattering theory machining error evaluation method, based on the analysis of the optical properties of the band error evaluation method, and so on.

The main contents in the second part include:

The seventh chapter introduces the basic concepts and characteristics of large and medium-sized optical mirror measurement techniques in manufacturing. This chapter is a brief description for the wider application of several measurement techniques, including coordinate measuring technology, a variety of interferometric techniques, computer generated hologram (CGH) technology, phase recovery technology, as well as sub-surface quality detection technology.

The eighth chapter introduces the optical and the aspherical lens coordinate measuring technology. First, it introduces the status and characteristics of the optical aspherical lens coordinate measuring technology in manufacturing, as well as typical measurement solutions and measurement systems; two kinds of optical coordinate measuring system: Cartesian coordinate measuring system and swing-arm polar measurement coordinate system, as well as the key technologies involved in these two developed systems.
The ninth chapter introduces the research subaperture stitching measuring method and system based on interferometry. In principle, the stitching measurement methods can be used to zero test, and also can be used to non-zero test. This chapter introduces the key technical issues of the standards-based interferometer, no auxiliary compensation mirror non-zero seat stitching measurement.

The tenth chapter introduces the phase recovery measuring method and system to study and explores it for in situ measurement in the manufacture processing. Phase recovery is a non-interference measurement method; using the CCD camera and a simple optical system, it only needs hardware utilization the light wave field diffraction model and algorithms to measure the surface-shape error of the measured mirror. This process is less sensitive to the environment.

The eleventh chapter introduces the subsurface quality measurement and assurance technology. This chapter introduces the caused mechanism of subsurface damage by grinding, lapping, and polishing process, measurement techniques and characterization methods, the spot test method by MRF, and the HF acid differential chemical etch rate test method as well as subsurface quality assurance in experimental studies.

The contents of this book came mostly from research by the teachers and students in our laboratory, and also used as references the results of previous studies and experience of the others. We strive to give detail of all the references, but any errors are solely ours.

Because the new methods and theories of large and medium-sized optical aspherical lens manufacturing developed rapidly, some of the new technologies and developments were not available to conduct in-depth research, so we offer our regrets about that. In addition, due to the limited conditions of our laboratory, especially involving large optical parts processing opportunities and capabilities, we hope that we covered the basic theories and methods in our book and that it plays a valuable role in further developments and experimentation for our readers.

Professors Shengyi Li and Yifan Dai organized the book and edited it. The first part of the book was contributed by Changjun Jiao, Xusheng Zhou, Guilin Wang, Xuhui Xie, Lin Zhou, Xiaoqiang Peng, Feng Shi, and Zhi Yang. The second part of the book was contributed by Shanyong Chen, Lide Jia, Ziqiang Yin, Xiaojun Hu, and Zhuo Wang.

Finally, we extend special thanks to all the staff of our research team, as well as all graduate students. It is their hard work that made the contents of this book into a system, and it is also their hard work that helped us to translate it from Chinese into English. Special thanks to the National Defense Industry Press and Wiley Press. Thanks to their strong support, the publication of this book was very smooth.

Shengyi Li
1

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
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 m² 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 m²/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 m² (made up of 18 hexagonal sub-mirrors), and its optical manufacturing capability is higher than 6.0 m²/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 m² of its area, is planned to be launched in 2018, with the manufacturing capacity of its optical components rising to an amazing 240 m²/year. However, at present, the processing capacity for the biggest mirrors of the world is less than 50 m²/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 light-weight, 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 \( \Delta \theta = \frac{1.22 \lambda}{D} \), 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/m². 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>
<thead>
<tr>
<th>Material parameters</th>
<th>Be</th>
<th>Si</th>
<th>Al</th>
<th>Cu</th>
<th>Mo</th>
<th>SiC</th>
<th>SiO₂</th>
<th>So-115 M</th>
<th>Zerodur</th>
<th>ULE</th>
<th>Expect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, $10^3$ kg/m³</td>
<td>1.85</td>
<td>2.3</td>
<td>2.7</td>
<td>8.9</td>
<td>10.2</td>
<td>3.05</td>
<td>2.2</td>
<td>2.5</td>
<td>2.5</td>
<td>2.21</td>
<td>Low</td>
</tr>
<tr>
<td>Modulus of elasticity E, GPa</td>
<td>280</td>
<td>157</td>
<td>69</td>
<td>115</td>
<td>325</td>
<td>390</td>
<td>70</td>
<td>92</td>
<td>92</td>
<td>67</td>
<td>High</td>
</tr>
<tr>
<td>Specific stiffness, E/10⁶ m</td>
<td>15.1</td>
<td>6.8</td>
<td>2.7</td>
<td>1.3</td>
<td>3.2</td>
<td>13</td>
<td>3.2</td>
<td>3.7</td>
<td>3.7</td>
<td>3.1</td>
<td>High</td>
</tr>
<tr>
<td>Thermal conductivity, W/mK</td>
<td>159</td>
<td>160</td>
<td>220</td>
<td>400</td>
<td>145</td>
<td>185</td>
<td>1.38</td>
<td>1.2</td>
<td>1.67</td>
<td>1.3</td>
<td>High</td>
</tr>
<tr>
<td>Coefficient of thermal expansion, $10^{-6}$ K⁻¹</td>
<td>11.4</td>
<td>2.5</td>
<td>23.9</td>
<td>16.5</td>
<td>5</td>
<td>2.5</td>
<td>0.55</td>
<td>0.15</td>
<td>0.05</td>
<td>0.03</td>
<td>Low</td>
</tr>
<tr>
<td>Coefficient of thermal deformation, $10^{-8}$ m/W</td>
<td>7.2</td>
<td>1.6</td>
<td>11</td>
<td>4.1</td>
<td>3.5</td>
<td>1.4</td>
<td>40</td>
<td>12.5</td>
<td>3</td>
<td>2.3</td>
<td>Low</td>
</tr>
</tbody>
</table>

Table 1.1  A variety of optical mirror material performance.
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 abnormal 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:

\[
\delta_{\text{max}} = 2.44 \times 10^{-4} DA^3
\]  

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 \( \mu_F \) 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.

\[
\mu_F = \left( \frac{dR}{dx} \right)_{avg} = \frac{R(x_2) - R(x_1)}{(x_2 - x_1)}
\]  

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 slope of aspheric surface deviating from the closest sphere, is, the more difficulty the aspheric processed is. Foreman points 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...