A review of recent advancements in the fabrication of astronomical telescopes

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Astronomical telescopes have significantly advanced modern deep space exploration thanks to their superior optical characteristics, such as high reflection and low aberration. However, the growing demands for high-efficiency, high-precision fabrication of large-aperture astronomical telescopes present significant challenges to traditional manufacturing techniques. A series of studies have been conducted and reported to address these challenges over the last few decades. Thus, this article comprehensively reviews the fabrication of astronomical telescopes, focusing on four key aspects: materials, diamond turning, grinding and polishing, and coating. Through a detailed overview of the manufacturing processes for astronomical telescopes, this review seeks to provide a systemic solution for the high-precision and high-efficiency manufacture of mirrors to meet specific requirements. Furthermore, the remaining challenges and potential future developments in this field are summarized and discussed.

1. Introduction

A larger aperture for astronomical telescope mirrors improves resolution, but larger mirrors bring machining challenges. High manufacturing precision is crucial for high-resolution, low-aberration imaging. Modern techniques face significant challenges in producing large-aperture, high-precision mirrors [1]. Recent decades have seen advancements in telescopes, with reviews on optical design [2], site selection [3], materials [4], structure design [5], manufacturing [6], and tests [7]. However, less focus has been on high-precision, high-efficiency fabrication of large mirrors . We summarize recent research on materials, diamond turning, grinding, polishing, and coating for telescope mirrors, aiming to provide a systematic overview. Finally, we present a summary and future outlook.

2. Materials for Astronomical Mirrors

With advancements in astronomy and space technology, the requirements for mirror materials are continuously evolving. The primary requirements include low thermal expansion coefficient, high specific stiffness, low density, high thermal diffusivity and good machinability. Table 1 summarizes the properties of materials commonly used in astronomical Mirrors.

Glass, with its low thermal expansion and ease of processing, is ideal for astronomical mirrors. ZERODUR®, a glass-ceramic, is used in major telescopes like Very Large Telescope, Keck, and CHANDRA due to its stability. Borosilicate glass, known for its optical properties, is used in Wolter Type I X-ray telescope mirrors, achieving specific curvatures through precise slumping processes.

Metal mirrors, with higher thermal diffusivity than glass, reach thermal equilibrium faster in space, reducing edge effects and spherical aberrations. They are easier to repair. Aluminum mirrors often use a Ni-P coating for better polishing. Beryllium, used in the James Webb Space Telescope(JWST), releases stress at low temperatures without shape change and is less prone to cracking. Silicon Carbide (SiC) has low thermal expansion, high stiffness, low density, and high thermal diffusivity, but is costly and hard to polish. Fig. 1 shows the world's largest 4-meter SiC aspheric mirror was made by the Changchun Institute of Optics Fine, Mechanics and Physics.(CIOMP).

Table 1. The comparison table of mirror parameter.

Materials	Density (g/cm3)	Elastic modulus (GPa)	Thermal expansion coefficient (1/K)	Specific stiffness (m)	Thermal diffusivity ($10^{-6}m^2/s$)
SiC	3.04	330	2.4	112	75
Beryllium	1.85	287	11.3	155	60
Aluminum	2.7	68	22.5	25.2	97
Glass	2.53	92	-0.09	36.4	0.8
Fused quartz	2.19	73	0.5	33.3	0.53

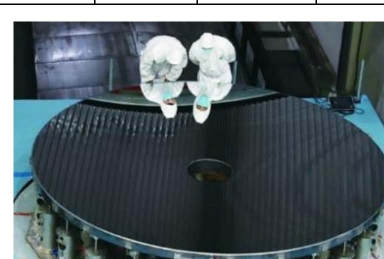

Fig. 1 4-meter SiC aspheric mirror.

3. Ultra precision turning for astronomical telescope

Ultra-precision turning creates precise optical surfaces, minimizing form errors and achieving acceptable surface roughness for high-performance optical systems [8]. Clamping errors in large telescopes can affect machining quality. Cyril Bourgenot et al. [9] used Finite Element Analysis to reduce fixture weight and improve stiffness. Ho-Sang Kim et al. [10] used a special chucking device to minimize elastic deformation. They compensated machine axes errors in real time with a fast tool servo and on-machine measurement and achieved a form accuracy of 0.7 μm peak-to-valley error for 620 mm diameter mirrors

Traditional ultra-precision turning surfaces exhibit serious diffraction in the visible light band. Surface roughness is key to diffraction effects [11]. Experiments show diffraction spot distribution relates to three-dimensional surface morphology [12]. Tomov et al. [13] classified factors affecting roughness, waviness, and surface shape accuracy by spatial wavelength. Roughness is a derived value (Fig. 2). Research suggests developing mathematical models to predict roughness profile parameters (R-parameter) based on kinematical–geometrical copying.

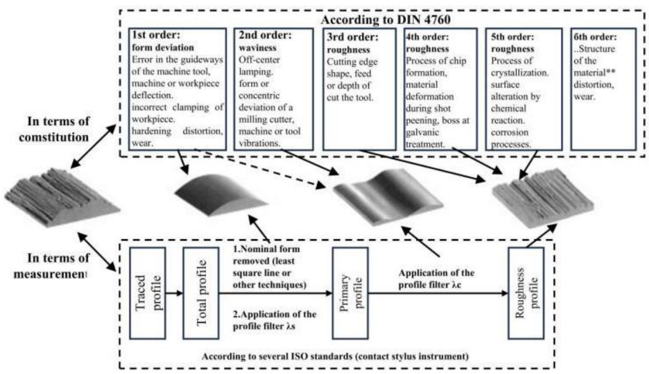

Fig. 2 Different orders of influencing factors on form error, waviness and surface roughness.

X-ray mirrors using total reflection require super-smooth surfaces due to the short X-ray wavelength. Electroless nickel is ideal for soft X-rays of a few nanometers wavelength. Kwon Su Chon et al. [14] examined X-ray mirror fabrication using SPDT with electroless nickel on flat aluminum alloy. Surface roughness was nearly independent of cutting speed and depth of cut (1-3 μm). However, roughness increased when the depth of cut was less than 0.5 μm, and surface quality degraded at feed rates below 0.5 μm/rev. A surface roughness of 0.95 nm rms was achieved.

4. Grinding and polishing

For space-based telescopes, the aperture size is constrained by the diameter and payload capacity of the launch vehicle. Consequently, monolithic mirrors typically do not exceed eight meters in diameter. To overcome this limitation, segmented mirror designs are employed. The JWST exemplifies this approach, utilizing a segmented primary mirror to achieve a larger effective aperture [15,16], as shown in Fig. 3. Its primary mirror is composed of 18 hexagonal segments made of beryllium.

The grinding and polishing of the mirrors for the JWST were carried out by Tinsley Laboratories. Early in the grinding process, the surface shape is measured using Tinsley's large Coordinate Measuring Machine (CMM). Later in the grinding process, an optical surface map is created using the Scanning Shack-Hartmann System (SSHS) (Fig. 4). During polishing, a visible interferometer with a Computer Generated Hologram (CGH) is employed for surface characterization.

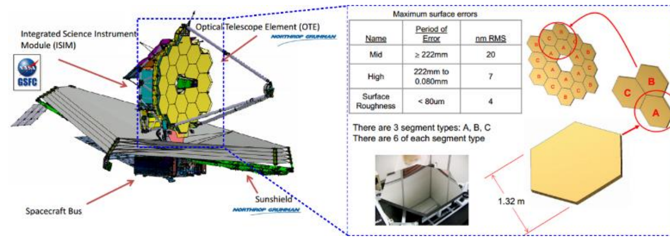

Fig. 1 JWST [15,16] segment types and surface accuracy requirements.

For telescopes like Thirty Meter Telescope (TMT) and Extremely Large Telescope (E-ELT), stressed-mirror polishing is used [17,18]. The aspheric surface is roughly shaped, deformed into a spherical shape under stress for polishing, then returns to its aspheric shape once stress is released. After manufacturing, the mirror is cut into hexagonal segments and undergoes ion beam figuring for a high-precision surface, avoiding the turned-down edge phenomenon. Nanjing Institute of Astronomical Optics & Technology (NIAOT) has developed a Stressed Mirror Continuous Polishing technique polishes over three segments simultaneously, enhancing production efficiency [19]. Using an Linear Variable Differential Transformer [20], it achieves 1.12 μm PV and 0.23 μm RMS accuracy on 8-meter off-axis mirrors.

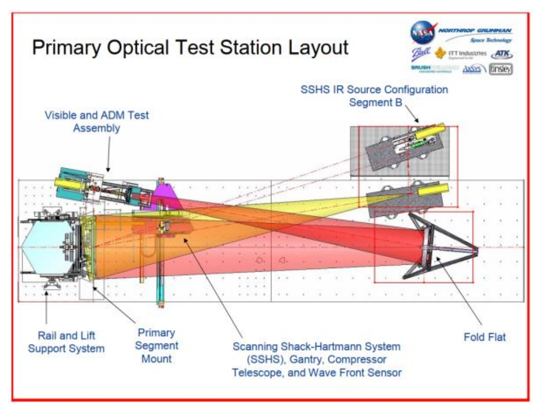

Fig. 4 Primary Optical Test Station at Tinsley for the JMST [15].

D. Walker et al. developed a novel process-chain to produce eight 1.4 m hexagonal segments [21]. Mirrors are initially shaped using the Cranfield University BoXTM ultra-precision grinding machine, inducing subsurface damage up to 10 μm deep, which is removed during polishing [21]. Bonnet polishing technology, proposed by the University of London and Zeeko Company, uses an inflatable airbag with a spherical crown and a polishing die. The airbag adapts to curved surfaces, suitable for rotating aspheric and free-form surfaces. Zeeko IRP1600 CNC polishing machine uses re-circulated cerium oxide slurry for polishing, form correction, and smoothing. Different bonnet sizes are used for various stages, with adjustments for edge polishing [22]. OpTIC-Glyndŵr integrated the Zeeko IRP1600 with a 10-meter high test tower for in-situ testing (Fig. 5) [21]. A linear profilometer and high-resolution on-machine stitching interferometer are used for local inspection of the mirror's shape profile and edges.

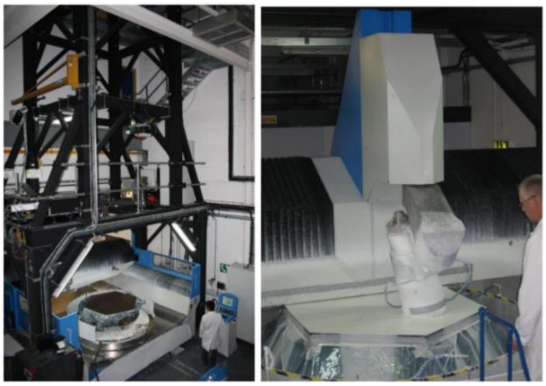

Fig. 2 Zeeko IRP1600 polishing machine and Optical Test Tower [21].

The primary concept of computer-controlled optical surfacing (CCOS) is to transform qualitative measurement and processing into quantitative ones [23]. The equipment uses a rigid tool smaller than the workpiece. Based on the difference between measured surface data and the ideal target, appropriate polishing parameters are selected. A control model and dwell time function are generated [23]. The tool's path, rotational speed, pressure, and dwell time are computer-controlled to correct surface shape errors and improve precision. CCOS is used in fabricating the 25-meter primary mirror segments of the Giant Magellan Telescope (GMT). Laps ranging from 4 to 40 cm are used, with 4 cm laps for final polishing and edge correction (Fig. 6). A rigid conformal tool with a non-linear visco-elastic filler ensures close contact and adapts to aspheric shapes [24]. High-frequency oscillation increases material removal, achieving a surface roughness below 10 Å.

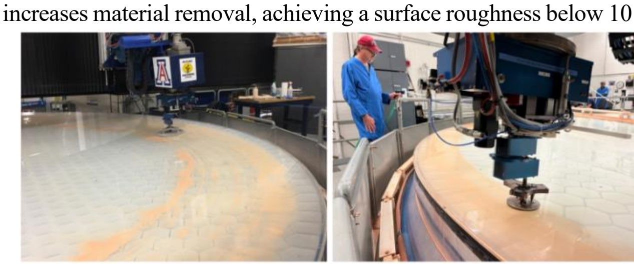

Fig. 3 GMT Segment 3 being polished with a 40 cm pitch lap at left and a 10 cm lap at right. Both laps are driven by the same orbital polisher [25].

Materials with low coefficients of thermal expansion, such as silicon carbide (SiC), ULE®, and Zerodur®, are widely used in space-based telescopes. SiC is noted for its high specific stiffness and dimensional stability [26]. To meet precision polishing requirements for large-aperture optical elements, CIOMP combines CNC generating, stressed lap grinding/polishing, CCOS, and Magnetorheological Finishing (MRF) polishing (Fig. 7) [26]. This approach achieves surface metrics of 15.2 nm RMS shape error, 6 nm RMS mid-spatial frequency (MSF) error, and 1 nm RMS roughness on a 4-meter SiC substrate [26]. Core technologies include a new MRF machine based on a robotic arm and a low-temperature silicon PVD cladding technique. The stressed lap adapts to curvature variations, allowing larger material removal and reducing mid-to-high frequency errors [27]. CIOMP's MRF machine, with a rationally laid-out magnetorheological fluid cycle system, shows excellent flexibility and scalability for mass production [28,29]. SiC materials are prone to porosity and defects, mitigated by high-density cladding. A 10–20 µm-thick silicon cladding layer enhances surface accuracy. CIOMP's test data fusion technique combines data from swing arm profilometry, CGH null interferometry, and phase deflectometry for precise CCOS guidance.

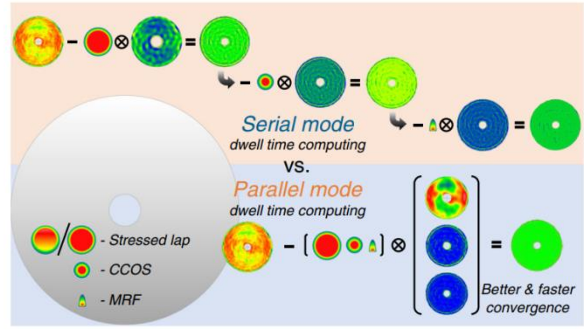

Fig. 4 “Parallel calculation and serial run" diagram [26].

X-ray telescopes study astrophysical phenomena like star formation, black hole activity, and gas expansion after stellar explosions. Their performance depends on the manufacturing quality of substrate mirrors. X-rays have high penetrability and short wavelengths, so "grazing incidence" techniques are used to enhance reflectivity. The smoother the mirror, the closer the reflectivity to the theoretical value. Manufacturing methods include direct polishing [30,31], replication [32], forming, bent silicon wafer methods, and single-crystal silicon slicing.

Replication transfers surface features using high-precision molds [33]. Nickel electroforming and aluminum-based epoxy replication are common. Nickel electroforming involves coating a mold with a reflective layer, immersing it in a nickel electroplating bath, and separating the nickel layer to obtain a reflective mirror. This method reduces costs and has been used in telescopes like BeppoSAX and Apollo [34]. Aluminum-based epoxy replication bonds an aluminum sheet to a glass mold with epoxy resin, producing lightweight mirrors used in ASTRO-E and ASTRO-H [32].

Thin thermally shaped replication heats thin glass to conform to a mold, creating high-precision mirrors. Direct thermal shaping contacts the convex mold for high accuracy, while indirect shaping allows complex molds but requires addressing bubble issues. This cost-effective method is suitable for mass production and has been applied in telescopes like Athena [35].

5. Coating

The coating materials for astronomical reflectors are crucial for enhancing optical performance and observational capabilities. Reflector coating technology has advanced significantly, with key requirements including high reflectivity, durability, thermal stability, and mechanical strength. Common techniques include PVD, CVD, ion plating, and chemical plating. Materials like aluminum, silver, gold, and multilayer dielectric films are frequently used. Aluminum coatings have high reflectivity in the visible and near-ultraviolet regions but lower reflectivity for infrared light. They are used in the DUV and VUV spectral ranges, with improved reflectivity using protective layers like LiF, MgF2, and AlF3. Aluminum coatings are used on the Hubble Space Telescope and the James Webb Space Telescope. Silver has very high reflectivity in the visible and near-infrared regions but requires a protective layer to prevent degradation. Suitable protective materials include metal oxides and nitrides. Optimized silver-based coatings achieve over 95% reflectivity and are used in the TMA telescope of the Jena Spaceborn Scanner. Gold is excellent for infrared and far-infrared regions and does not require a protective layer due to its chemical stability. Gold coatings are used in the JWST. Multilayer dielectric films, like Mo/Si and Sc/Si, enhance reflectivity and broaden the spectral range, achieving up to 40% reflectivity in the 20-50 nm range. SiC and B4C are ideal for broadband reflectors in the extreme ultraviolet region due to their high reflectance and thermal stability. Single-layer SiC and B4C coatings are simpler to prepare and more durable. Amorphous silicon layers, deposited on diamond-turned metal surfaces using magnetron sputtering, offer low roughness and high reflectivity for ultraviolet and visible spectrum applications. These layers can achieve a root-mean-square roughness of less than 0.5 nm after polishing with magnetorheological fluids, enhancing optical component performance.

6. Ultra precision turning for astronomical telescope

This article summarizes recent advancements in the fabrication of astronomical telescopes, focusing on materials, diamond turning, grinding and polishing, and coating. Despite substantial progress, significant challenges remain. The roadmap for next-generation telescopes includes optimizing coating materials, AI-enhanced ultra-precision diamond turning, and large-scale manufacturing and testing.

(a) AI-enhanced ultra-precision diamond turning: SPDT with real-time feedback control systems will enhance precision and efficiency. AI-driven diagnostics in SPDT will reduce production time and cost, overcoming limitations in processing large-sized telescopes.

(b) Large-scale manufacturing and testing: Technologies for manufacturing and testing optical components must address the demand for processing more sub-mirrors. Ground-based telescopes use hundreds of sub-mirrors, but mass production techniques are still developing. High-precision and rapid testing technologies for large-aperture optical components are urgently needed. Integrated processing and testing equipment will accelerate iteration speed. For large-aperture primary mirrors composed of sub-mirrors, edge effects are significant. Regular polishing trajectories can lead to mid-spatial frequency errors. Breakthroughs in suppressing and eliminating edge effects and mid-spatial frequency errors will drive progress in optical component manufacturing.

(c) Optimization of coating materials: Future mirror materials will focus on higher performance and efficiency, especially in terms of lightweight, thermal stability, and durability. Emerging materials like Silicon Carbide (SiC) and beryllium-aluminum alloy meet high-precision observation needs. 3D printing technology offers design flexibility for lightweight mirrors with complex geometries. Advances in materials with high thermal conductivity and good machinability will improve performance and drive space observation technology. Coating materials like aluminum, silver, gold, and alloys, with high reflectivity and excellent optical properties, are crucial. Multilayer dielectric coatings enhance reflectivity and reduce light loss. Surface treatment techniques like chemical plating and Physical Vapor Deposition enhance durability and corrosion resistance.

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