applied optics

Design and fabrication of lightweight additively manufactured mirrors for aviation

Songnian Tan,[1,2,3] Quanchao Li,[1,2,3] Yongsen Xu,[1,3] Honghai Shen,[1,3] Yanping Cheng,[1,3] Ping Jia,[1,3] and Yulei Xu[1,3,*]

[1]Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, 3888 Southeast Lake Road, Changchun, 130033, China
[2]University of Chinese Academy of Sciences, Yuquan Road, Beijing, 100049, China
[3]Key Laboratory of Airborne Optical Imaging and Measurement, Chinese Academy of Sciences, 3888 Southeast Lake Road, Changchun, 130033, China
*Corresponding author: yuleixu@ciomp.ac.cn

Received 8 December 2021; revised 13 February 2022; accepted 17 February 2022; posted 17 February 2022; published 14 March 2022

This paper proposes a design process for additively manufactured mirrors. A central support aspheric mirror and tripod support structure were manufactured via selective laser melting. To achieve substantial weight reduction, an additively manufactured body-centered cubic lattice structure was used in the mirror design. Simulation analysis showed that the mirror had good rigidity. Single-point diamond turning was applied to obtain an optical quality mirror. After assembly, the rms surface shape accuracy of the mirror was 0.069λ (λ = 632.8 nm). The surface roughness (Ra) of the additively manufactured metal mirror was 8.125 nm. These findings provide a strong theoretical basis and technical support for the preparation and application of lightweight metal mirrors.

https://doi.org/10.1364/AO.450663

1. INTRODUCTION

With the continuous development of optical measurement and remote sensing, more stringent requirements have been established for the weight, volume, preparation speed, and environmental adaptability of optical components [1,2].

Silicon carbide material is currently the preferred material for aerospace mirrors, with the best specific stiffness and stability [3]. However, the processing route of silicon carbide material is cumbersome, and the entire processing cycle is long. Therefore, rapid production is unachievable. In addition, the aluminum alloy material is still the main material of the load frame structure. When a silicon carbide mirror is mounted on a support structure, multiple material transitions are required, which increases the difficulty of design and processing. Meanwhile, to reduce the sensitivity of the optical lens to temperature changes, the aluminum alloy mirror can be manufactured from the same material as the support structure [4]. Aluminum alloy materials are easy to manufacture at a low cost. To meet the need for rapid preparation of small and medium aperture mirrors, metal mirrors have become an option for the optical components of aeronautical optical equipment [5]. Compared to other mirror-preparation materials, the specific rigidity (E/ρ) of metal mirror materials is lower [6]. It is therefore necessary to improve the rigidity of mirrors in the structural design phase. Current aviation airborne photoelectric remote sensing equipment has strict requirements in terms of the volume and weight of the optical system. Achieving a reasonable balance between weight and rigidity remains a technical challenge in the design of metal mirrors.

An advantage of additive manufacturing technology is that it can realize complex lightweight structures, reduce weight, and achieve high structural rigidity [7]. It thus can effectively resolve the conflict between weight and stiffness to meet the need in terms of practicality and speed more effectively [8]. Consequently, additively manufactured metal mirrors have received increasing attention [9,10].

The lightweight design of the additively manufactured mirrors is one of the highlights of the previously reported literature, and relevant scholars have conducted considerable research on this topic. The one-piece mirror structure [11], the internal flow channel type mirror [12], and the honeycomb design sandwich structure mirror [13] are some of the structures that are relatively easy to fabricate by additive manufacturing. To achieve a highly lightweight state, the lightweight structure form inside the mirror is particularly important [14]. The hollow lattice structure is a unique lightweight structure that is used for additive manufacturing [15]. It can achieve a perfect balance among engineering strength, function, durability, statics, and dynamics. The hollow lattice is designed and manufactured by periodically replicating a large number of individual cells. Its mechanical properties, such as strength, can be adjusted by altering the relative density of the lattice and the shape and size of the cell [16]. It is thus an ideal lightweight method.

Post-processing of additively manufactured metal mirror substrates is critical for mirror fabrication. The internal stress of the additively manufactured mirror substrate can be released through a suitable heat treatment process to ensure good dimensional stability [17]. Additively manufactured mirror substrates have good processability and can directly perform optical processing such as single-point turning and polishing [18–20].

This paper introduces a method to design and fabricate an additively manufactured mirror with a lightweight lattice structure. The method flows from design to preparation with a goal to significantly reduce the weight. According to this premise, the design and preparation of an aspheric mirror were realized. To improve the structural rigidity of the metal mirror and achieve a higher degree of weight reduction, a body-centered cubic lattice structure was used in the lightweight design of the mirror. The optical processing of the mirror was completed using single-point diamond turning (SPDT). Related theoretical research can be performed on the preparation of extremely lightweight additively manufactured metal mirrors.

2. METHODOLOGY

The elements of the mirror and mirror support structure were designed according to input conditions, such as optical indicators and volumetric weight. First, the diameter-to-thickness ratio of the mirror [21] and the support method were determined. Then, according to the lightweight rate index, a lightweight mirror structure was designed. Finally, the rationality of the design of the mirror assembly was determined by analyzing the surface accuracy, natural frequency, and optical processing methods [22]. The design and analysis flow for the additively manufactured mirror are shown in Fig. 1.

A. Diameter-to-Thickness Ratio

The diameter-to-thickness ratio of the mirror affects the accuracy of the surface shape. Yoder [23] conducted a detailed study of a mirror with a circular edge. They determined the relationship between the diameter-to-thickness ratio and the deformation caused by the weight of the mirror itself. The empirical formula for the maximum surface deflection of the mirror is given by

$$\delta = \frac{3(1-\mu^2)\rho g r^4}{16 E t^2}, \tag{1}$$

where r is the diameter, t is the thickness, ρ is the material density, g is the acceleration of gravity, μ is the poisson ratio, and E is the elastic modulus of the material.

B. Support Method

The support form of the mirror was designed by determining its diameter and thickness. A mirror back support, which can reduce space and volume, is the most commonly used support method [24]. The number of support points on the back of the mirror is related to the material of the mirror, the size of the mirror, and the required amount of deformation. When the number of supporting points increases, the distribution of gravity becomes more uniform, which enables better deformation of the mirror. However, an increase in the number of supports will cause problems, such as positioning and assembly difficulties, and increase the mass of the entire component and complex thermal deformation. Therefore, the supporting principle of the mirror is that, under the premise of meeting the requirements of the mirror surface deformation, the smaller the number of supporting points, the more effective it will be. Hall [25] provided a formula to calculate the number of support points N of a circular mirror:

$$N = \left(\frac{1.5 r^2}{t}\right)\sqrt{\frac{\rho g}{E\delta}}. \tag{2}$$

C. Lightweight Structure

Adopting a lightweight design is an effective means to solve the problem of the excessive weight of mirrors, especially for use in aerospace. To reduce the weight of the mirror alone, the back shape of the large-diameter mirror is often designed in

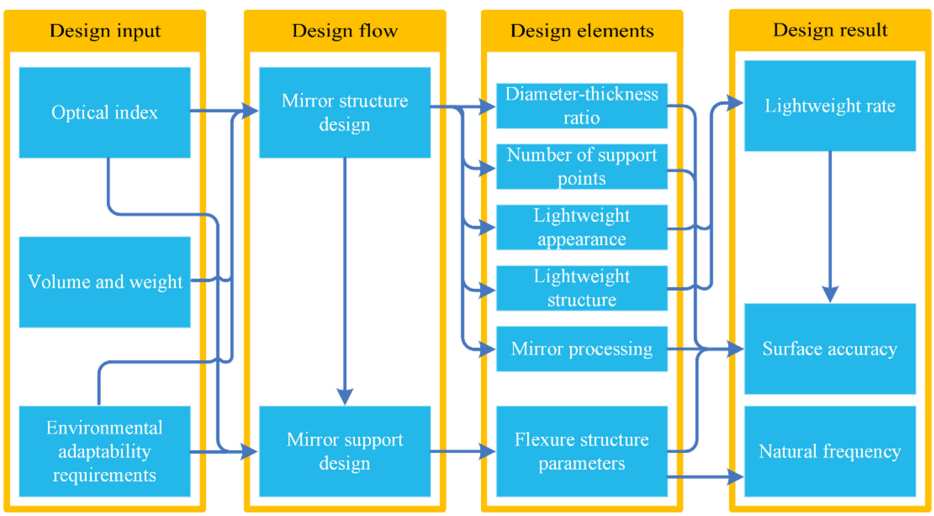


Fig. 1. Design and analysis flow of additive mirror manufacturing.

a specific shape, mainly flat back, concentric circles, nonconcentric circles, cones, double arches, single arches, and other shapes. In comparison, shapes such as nonconcentric circles, double arches, and cones are lighter; however, the corresponding structural rigidity is lower. Therefore, it is necessary to select a reasonable structural form comprehensively in the actual design and application. After determining the shape, an internal lightweight structure is realized through the additive manufacturing method. There are three main structures: hollow sandwich and thin-walled reinforced structures [26], hollow lattice structures [27], and special-shaped topology optimization structures [28].

1. Hollow Sandwich and Thin-Walled Reinforced Structures

These are similar to the closed-back structure in the traditional lightweight structure. With a combination of a thinner panel and thicker core, the panel material bears tensile and compressive stresses under a bending load, and the sandwich structure bears the shear stress and part of the compressive stress.

2. 3D Hollow Structures

This structure type has a high degree of spatial symmetry, which can evenly decompose the external load to ensure the carrying capacity. In areas with high structural strength requirements, the density of the lattice unit is increased, and a hollow lattice unit with high structural strength is chosen. In areas with high weight reduction requirements for structural parts, hollow lattice units with a large lightweight range are added to fulfill the demand for considerable weight reduction. A typical additive manufacturing hollow lattice structure is shown in Fig. 2.

3. Topological Optimization Structure

In a given design field, the optimal material distribution of a part can be achieved. The combination of additive manufacturing and topology optimization involves topology optimization methods to leverage the advantages of additive manufacturing technology. Accordingly, complex structures can be prepared in part manufacturing, and an optimal lightweight configuration can be obtained. The combination of topology optimization and additive manufacturing also fully leverages their respective advantages and realizes the potential for topology optimization.

These three methods are effective in achieving lightweight structures. In terms of design difficulty, hollow sandwich and thin-walled reinforced structures are the simplest structural forms. Meanwhile, topological optimization forms are the most complex, although the obtained structures are more reasonable and rigid. Therefore, choosing a hollow lattice structure as the lightweight structure of an additively manufactured mirror can simplify the design process, while obtaining a high rigidity and lightweight, which can produce better results compared to traditional metal mirrors [29].

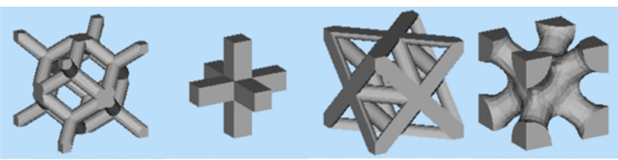


Fig. 2. Lattice structures.

D. Optical Processing

Mirror processing is an important element in mirror preparation. With the wide application of SPDT technology, the aspheric machining of aluminum alloy mirrors has achieved economic benefits and efficiency [30]. The optical mirror surface of an additively manufactured mirror can be directly processed using SPDT [31,32]. Small-diameter mirrors are relatively easy to process by hot-melt adhesive bonding on the fixtures or direct mounting on the SPDT lathe [33]. However, large-diameter mirrors must be designed with reasonable processing fixtures to eliminate the stress caused by the installation during mirror processing.

The design of mirror fixtures must consider the following two points: the stability of the mirror during processing and the installation stress between the mirror and mirror fixtures.

In optical processing, such as high-speed rotation and turning processes as well as mirror polishing processes [34], it is necessary to ensure that external forces do not affect the surface accuracy of the mirror. The assembly process for the mirrors and fixtures adds stress to the structure. It is necessary to ensure that the surface shape accuracy of the mirror changes minimally after the mirror is removed from the mirror fixtures.

3. MIRROR DESIGN AND ANALYSIS

A. Design Input

The optical system of this study has a re-entrant optical structure. The main mirror is a reflecting mirror, and the remaining mirrors are lenses. Compared to a traditional transmission system, the optical aperture of the focusing lens is greatly reduced, and the weight and volume of the optical system are smaller. The main mirror is a typical reflective mirror with a lightweight additive manufacturing structure. The optical system is illustrated in Fig. 3.

The optical index requirements are shown in Table 1. The mirror was aspherical, and a margin of 4.5 mm was set on one

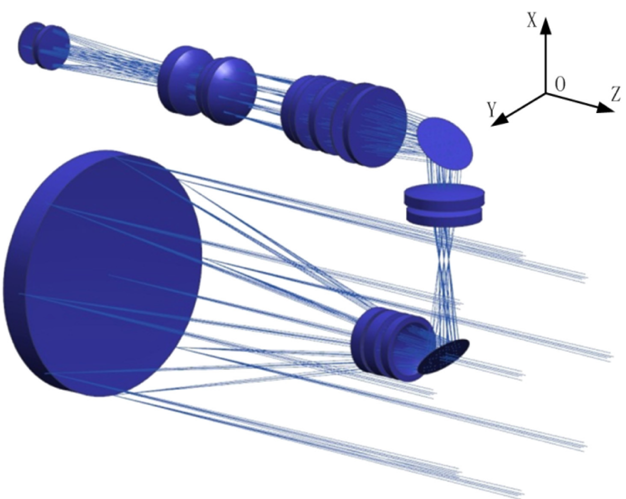


Fig. 3. Optical system.

side. The mechanical structural size of the mirror was determined to be Φ149 mm in diameter. The parameters were inserted into Eq. (1), and the theoretical thickness was determined to be 5.98 mm. To ensure a certain margin, a safety factor of four was adopted, and the thickness of the designed mirror was 24 mm. The parameters, including the diameter and thickness of the mirror, were inserted into Eq. (2), and the number of support points were $N = 0.863$. Therefore, the number of support points was 1, and the center support method was selected.

A centrally supported reflector with a diameter of φ149 was designed. The material used for the mirror fabrication was AlSi10Mg, which is widely used in additive manufacturing [35]. Considering the environmental conditions in which the optical system is located, the structural parts should be as light as possible to ensure appropriate structural performance. Therefore, the design goal for lightweight additively manufactured mirrors is 70%.

B. Lightweight Design of Additively Manufactured Mirrors

Considering the mirror shape, a mirror with a double-arch structure has a higher weight-reduction rate. It is also suitable for centrally supported small-diameter mirrors. The double-arch structure is conducive to adopting a lightweight structure form of additive manufacturing. Through reasonable matching of materials, the reflector can achieve high rigidity. Therefore, a double-arch-shaped structure with a closed-shape structure was selected. On this basis, an internal lightweight structure design was developed.

A lightweight structure was designed inside the arched reflector structure. By appropriately setting the parameters—the layer number, diameter, and cell spacing—of the lattice rods, the target lightweight rate value could be obtained. A regular octahedral body-centered cubic cell structure was used for the lightweight structure. Body-centered cubic structure is a typical crystal structure of metals. Metals and alloys containing this structure exhibit high strength and lattice friction in a wide temperature range and strain state. The body-centered cubic structure, which is a typical lightweight unit of additive manufacturing, can achieve a relatively high support height and lightweight rate. The internal lattice structure was symmetrically distributed. The diameter of the lattice rod was 0.8 mm, the cell spacing of the array was 8 mm, and the lattice structure had two layers. It thus fulfilled the requirements of lightweight manufacturing. Because the reflector was a closed lightweight structure, it was necessary to arrange four powder discharge holes evenly around it to ensure the smooth discharge of the internal powder. The lightweight structure of the mirror (partially hidden) is shown in Fig. 4(a).

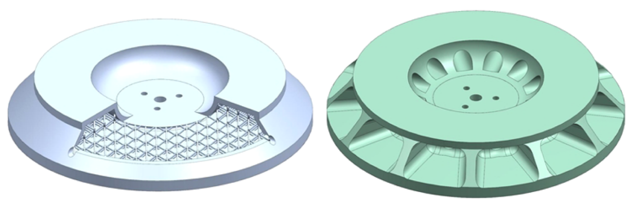
Table 1. Optical Index Requirements

Effective Aperture (mm)	Surface Accuracy Requirements (RMS)	Natural Frequency (Hz)	Optical Band (μm)
Φ140	1/10λ (λ = 632.8 nm)	>200	3.7–4.8

The structure of the traditional aluminum alloy mirror is shown in Fig. 4(b). It has a lightweight structure with peripheral machining. Compared to a traditional aluminum alloy mirror, the weight reduction rate of the additively manufactured mirror was 69.87%, which is an increase of 18%. Considering the errors in the preparation process, the weight reduction rate was also considered to meet the index requirements. The comparison results are listed in Table 2. It can be observed that the mirror that was designed and manufactured using additive manufacturing technology significantly improved the weight-reduction rate. When the diameter of the mirror was increased, a greater amount of weight could be saved, an advantage that became more obvious. The fixed constraint was applied through the position of the mounting hole on the back, and the natural frequency of the mirror was calculated. Table 2 presents a comparison of additively manufactured mirrors and traditional aluminum alloy mirrors, where the additively manufactured aluminum alloy mirrors have higher structural rigidity.

A central flexible support structure was used to support the additively manufactured mirror. The support was a tripod flexible support, as shown in Fig. 5. Being a semi-moving support, tripod support has the advantages of no hysteresis, no friction effect, and no required maintenance. Compared to a traditional bipod support structure [36], a tripod flexible support can provide higher 3D rigidity and is a more suitable structure for center supports. The material was AlSi10Mg, which can ensure structural rigidity. The same material can avoid changing the mirror surface shape due to the difference in the linear expansion coefficient when the temperature changes.

The flexible support consists of three flexible rods that are conical in their spatial arrangement. Any two flexible rods were at the same angle, and they were evenly distributed along the centerline of the cone. Three flexible links were provided on



(a) (b)

Fig. 4. Aluminum mirror: (a) lattice lightweight structure and (b) traditional lightweight structure.

Table 2. Comparison of Additively Manufactured Mirrors and Traditional Aluminum Alloy Mirrors

Name	Material	Mass (g)	Weight Reduction Rate	Modal First-Order (Hz)
Traditional aluminum mirror	6061-T6	484	51.87%	603.55
Additively manufactured mirror	$AlSi_{10}Mg$	303	69.87%	712.57

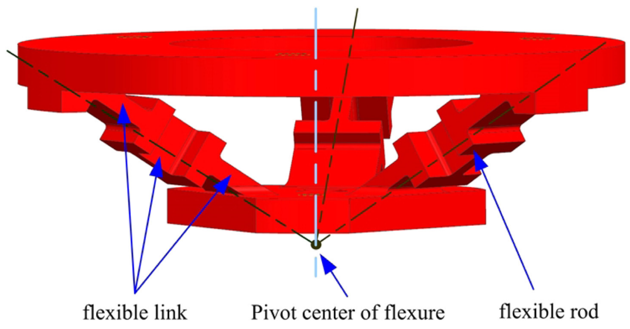


Fig. 5. Tripod flexure.

each flexible rod. The flexible link could use the elastic deformation of the material to transfer movement, force, or energy. Through the deformation of the flexible link, the assembly stress of the mirror and supporting material was compensated, and the high-precision support of the mirror was ensured. The extension lines of the three flexible rods intersected at a point that was the pivot center of flexure. When the neutral surface of the mirror is approximately coincident with the aforementioned point, the influence of the mirror's bending moment due to gravity on the mirror's surface shape accuracy can be reduced. The aluminum alloy mirror could obtain the best surface accuracy without astigmatism [37].

C. Simulation

1. Finite Element Model of an Additively Manufactured Mirror

To improve the efficiency of the optimal design, the model was analyzed. A finite element model of the additively manufactured mirror was established, and its surface shape under the action of gravity was simulated and assessed. The 3D model was imported into the hypermesh for meshing. Features such as the powder discharge hole of the mirror were removed. The grid size had to be set appropriately. The outer mesh size was sparse, which improved the calculation efficiency. In addition, the mesh was divided and refined on the force transmission path of the key parts. Furthermore, the grid of the internal lattice support structure was refined. The mass, center of mass position, and mass distribution of the finite element model should have been as equivalent to the actual structure as possible to reflect the force of the structure accurately, ensure equivalent stiffness, and guarantee the accuracy of the analysis. A four-node hexahedral element was used to divide the finite element model of the mirror. The meshing scenario is shown in Fig. 6. The finite element model of the mirror had 2,309,656 nodes and 10,031,791 elements. The number of nodes on the mirror surface was 4814. The boundary conditions, load size, and acting position were consistent with the actual working state.

2. Surface Accuracy

When the mirror was arranged in the working environment, the factors affecting its surface shape accuracy mainly include the maximum acceleration and the maximum temperature difference of the vibration environment. Both may act on the mirror simultaneously. Therefore, to ensure that the surface shape accuracy of the mirror under the worst focus adjustment

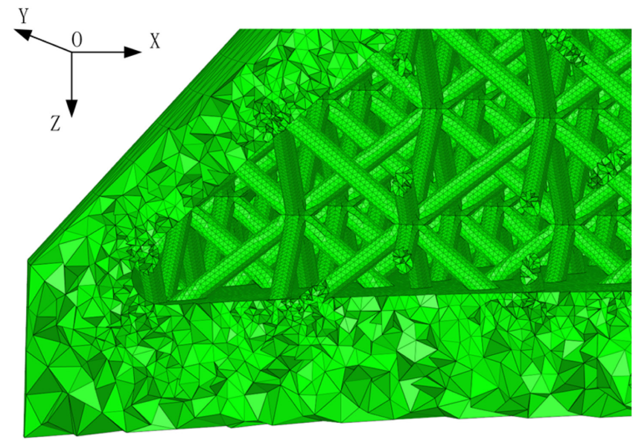


Fig. 6. Finite element mesh model of additively manufactured mirror.

can meet the requirements, the maximum acceleration of 2 g and maximum temperature change of 5°C (under temperature control) are used as boundary conditions to analyze the surface shape accuracy of the mirror.

When the aerial photoelectric payload is imaged externally, the direction of the observation scene changes over time. The direction of acceleration that the mirror receives when it operates also constantly varies. Therefore, it is necessary to analyze the shape accuracy of the mirror in each direction. The optical axis direction of the model was in the z direction. Through finite element analysis, the displacement of all the nodes on the surface of the mirror was determined. Additionally, the initial coordinates and displacement of the mirror surface were input into Matlab software to fit the surface displacement of the mirror. The shape accuracy of the central single-point support mirror under maximum temperature change and maximum acceleration is shown in Fig. 7, where the directions of maximum acceleration are in the X, Y, and Z directions. The first four Zernike items Z1, Z2, Z3, and Z4 were deleted, where Z1, Z2, Z3, and Z4 refer to offset, tilt A, tilt B, and defocus, respectively. These terms for aspheric mirrors can be corrected during the optical system installation and adjustment process, and they are usually removed from the simulation results [28]. The Z direction is the direction in which the surface shape changes the most, and the rms value is 9.00 nm.

3. Modal Analysis

The fundamental frequency of the mirror component not only determines the stability of the mirror after assembly, but also affects the stability of the SPDT process. To ensure sufficient rigidity, the fundamental frequency of the mirror assembly was

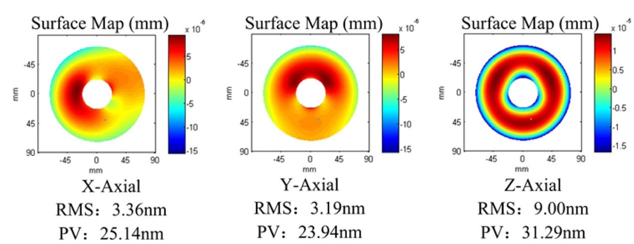


Fig. 7. Shape accuracy of the mirror under the action of gravity.

not less than 200 Hz. The natural frequency vibration mode of the main mirror assembly is shown in Fig. 8. The first-order mode of the mirror assembly is twisted around the X axis, and the natural frequency is 305.8 Hz. Through finite element analysis, it can be preliminarily determined that the flexible support structure of the mirror assembly meets the rigidity design requirements.

D. SPDT Fixture Design

To satisfy the stability of the mirror during processing and eliminate the assembly stress, the SPDT fixture scheme was designed, as shown in Fig. 9. The following measures were taken to ensure optical processing of the mirror.

First, the mirror was connected to mirror fixture 1 through a tripod support structure. Because the tripod support structure had a certain degree of flexibility, it could reduce the stress impact caused by installation.

After the mirror had been installed on fixture 1, it was connected to the SPDT machine through fixture 2. The force transmission path was lengthened to avoid the influence of the vacuum suction of the SPDT machine on the shape of the mirror.

To ensure the stability of the mirror during processing, two layers of hot-melt adhesive were evenly coated on the periphery of the mirror. The gap between the edge of the mirror and the fixtures was less than 0.5 mm, ensuring that the hot-melt glue would not flow to the side of the mirror.

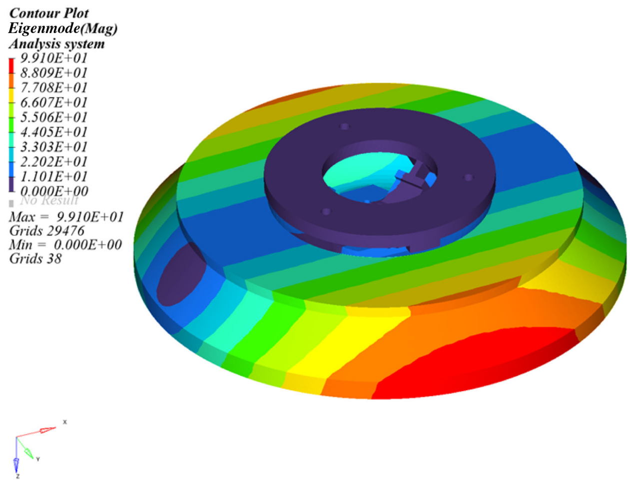


Fig. 8. First-order mode shape of mirror.

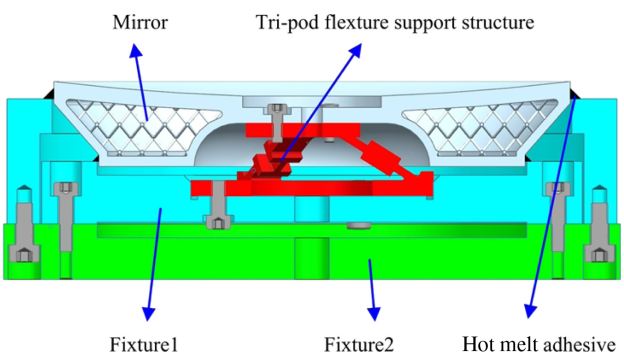


Fig. 9. Mirror assembly scheme under SPDT.

E. Preparation and Testing of Additively Manufactured Mirrors

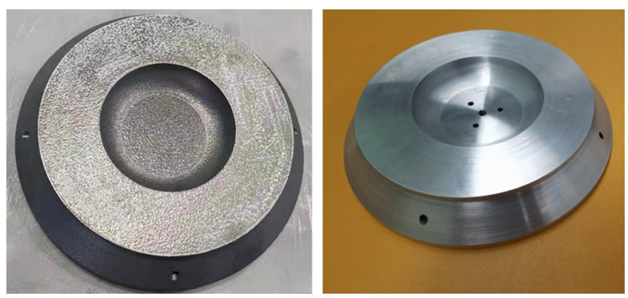
The additively manufactured mirror was fabricated by selective laser melting (SLM) using M290 equipment, which was equipped with a YB-fiber laser with a 400 W laser power. The laser scanning speed and laser spot size are 1050 mm/s and 0.09 mm, respectively, and the scan spacing is set to 0.07 mm. To reduce the residual stress, the interlayer alternate scanning mode is adopted, and the phase angle is selected as 67°. The additively manufactured mirror substrate is illustrated in Fig. 10. In the SLM process, to ensure that the mirror surface had a high density, the mirror surface was oriented downward. The mirror is formed horizontally without adding auxiliary support structures. The mirror was removed from the substrate through a wire-cutting process.

The 3D printed components always possess high inner stress, which affects the stability of the mirror surface accuracy. To eliminate the internal stress of the additively manufactured mirror, heat treatment and finishing were subsequently initiated. The heat treatment method has six steps:

(1) Hot isostatic pressing (HIP). The processing temperature is 510°C ± 5°C, the pressure range is 102 ± 2 MPa, and the hold time is 2 h. After HIP, additive manufacturing of metal mirrors can increase their density [38].
(2) Solution treating. The mirror is placed at 530°C and maintained for 2 h.
(3) Quenching. After solution treating, the mirror is quenched in water within 10 s.
(4) Uphill quench. The mirror is placed in liquid N2 for 30 min. Subsequently, the mirror is submerged in boiling water. Uphill quench is used to balance the residual stress generated during the solid solution treatment.
(5) Age hardening. Finally, the mirror is aged at 177 ± 5°C, and kept for 8 h. Age hardening is required in the subsequent processing.
(6) Thermal cycle treatment. After finishing, a heat cycle treatment is done three times. The temperature range is between −190°C and +160°C, and the temperature change rate does not exceed 2°C/min.

The mirror after finishing is shown in Fig. 10(b). The mounting surface of the support structure was grounded.

To show the lightweight structure of the mirror more clearly, the back of the spare mirror (another one being fabricated simultaneously) was machined to expose the internal lattice structure, as shown in Fig. 11. The internal lattice support structure was



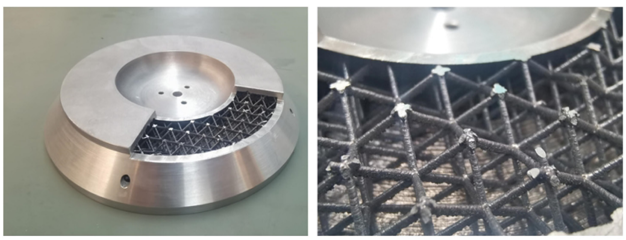
(a) (b)

Fig. 10. Preparation of additively manufactured mirror: (a) as-built state and (b) after finishing.

evenly arranged. The supporting structure was of good quality, and the surface was relatively smooth, without obvious defects. Therefore, the lattice support structure was an ideal internal lightweight structure with low weight and good processing quality.

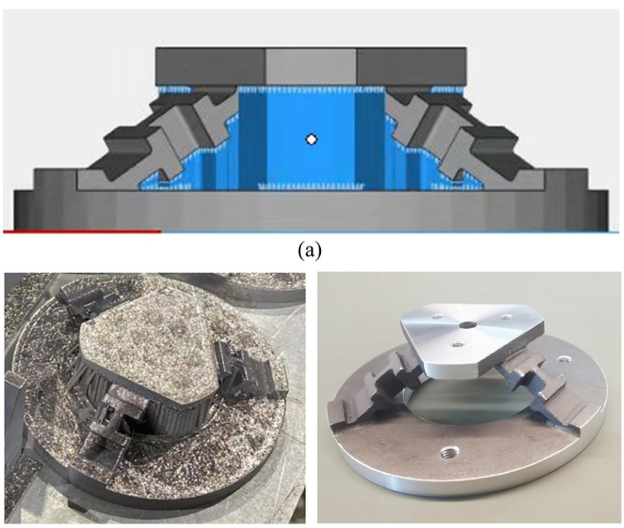
The tripod flexible support structure of the mirror was also prepared by SLM, as shown in Fig. 12. As the tripod flexure structure is partially suspended, auxiliary support structures must be added. The auxiliary support structures are an array of support columns that are thinner on both sides and thicker in the middle, which can be easily removed. All surfaces of the flexible support structure of the mirror were polished to ensure smoothness and the presence of no burrs. The mounting surface had to be ground precisely to ensure that the shape of the mirror did not change after installation. The flatness of the mounting surface was better than 2 μm. The mirror flexible support structure was installed on the mirror support. The flatness of the installation surface of the mirror support was better than 2 μm, ensuring that the maximum cumulative error of the assembly after the installation of the mirror was 4 μm.

After heat treatment, the additively manufactured mirror and flexible support structure were assembled with the fixtures. Then, SDPT was performed. To obtain the ideal surface shape, the turning tool trajectory was compensated during the machining process, as shown in Fig. 13. After the SPDT of the mirror, the surface shape of the mirror was tested.



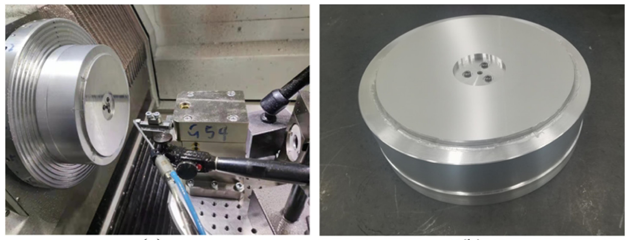
(a) (b)

Fig. 11. Lightweight structure of additively manufactured mirror: (a) internal lightweight structure and (b) lattice rod structure.



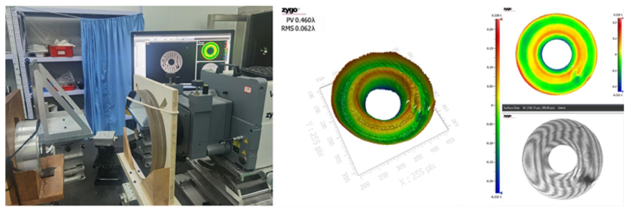
(a) (b) (c)

Fig. 12. Flexible support structure: (a) design model (b) as-built state, and (c) after finishing.



(a) (b)

Fig. 13. Processing of additively manufactured mirror: (a) during SPDT and (b) after SPDT.



(a) (b)

Fig. 14. Mirror test: (a) test equipment and (b) surface accuracy.

A Zygo laser interferometer was used to detect the accuracy of the mirror surface. After the interferometer beam was emitted from the laser, the beam was expanded and collimated. Then, the beams were split by the internal beam splitter, and the two beams of light passed through the fixed mirror inside the interferometer and the external mirror to be tested. The reflected light beams from the two locations converged on the beam splitter to produce interference fringes.

A commonly used detection method for concave parabolic mirrors is to combine an interferometer with an optical plane mirror and to install an F1 spherical lens on the Zygo laser interferometer. The exit beam exits at the focal point of the parabolic mirror. It is reflected on the parabolic mirror to be detected and becomes parallel light, which is perpendicular to the reference plane mirror. It then reflects back to the parabolic mirror and finally enters the interferometer to form interference fringes. The testing equipment is illustrated in Fig. 14.

The surface accuracies of the mirrors in different states are listed in Table 3. After the mirror was disassembled from the fixtures, the surface shape accuracy underwent some changes; however, it was within the allowable range. After the mirror was assembled into the optical system, there was a scant difference in the surface shape accuracy of the bare mirror. The surface shape accuracy was 0.069λ (RMS). The effectiveness of the optical processing fixtures and supporting structure of the mirror was demonstrated.

Table 3. Comparative Summary of the Surface Quality at Different Steps

Process Step	PV	rms	Power
After SPDT	0.460λ	0.062λ	0.158λ
After disassembly from fixtures	0.527λ	0.072λ	0.521λ
After assembly in optical system	0.530λ	0.069λ	0.539λ

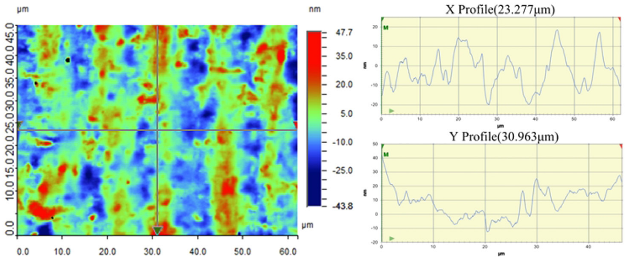


Fig. 15. Surface roughness measurements.

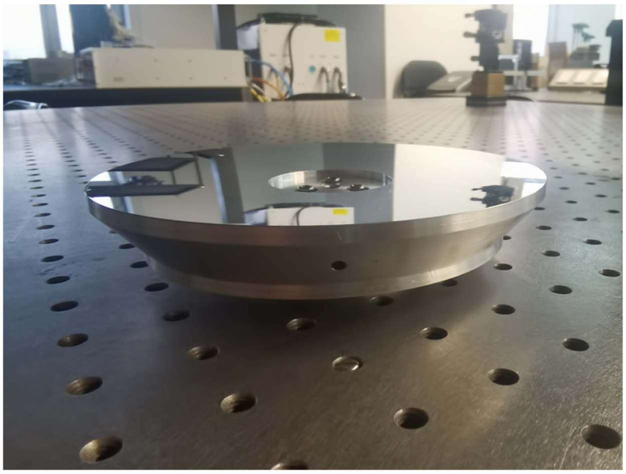


Fig. 16. Additively manufactured mirror.

The surface roughness measurement is crucial to evaluate the surface properties; in addition, the surface roughness of a mirror has a direct impact on the scattered light. Additively manufactured metal mirrors were subjected to 3D surface roughness measurements. The noncontact measurement method of white light interferometry was used for testing. The equipment used was ContourGT-X (Bruker, Billerica, MA, USA), and the measurement range of the equipment was 60 μm × 45 μm. The surface test result is shown in Fig. 15. The surface roughness (Ra) of the additively manufactured metal mirror is 8.125 nm.

The finished highly lightweight additively manufactured mirror is shown in Fig. 16. The successful preparation of the aspheric mirror clarifies the manufacturing process of the additively manufactured mirror to achieve a light weight. It is an effective method to prepare lightweight mirrors.

4. CONCLUSIONS

This paper summarized the design process for lightweight additively manufactured mirrors and presented an analysis of the key design elements. A typical additive manufacturing lightweight structure for aspheric mirror preparation was realized. An octahedral body-centered cubic cell lightweight structure was selected, which achieved a weight reduction rate of 69.87%. The tripod supporting structure was reasonably set up, and the ideal surface shape was achieved through optical processing; the surface shape accuracy was 0.069λ (rms). The Ra of the additively manufactured metal mirror was 8.125 nm. Metal mirrors constitute an innovative direction for additive manufacturing to prepare optical components. This study verified the feasibility of additively manufactured mirrors and lays the foundation for further research on high-precision additively manufactured mirrors. Related methods can be used to prepare mirrors in aerospace optoelectronic payload optical systems. Manufacturing large-diameter metal mirrors has always been a challenge. However, the research theories and results related to this study can be extended to the preparation of such mirrors. The light weight and high rigidity of additive manufacturing metal mirrors make them an advantageous choice.

Funding. Instrument and Equipment Development of the Chinese Academy of Sciences (YJKYYQ20190083); National Natural Science Foundation of China Youth Fund (61905242).

Acknowledgment. The authors would like to recognize support from the Key Laboratory of Airborne Optical Imaging and Measurement, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences.

Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

REFERENCES

1. H. P. Stahl, "Development of lightweight mirror technology for the next generation space telescope," Proc. SPIE **4451**, 1–4 (2001).
2. L. E. Matson and M. Y. Chen, "Enabling materials and processes for large aerospace mirrors," Proc. SPIE **7018**, 70180L (2008).
3. K. S. Woodard, L. E. Comstock, L. Wamboldt, and B. P. Roy, "Cost-effective lightweight mirrors for aerospace and defense," Proc. SPIE **9451**, 94511W (2015).
4. I. Azam, A. Abdul, K. Altaf, T. V. V. L. N. Rao, and H. A. Zaharin, "An in-depth review on direct additive manufacturing of metals," IOP Conf. Ser. **328**, 012005 (2018).
5. Y. Bai, Z. Zhang, D. Xue, and X. Zhang, "Ultra-precision fabrication of a nickel-phosphorus layer on aluminum substrate by SPDT and MRF," Appl. Opt. **57**, F62–F67 (2018).
6. K. S. Woodard, L. E. Comstock, L. Wamboldt, and J. S. Sutherland, "Optimum selection of high performance mirror substrates for diamond finishing," Proc. SPIE **9822**, 98220C (2016).
7. M. Brunelle, I. Ferralli, R. Whitsitt, and K. Medicus, "Current use and potential of additive manufacturing for optical applications," Proc. SPIE **10448**, 104480P (2017).
8. M. Sweeney, M. Acreman, T. Vettese, R. Myatt, and M. Thompson, "Application and testing of additive manufacturing for mirrors and precision structures," Proc. SPIE **9574**, 957406 (2015).
9. K. S. Woodard and B. H. Myrick, "Progress on high-performance rapid prototype aluminum mirrors," Proc. SPIE **10181**, 101810T (2017).
10. J. Hartung, M. Beier, and S. Risse, "Novel applications based on freeform technologies," Proc. SPIE **10692**, 106920K (2018).
11. X. Han, N. Kang, J. Jiao, and C. Wang, "Research for surface characteristics of aluminum mirrors made by laser additive manufacturing," Proc. SPIE **11333**, 113331 (2019).
12. R. Ellis and J. Hosea, "Additive manufacturing of steady-state mirrors for the KSTAR ECH launchers," in *26th Symposium on Fusion Engineering (SOFE)* (IEEE, 2015), pp. 1–5.
13. M. Roulet, C. Atkins, E. Hugot, S. Lemared, and S. Lombardo, "3D printing for astronomical mirrors," Proc. SPIE **10675**, 1067504 (2018).
14. H. von Lukowicz, J. Hartung, E. Hilpert, C. Damm, T. Peschel, and N. Heidler, "Optimization and additive manufacturing of a three-mirror-anastigmatic telescope," Proc. SPIE **11852**, 1185206 (2021).

15. C. Yan, L. Hao, A. Hussein, P. Young, J. Huang, and W. Zhu, "Microstructure and mechanical properties of aluminium alloy cellular lattice structures manufactured by direct metal laser sintering," Mater. Sci. Eng. A **628**, 238–246 (2015).
16. S. Verma, C. K. Yang, C. H. Lin, and J. Y. Jeng, "Additive manufacturing of lattice structures for high strength mechanical interlocking of metal and resin during injection molding," Addit. Manuf. **49**, 102463 (2022).
17. A. Salmi, E. Atzeni, L. Iuliano, and M. Galati, "Experimental analysis of residual stresses on $AlSi_{10}Mg$ parts produced by means of selective laser melting (SLM)," Proc. CIRP **62**, 458–463 (2017).
18. N. Heidler, E. Hilpert, J. Hartung, H. von Lukowica, C. Damm, T. Peschel, and S. Risse, "Additive manufacturing of metal mirrors for TMA telescope," Proc. SPIE **10692**, 106920C (2018).
19. H. Herzog, J. Segal, J. Smith, R. Bates, J. Calis, A. D. L. Torre, D. W. Kim, J. Mici, J. Mireles, D. M. Stubbs, and R. Wicker, "Optical fabrication of lightweighted 3D printed mirrors," Proc. SPIE **9573**, 957308 (2015).
20. C. Atkins, W. Brzozowsk, N. Dobson, M. Milanov, S. Todd, D. Pearson, C. Bourgenot, D. Brooks, R. Snell, W. Sun, P. Cooper, S. G. Alcock, and I. Nistea, "Additively manufactured mirrors for CubeSats," Proc. SPIE **11116**, 1111616 (2019).
21. J. Zhang, X. Zhang, S. Tan, and X. Xie, "Design and manufacture of an off-axis aluminum mirror for visible-light imaging," Curr. Opt. Photon. **1**, 364–371 (2017).
22. K. Wang, J. Dong, X. Wang, and C. Chi, "Design of frame-type support structure for space-based rectangular convex mirror tested on the back," Optik **212**, 164712 (2020).
23. P. Yoder, *Opto-Mechanical System Design*, 2nd ed. (Marcel Dekker, 1993).
24. N. Zhu, Q. Bo, G. Ren, F. Zhu, and Z. Ai, "Study on the support technology of the light-weighted mirror," Proc. SPIE **9682**, 96820X (2016).
25. E. Friedman and J. L. Miller, *Photonics Rules of Thumb* (McGraw-Hill, 2003).
26. E. Hilpert, J. Hartung, S. Risse, R. Eberhardt, and A. Tünnermann, "Precision manufacturing of a lightweight mirror body made by selective laser melting," Precis. Eng. **53**, 310–317 (2018).
27. R. Snell, C. Atkins, H. Schnetler, I. Todd, E. Hernandez-Nava, A. R. Lyle, G. Maddison, K. Morris, C. Miller, M. Roulet, E. Hugot, F. Tenegi-Sangines, A. Vega-Moreno, L. T. G. van de Vorst, J. Dufils, L. Brouwers, S. Farkas, G. Mezo, M. Beardsley, and M. Harris, "An additive manufactured CubeSat mirror incorporating a novel circular lattice," Proc. SPIE **11451**, 114510C (2020).
28. E. Hilpert, J. Hartung, H. von Lukowicz, T. Herffurth, and N. Heidler, "Design, additive manufacturing, processing, and characterization of metal mirror made of aluminum silicon alloy for space applications," Opt. Eng. **58**, 092613 (2019).
29. N. Horvath and M. Davies, "Advancing lightweight mirror design: a paradigm shift in mirror preforms by utilizing design for additive manufacturing," Appl. Opt. **60**, 681–696 (2021).
30. M. Gary, "Single point diamond machining of optical and related mounting surfaces," Proc. SPIE **4471**, 304–307 (2002).
31. C. Atkins, C. Feldman, D. Brooks, S. Watson, W. Cochrance, M. Roulet, E. Hugot, M. Beardsley, M. Harris, C. Spindloe, S. G. Alcock, I. Nistea, C. Morawe, and F. Perrin, "Topological design of lightweight additively manufactured mirrors for space," Proc. SPIE **10706**, 107060 (2018).
32. F. Biondani, G. Bissacco, P. T. Tang, and H. N. Hansen, "Additive manufacturing of mould inserts with mirror-like surfaces," Proc. CIRP **68**, 369–374 (2018).
33. S. N. Tan, Y. L. Ding, Y. S. Xu, and L. Shi, "Design and fabrication of additively manufactured aluminum mirrors," Opt. Eng. **59**, 013103 (2020).
34. C. Atkins, W. Brzozowski, N. Dobson, M. Milanova, S. Todd, D. Pearson, C. Bourgenot, D. Brooks, R. Snell, W. Sun, P. Cooper, S. G. Alcock, and I. Nistea, "Lightweighting design optimization for additively manufactured mirrors," Proc. SPIE **11116**, 1111617 (2019).
35. T. DebRoy, H. L. Wei, J. S. Zuback, T. Mukherjee, J. W. Elmer, J. O. Milewski, A. M. Beese, A. Wilson-Heid, A. De, and W. Zhang, "Additive manufacturing of metallic components - process, structure and properties," Prog. Mater. Sci. **92**, 112–224 (2018).
36. L. J. Sun, Y. Q. Zhang, S. Y. Li, Z. H. Zhang, and L. B. Li, "Optimum design of flexible support structure for space mirror," Proc. SPIE **11341**, 113410 (2019).
37. K. Wang, J. Dong, Y. Zhao, C. Chi, P. Jiang, and X. Wang, "Research on high performance support technology of space-based large aperture mirror," Optik **226**, 165929 (2021).
38. M. N. Gussev, N. Sridharan, Z. Thompson, K. A. Terrani, and S. S. Babu, "Influence of hot isostatic pressing on the performance of aluminum alloy fabricated by ultrasonic additive manufacturing," Scr. Mater. **145**, 33–36 (2018).