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Review

A Review of Lightweight Design for Space Mirror Core Structure: Tradition and Future

Changhao Zhang [1,2,3] **and Zongxuan Li** [1,3,*]

[1] Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China
[2] University of Chinese Academy of Sciences, Beijing 100049, China
[3] Key Laboratory of Space-Based Dynamic and Rapid Optical Imaging Technology, Chinese Academy of Sciences, Changchun 130033, China
* Correspondence: lizongxuan@ciomp.ac.cn

Abstract: With the continuous improvement of the imaging quality requirement of the space optical system, the large-aperture mirror becomes the research focus. However, the increase of the aperture will increase the whole weight which results in high launch cost and degrades the mirror surface figure accuracy. Therefore, the lightweight design method of the mirror structure is of great importance. In recent years, many space telescope system schemes have demonstrated the progress of the structural lightweight design of mirrors, such as Spitzer, SOFIA, JWST, etc. This article reviews the main content and innovations of the research on the structural designs of mirrors including conventional machining designs and topology optimization structures. Meanwhile, some emerging designs (e.g., lattices and Voronoi structures) considering additive manufacturing (AM) are also introduced. Several key elements of different structural design approaches for lightweight mirrors are discussed and compared, such as material, lightweight ratio, design methods, surface figure, etc. Finally, future challenges, trends, and prospects of lightweight design for mirrors are discussed. This article provides a reference for further related research and engineering applications.

Keywords: lightweight structure; mirror; topology optimization; additive manufacturing technology; Voronoi diagram

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1. Introduction

With the increasingly important applications of modern space optical technology in civilian, military, and commercial fields, there is a demand for optical systems with the improvement of resolution [1]. As we know, the larger the aperture of the telescope, the longer the focal length, and the better to obtain a stronger light collection ability and higher resolution [2]. It's noteworthy that mirrors, as the core component of the telescope, are critical elements that directly affect the resolution and other optical systems' characteristics. Meanwhile, the increase of the aperture of the space mirror will enlarge the weight of the whole structural system, thus raising the launch cost. Consequently, to reduce the cost, and to control the rigid body motion and surface figure error of the mirror under the gravity load, the space mirror must be lightweight [3]. The design and optimization of lightweight mirrors have become a major challenge for optical scientists and engineers [4].

Over the last decades, multifarious lightweight design methods have been proposed, among which contoured-back solid mirrors, open-back mirrors, and sandwich mirrors are the most representatively and widely used in engineering (Figure 1a–c) [5]. These conventional designs are convenient to be designed and processed, and many researchers designed the mirror assembly by experience. However, with increasing requirements of the mass and precision requirement of optical-space systems, the mirrors must be further optimized. Topology optimization has been developed as a mainstream structural design technique for lightweight design. On the one hand, the mirror's structures with a conventional design could be optimized as a starting point to obtain ameliorated structure (Figure 1d) [6]. On the other hand, due to the development of manufacturing technology, complex structures obtained by topology optimization can be directly processed. Subsequently, with the use of 3D printing in opto-mechanical manufacturing, newly unconventional structures are adopted gradually in recent years, which opens a special spectrum of creativity for mirror design. The work of design and optimization of lattices and Voronoi structures of lightweight mirror have been brought forward and the prototypes printed in metals also show excellent performance [7]. Figure 1e,f highlight some examples of how lattices and Voronoi cells were implemented in lightweight design [8,9].

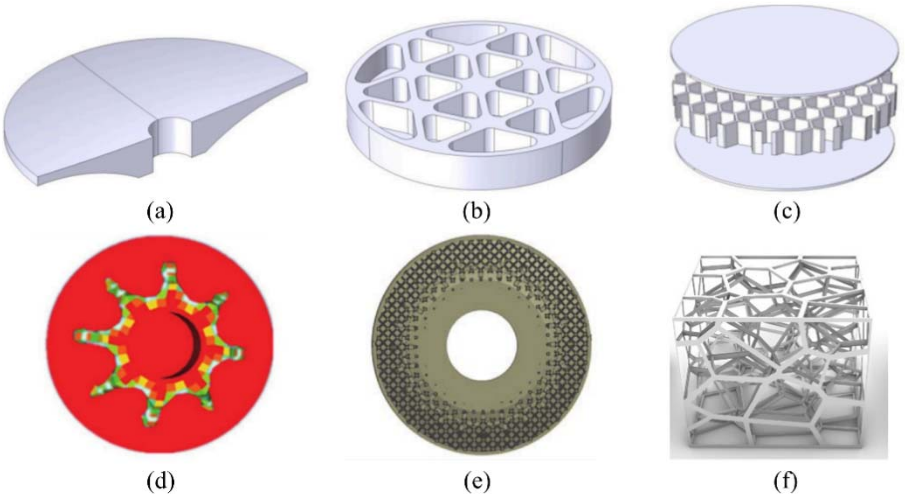


Figure 1. (**a**) Model of a contoured-back solid mirror, (**b**) Model of an open-back mirror, (**c**) Model of a sandwich mirror, (**d**) Topology optimization result of a space mirror, (**e**) The sectional view of lattice arrangement in a mirror's closed cavity, (**f**) An open 3D Voronoi structure.

This paper aims to review the recent advances in lightweight mirror designs and provide future trends. Firstly, the summary and comparison among conventional designs have been made in Section 2. Some research progress and innovations on topology optimization for reduced-weight mirrors are listed in Section 3. Then, Section 4 introduces non-conventional designs, especially lattices and Voronoi structures for mirrors. Lightweight mirrors' current process and future trends are discussed in Section 5. Finally, Section 6 illustrates the conclusion.

2. Conventional Design

2.1. Contoured-Back Solid Mirrors

Thinning the baseline substrate is a rapid and convenient way to lightweight solid mirrors with concave, flat, and convex first (reflecting) surfaces. However, this method will reduce stiffness, increase self-weight deflection, and increase susceptibility to acceleration forces. Hence, a better way to reduce the weight of mirrors is to contour the second (back) surface. Seven models were shown in Figure 2, in which the mirror diameters, thicknesses, radii of curvature of the reflecting surfaces, and material types were identical, but their R_2 surfaces were contoured in diverse ways. Yoder discussed them comprehensively and obtained Table 1 to show the volumes, weights, and other relevant parameters for these optically equivalent mirrors [10]. The KAO (Korea Astronomy Observatory) telescope used a Zerodur primary mirror which has a double arch back contour shape [11]. The Spitzer space telescope was launched on 25 August 2003, which is a typical example of an ultra-lightweight single arch mirror [12].

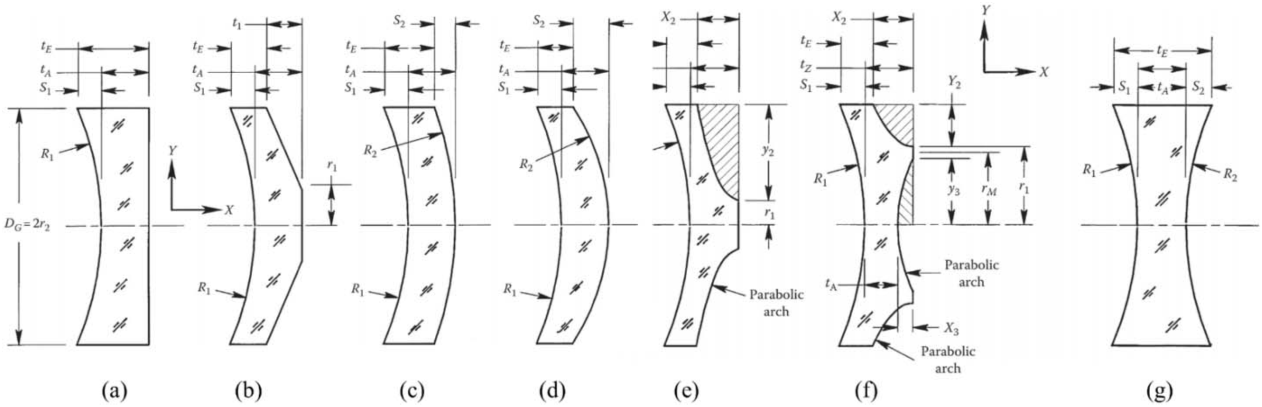


Figure 2. (**a**) Baseline with flat rear surface, (**b**) Tapered (conical) rear surface, (**c**) Concentric spherical front and rear surfaces with $R_2 = R_1 + t_A$, (**d**) Spherical rear surface with $R_2 < R_1$, (**e**) Single-arch configuration, (**f**) Double-arch configuration, (**g**) Double-concave configuration (not lightweighted) for comparison [13].

Table 1. Comparison of Volumes and Weights of Contoured-Back Mirrors [13]. D_G = 457.2 mm (18.0 in.), t_A = 76.2 mm (3.0 in.), R_1 = 1828.8 mm (72.0 in.), Corning ULE.

Configuration	Figure View	Volume	Weight	Lightweight Rate [1]	Pearson's Ratio [2]
Flat back (baseline)	Figure 2a	13,686.4 cm^3	30.2 kg	0%	4.9
Tapered back	Figure 2b	7472.5 cm^3	16.5 kg	45.5%	8.9
Concentric meniscus	Figure 2c	12,557.3 cm^3	27.7 kg	8.3%	5.3
Meniscus ($R_2 < R_1$)	Figure 2d	7542.9 cm^3	16.6 kg	44.9%	8.8
Single-arch (*Y*-axis parabolic)	Figure 2e	4218.0 cm^3	9.3 kg	69.2%	15.8
Single-arch (*X*-axis parabolic)	Figure 2e	3923.0 cm^3	8.7 kg	71.3%	16.9
Double-arch	Figure 2f	6377.8 cm^3	14.1 kg	53.5%	10.4
Double concave (not lightweighted)	Figure 2g	14,861.4 cm^3	32.8 kg	N/A	4.5

[1] The lightweight rate is (the loss weight of optimized mirror)/(the weight of original mirror) in this review.
[2] Pearson suggested that the ratio (surface area)$^{1.5}$/(mirror volume) > 7, the mirror could be defined as a lightweight mirror [14].

2.2. Open-Back Cellular Mirrors

A mirror lightweighted with a cellular section is usually structurally more efficient than its equivalent-sized solid version. This type of design could be divided into two types, open-back, and sandwich mirrors, according to whether a back sheet exists. Open-back mirrors consist of a thin face sheet stiffened or reinforced with a regular arrangement of perpendicular ribs forming open pockets or cells in the back of the mirror, as shown in Figure 3. So the fabrication is usually less difficult than the more complex sandwich structure and the application is also more general [10,15].

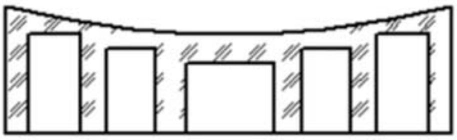


Figure 3. Cross section of open-back mirrors.

Five common polygon core configurations are shown in the Figure 4 [16]. Trapezoidal pockets are generally used for circular mirrors with a central hole. Circular holes which have low lightweight ability could be regarded as the simplification of hexagonal pockets; however, the uneven spacings between circular cells negatively affect the structural stiffness of the mirror [17,18].

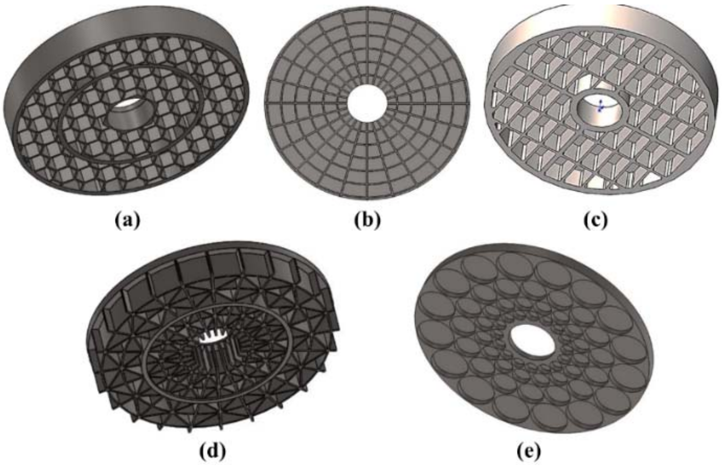


Figure 4. (**a**) Hexagonal pockets, (**b**) Trapezoidal pockets, (**c**) Rectangular pockets, (**d**) Triangular pockets, (**e**) Holes.

Considering the complexity of design and processing, triangular and hexagonal pockets are widely adopted in the lightweight design of mirrors. Here are two examples, below. Chen ya et al. designed the triangular cells scheme based on the oval planar reflector, and the lightweight rate of the lightweight reflector is 33% (Figure 5a) [15]. The team from Corning fabricated a small mirror with honeycombed lightweight structure by DMLS (Direct Metal Laser Sintering) in 2015 in Figure 5b [19]. There are multiple instructive studies about which of the two kinds of designs, triangular or hexagonal pockets, has better performance. So typical research and conclusions for this issue were listed to provide information on the relative merits of designs in Table 2.

Table 2. Typical research for "Hexagonal vs. Triangular".

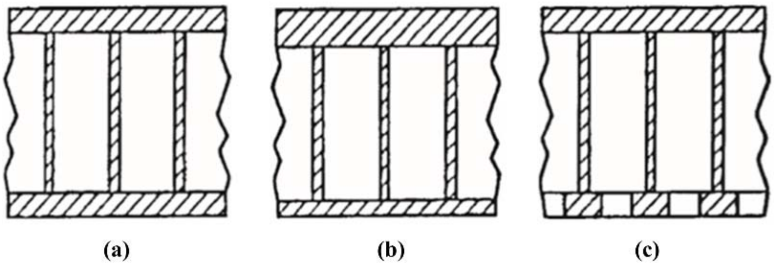
Researcher	Hexagonal vs. Triangular	Comment
Barnes, W.P. [20]	The hexagonal structure is superior, substantially stiffer (about 20%), showing less deflection overall.	The superiority of the hexagonal core mirror might be 5% instead of 20% [21,22].
Richard, R.M.; Malvick, A.J. [23]	Both structural deformation and deviation are shown to be dependent upon cell-wall thickness and generally independent of cell shape.	The element used for this research might not have been accurate enough to produce satisfactory results [22].
Simon, C.; Sheng, F. [24]	The stiffness of following core geometries decreases in order: the triangular core, square core, and hexagonal core.	Torsion loading makes the hexagonal cell configuration much weaker for open-back mirror structures [24,25].
Yu, k.; et al. [26]	One kind of triangular hole element array shows best overall performance in the comparison of multiple graphic structures.	N/A
Udit, B.; Shah, R.; Kapania, K. [27]	The triangular cores outperform hexagonal cores for applications where in-plane loading is dominant.	N/A

(a) (b)

Figure 5. (**a**) Polished mirror with triangular lightweight, (**b**) Mirror with honeycombed lightweight.

2.3. Sandwich Cellular Mirrors

The sandwich mirror adds a back sheet compared to the open-back mirror, consisting of a core intercalated between two solid layers. The typical sections of sandwich mirrors are shown in Figure 6. They are traditionally produced by bonding plate material to a honeycomb core or using reaction-bonded technology in the mirror manufacturing industry [28]. Symmetry for a sandwich mirror means that the thickness of the face and back sheets are the same and that the inscribed circle diameter and rib thickness are constant. However, mirror performance is not improved with a non-symmetric design (Figure 6b), which is normally used to allow for more material removal during the grinding and polishing of the optical surface [10].



(a) (b) (c)

Figure 6. (**a**) Symmetrical sandwich, (**b**) Unsymmetrical sandwich, (**c**) Partially open back.

Wang Xiaoyong et al. [29] adopted the arch back thick honeycomb sandwich structure according to the technical requirements of the 1.3 m-caliber space mirror, as shown in Figure 7. The sandwich structure consists of a reflector, a base plate, and a sandwich layer. After optimizing optical processing and other processes, the developed reflector components have been analyzed by FEA (Finite Element Analysis), tested in a lab, and reached the technical requirements.

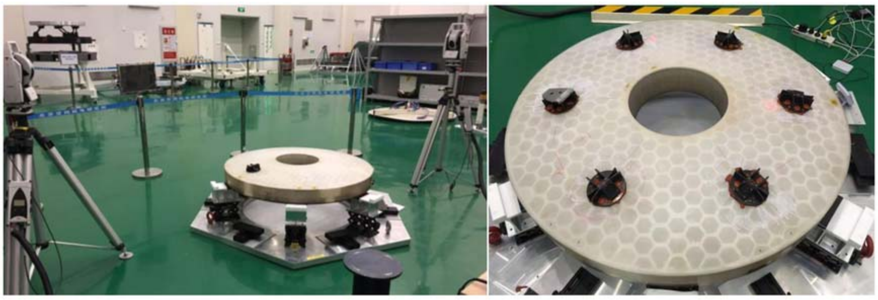
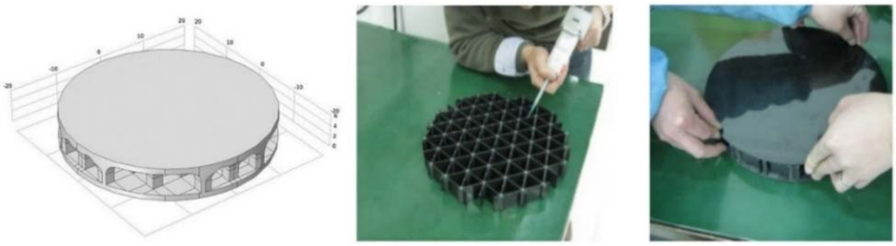


Figure 7. The honeycomb sandwich mirror.

Carolyn Atkins et al. [30,31] aimed to investigate different AM materials and methods toward lightweight mirrors for space. The mirror lightweighted in the form of arches (Figure 8a) was printed commercially using metal laser sintering (MLS) in the aluminum alloy $AlSi_{10}Mg$ and was lightweighted to 44% of a solid equivalent. They compared the properties of a mechanical manufacturing honeycomb design with a 3D-printed lightweight design (arches) by FEA. The arch design was stiffer and showed fewer node displacements than the honeycomb design [32]. Accounting for the actual process properties of CFRP (Carbon Fiber Reinforced Plastic), Ding Jiaoteng et al. [33] formed mirror panels laminated based on thermal stability design for a Φ 300 mm CFRP mirror. Then, the honeycomb sandwich structure was fabricated using one innovative inlaying-grafting design method as shown in Figure 8b,c.



(a) (b) (c)

Figure 8. (**a**) The arch design model, (**b**,**c**) The production of lightweight CFRP sandwich mirror.

In the study of Enrico Hilpert et al. [34], a series of different mirror designs were investigated, including a full solid mirror, an empty shell model, and three different designs. Figure 9a shows the model which contains holes in a cross-directional pattern along the neutral plane and represents a lightweight design manufacturable by cutting techniques. The “honeycomb” mirror was developed (Figure 9c), which could only be manufacturable by AM. The inner part of the mirror consists of a hexagon (honeycomb) structure, with additional holes on all faces. Although the mass reduction of this design, 63.5%, is less than the honeycomb mirror (Figure 9b), it has a higher stiffness compared to other designs tested by FEA.

(a) (b) (c)

Figure 9. (**a**) Model of the “drill” mirror, (**b**) Model of honeycomb mirror with open backside (upside down), (**c**) Model of the honeycomb mirror with sectioning planes added to demonstrate the hollow structure.

2.4. Summary

Table 3 summarizes typical conventional designs. The manufacture and installation of contoured-back solid mirrors are relatively easy; however, the weight reduction effect and deformation cannot be outstanding at the same time [10,35]. Mirrors lightweighted with a cellular section are usually structurally more efficient than their equivalent-sized solid version. Open-back lightweight mirrors display high effective weight loss, which is also more common because fabrication is always less difficult than the more complex sandwich structure. However, better structural performance is obtained with a sandwich scheme [18]. With the rapid development of AM technologies, it is possible to fabricate a closed-back sandwich mirror with a complex internal structure [36].

Table 3. Technical parameters of typical research on conventional design.

Designer	Material	Dimensions	Lightweight Design	Lightweight Rate	Surface Accuracy
Moon, I.K. et al. [11]	Zerodur	∅ 1000 mm	double arch back	30%	63.3 nm (RMS)
Chen ya et al. [15]	Glass-ceramic	Ellipse 730 × 525 mm	Triangular hole, open-back	33%	32.96 nm (PV) 8.68 nm (RMS)
Carolyn Atkins et al. [30,31]	$AlSi_{10}Mg$	∅ 40 mm	Arches, sandwich	44%	16 nm (RMS)
Zhang Dandan et al. [37]	Zerodur	∅ 280 mm	Single arch back	51.7%	48.34 nm (PV) 15.56 nm (RMS)
Zhang Dandan et al. [37]	Zerodur	∅ 280 mm	Hexagonal hole, open-back	52.9%	34.08 nm (PV) 10.29 nm (RMS)
Enrico Hilpert et al. [34]	$AlSi_{12}$	∅ 200 mm	Hexagonal hole, sandwich	63.5%	12.5 nm (RMS)
Zhou Hao et al. [38]	C/SiC	Ellipse 225 × 165 mm	Hexagonal hole, open-back	65%	38.27 nm (PV)
Ch. Wührer [39,40]	Glass	Ellipse 732 × 690 mm	Triangular hole, open-back	close to 90%	50 nm (RMS)

Polina A. Abdula et al. [41] have verified the above conclusion by comparing the performance of different designs. The team achieved a simulation and comparative study of the typical structures by diverse sorts of models as shown in Table 4. The parameters of the initial model are as follows:

Table 4. Summary table for typical designs.

Design		Mass	Lightweight Rate	Maximum Deformation
Contoured-back solid mirrors	Single arch	160.53 kg	66%	1.088 µm
	Double arch	246.38 kg	48%	0.112 µm
Open-back mirrors	Holes	174.95 kg	63%	0.485 µm
	Trapezoidal pockets	151 kg	68%	0.375 µm
	Triangular pockets	174.7 kg	63%	0.264 µm
	Hexagonal pockets	227.4 kg	52%	0.429 µm
Sandwich		185.77 kg	61%	0.236 µm
Solid		478.48 kg	0%	0.191 µm

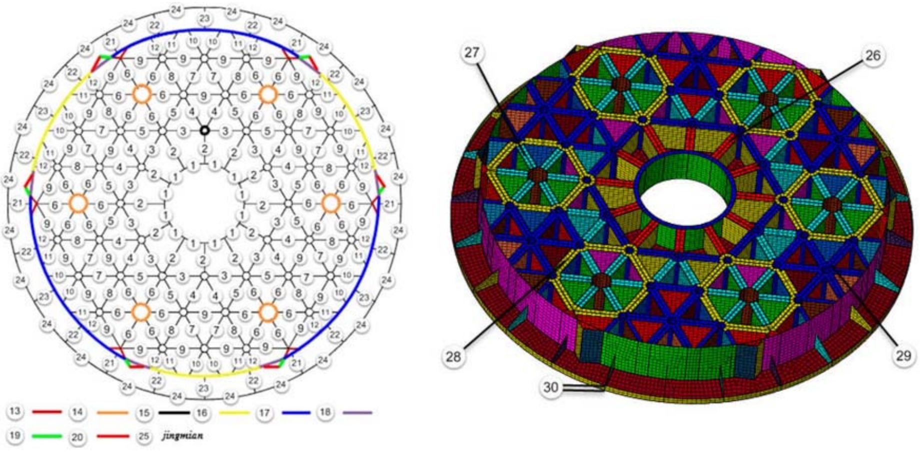
Diameter, 1 m; Thickness, 0.15 m; Central screening, 20%; Material, Titanium; Surface type, Spherica.

3. Topology Optimization

Topology optimization technology is an advanced structural design method which can obtain the optimal structure configuration via reasonable material distribution satisfying specified load conditions, performance, and constraints [42]. Since the theoretical background of topology optimization was set by Bendsøe and Kikuchi in 1988, this technology has been developed rapidly [43]. With the increasing improvement of the lightweight ratio and performance of modern space optical systems, the traditional cellular designs gradually could not satisfy engineering requirements. The technology of topology optimization has played an important role and gained popularity in lightweight design studies with a conventional open-back or sandwich design as a baseline. With the advance of technology in AM, topologically optimized structures with complex geometric configurations could also be directly processed, which provides more possibilities for the non-conventional lightweight designs of space optical mirrors [44–46].

3.1. Topology Optimization with a Baseline

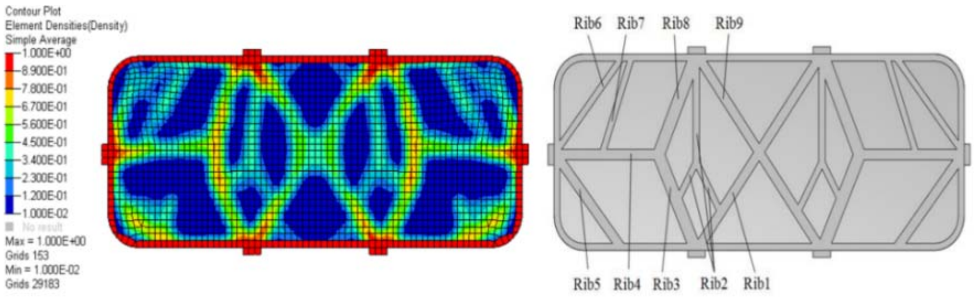
Liu Fengchang et al. [47] proposed a topology optimization method by using triangular polygon core configurations as the initial design. The lightweight ribs are grouped according to the optimal material distribution obtained from topology optimization (Figure 10). They used the compromise programming method to find a compromise solution because this design is a multi-objective optimization problem, such as the RMS value of the surface shape error, the total mass, and the eigen-frequency. The FEA results show that this design method is relatively effective.



(a) (b)

Figure 10. Grouping of the mirror ribs based on topology optimization. (**a**) the mirror face and each ribs group number, (**b**) the back face and edge rib height group number.

Qu Yanjun et al. [48] optimized the horizontally placed mirror using six-point peripheral supports under the effect of gravity by OptiStruct. According to the topology optimization results in Figure 11a, they modified the initial structure and established a 3D model in Figure 11b. Through the above calculation and analysis, the ratio of lightweight, structure stiffness, and surface accuracy of the optimized rectangular mirror was superior to that of the traditional triangular lightening mirror.



(a) **(b)**

Figure 11. (**a**) Optimization results of the reflector, (**b**) Optimal model.

Li Yewen et al. [49] used the topology optimization method with variable density to obtain the mirror topology models with maximum stiffness and maximum first-order frequency respectively (Figure 12). The integrated design scheme of the mirror was obtained by synthesizing the two topology models. The result of FEA showed that the surface figure of the mirror after optimization has been significantly improved.

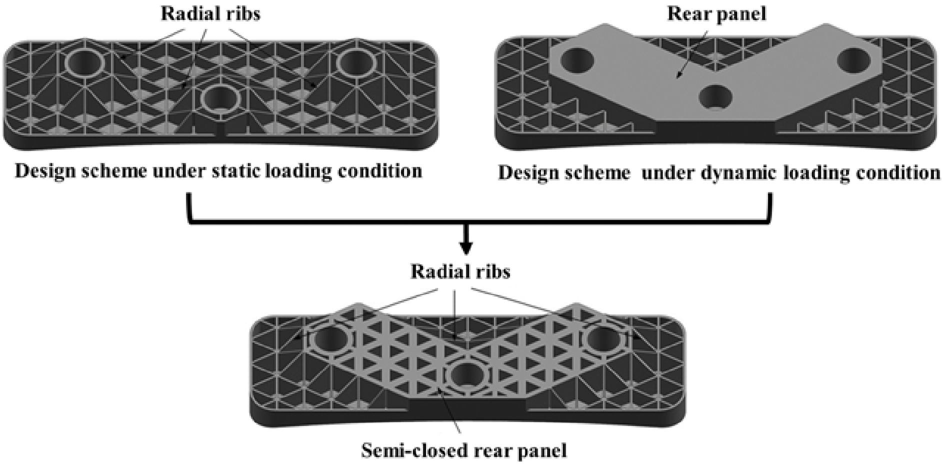


Figure 12. Mirror design schemes combining different loading conditions.

3.2. Direct Topology Optimization and Design

Harrison Herzog et al. [50] optimized the mirror using Altair Hyperworks with minimal surface displacement as a merit function. As shown in Figure 13a,b, two different models obtained, top mount and side mount, were optimized, processed, and tested in both aluminum and titanium, then, both of them can meet the needs of practical optical applications. Dong Deyi et al. [51] fabricated the lightweight 3D model established directly according to the topology optimization results, then, they used the method of density filtering to solve the problem of unsmooth structure. As shown in Figure 13c is the radial structure manufactured by selective laser melting (SLM) technology. The surface density and the mirror deformation under the self-weight of the mirror all met the requirements after tests in a lab.

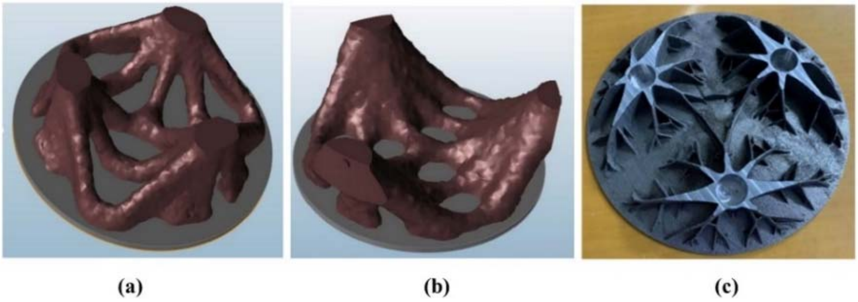


Figure 13. (**a**) Model of top mount, (**b**) Model of side mount, (**c**) The optimized mirror manufactured by SLM.

Carolyn Atkins et al. [30,31] designed the non-conventional lightweight mirror designs by the FEA tool topology optimization. Figure 14 shows the process of the design and after some detailed adjustments, the final optimized samples depicted in Figure 14e,f are a series of co-axial tapered rings radiating from a central pillar. The design did show better PV and RMS; however, the expected surface roughness figure was not achieved.

Table 5 summarizes typical topological optimization designs for space mirrors.

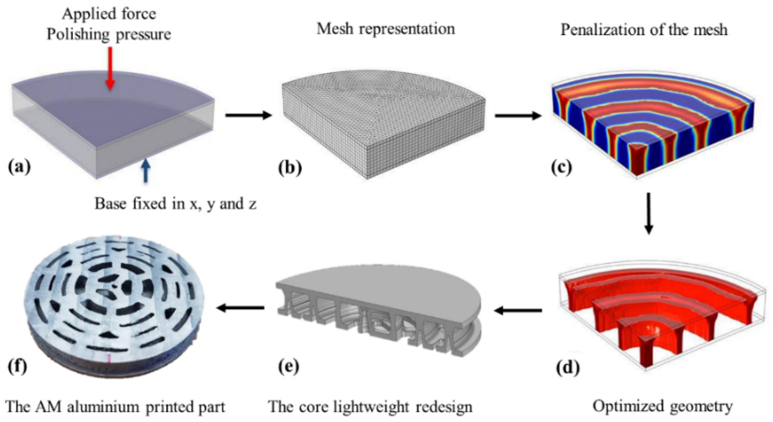


Figure 14. The technological process of a topology optimized mirror.

Table 5. Summary table for typical topological optimization designs.

Design	Material	Dimensions	Optimization Methods and Software		Lightweight Rate	Surface Accuracy
Liu Fengchang et al. [47]	SiC	∅ 800 mm	The parametric design, The compromise programming method	• Consider the RMS values of the surface shape error, the eigen-frequency, and the mass	8.6% [1]	N/A
Qu Yanjun et al. [48]	SiC	Rectangular 700 × 280 mm	OptiStruct, The mathematical programming method	• Maintain the high surface accuracy and structure stiffness • Reduce the weight	62.05%	26.59 nm (PV) 5.82 nm (RMS)
Li Yewen et al. [49]	SiC	Rectangular 800 × 230 mm	SIMP, The integrated optimization method	• Maintain the PV values and weight • Maximize stiffness and first-order frequency	80.9%	23.70 nm (PV) 4.54 nm (RMS)
Harrison Herzog et al. [50]	Ti6Al4V, $AlSi_{10}Mg$	∅ 101.6 mm (4 in)	Altair Hyperworks	• Maximize the stiffness and lightweight rate • Maintain natural frequency	N/A	255 nm (PV) 22 nm (RMS) ($AlSi_{10}Mg$)
Dong Deyi et al. [51]	Al alloy	∅ 600 mm	SIMP, The density filtering method	• Minimize the structural flexibility • Consider the self-weight load condition	81.2%	25.91 nm (RMS)
Guo Liang et al. [52]	SiC	∅ 676 mm	SIMP, The orthogonal arrays method	• Maintain the high surface shape error and high dynamic stiffness • Reduce the mass	About 78%	2.39 nm (RMS)

[1] This lightweight rate is obtained by comparing the optimized mirror and the initial cellular mirror.

4. Non-Conventional Design

4.1. Foam Cores

For conventional lightweight mirrors (Section 2), the core mesh must be separated by distances large relative to their thickness, thereby allowing the mirror face sheet to sag between the webs during polishing forces or under the gravitational load. Mirrors with foam cores significantly improve these problems in several aspects. Due to the fact that a large percentage of open space (typically 90%) within the foam structure, a high lightweight ratio could also be realized. Goodman and Jacoby compared some characteristics of conventional webs and foam cores for mirrors, as indicated in Table 6 [53].

Table 6. Advantages of foam core mirrors relative to conventional web core mirrors.

Roles/Requirements	Foam	Webs
Self-weight deflection (varies with pocket width)	Pockets typically 10 µm	Pockets typically 10 to 100 mm
Micrometeoroid susceptibility	Natural bumper material and ripstop	Little or no protection
Support against polishing pressure	Distributed load paths under mirror surface, easier to support axially	Concentrated load paths leading to print-through of web outlines
Dynamics/stability/stiffness/vibrational mode frequency	Higher stiffness, higher resonance frequency	More mass for the same stiffness and resonant frequency
Reliability/redundancy	Many alternate load paths, moregraceful failure	Structural failure effect, greater, catastrophic failure

Goodman et al. [54–57] used silicon foam which can be machined to any shape (sphere, asphere, etc.) to manufacture the silicon lightweight mirror (SLM). The basic structure for a silicon foam composite optic is shown in Figure 15a and the basic elements of it are two silicon faceplates that are bonded to an open-cell silicon foam core. Then, they developed silicon and silicon carbide lightweight mirror systems (SLMS^{TM} and SiC-SLMS^{TM}). The manufacturing process of the SLMS^{TM} described above is shown in Figure 16.

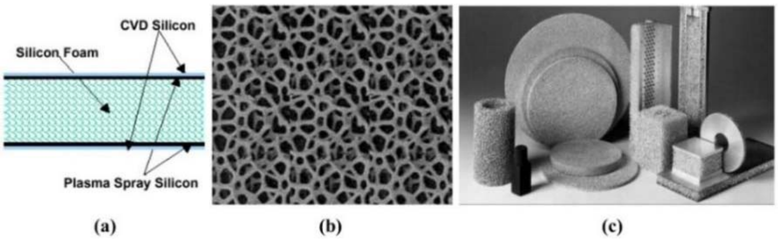


Figure 15. (**a**) SLM composite structure, (**b**) SLMS^{TM} composite structure, (**c**) Open-cell foam can be CNC machined into virtually any shape.

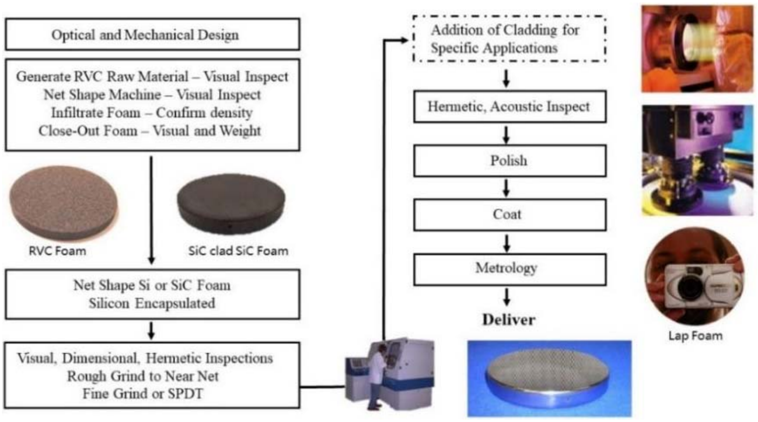


Figure 16. SLMS^{TM} manufacturing process.

4.2. Lattices

For conventional methods of fabricating metallic cellular materials which allow for some control over pore shape and size, they remain limited to producing randomly organized structures. Additive manufacturing (AM), also known as 3D printing, manufactures parts via joining the material layer-by-layer. The layer-upon-layer methodology dramatically increases the design possibilities of non-conventional structures that exhibit complex structural configurations and the ease and speed by which fabrication occurs. This contrasts with AM which enables the creation of non-conventional structures with a predefined external geometry and internal architecture. In recent years, AM has shown an effective way of fabricating components with complex configurations, opening the possibility to manufacture complex lightweight structures for mirrors, especially for lattice and foam structures [58–60].

In the context of modeling for AM, a lattice is a set of points and line segments between the points embedded in the 3-dimensional space of the mirrors [61]. Lattice unit cells can be constructed using (a) strut-based members which are more widely used in optical mirror manufacturing or (b) surface-based representation. The nomenclature for the library of strut-based unit cells presented in Figure 17 are as follows: BCC is Body Cantered Cubic; BCCz is BCC with 'z' direction reinforcement; FCC is Face Centered Cubic; FBCC results from the union of FCC and BCC; names with 'S' prefix are self-supporting variants which have no members that lay parallel to the x-y plane [62]. From the existing research, the BCC lattice is adopted most concerning the stability of the space truss structure and design difficulty.

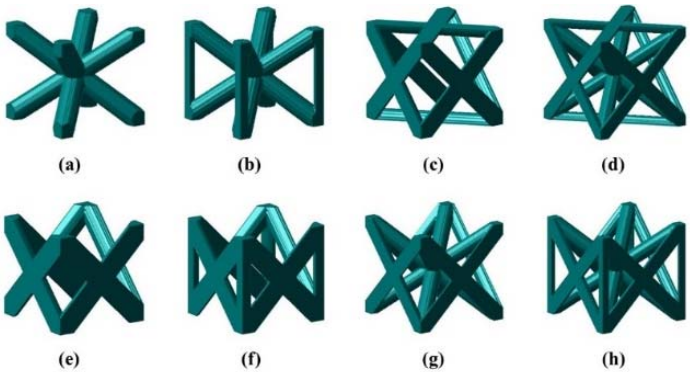


Figure 17. Library of truss-based unit cells (Vf = 0.2): (**a**) BCC, (**b**) BCCz, (**c**) FCC, (**d**) FBCC, (**e**) S-FCC, (**f**) S-FCCz, (**g**) S-FBCC, (**h**) S-FBCCz.

In 2021, Zhang Muyao et al. [63] introduced the BCC lattice structure into a small-diameter aluminum alloy mirror structure design, as shown in Figure 18. They topologically optimized the lattice structure based on the MIST method, and the cross-sectional area of the rod is taken as the optimization object. It is verified by FEA that the lightweight rate and surface accuracy requirements of the optimized reflector are better than those of the traditional lightweight form reflector.

Carolyn Atkins et al. [64] selected three lattice structures which are Star (BCCz), Icosahedron, and Tetra, shown in Figure 19 for further study. The two plots in Figure 20 show that the star lattice exhibits the minimum change in displacement with cell length and presents a clear reduction in weight for given displacement in relation to the other lattices. Then, they optimized the Star lattice by two properties, the length of the unit cell and the threshold value of the optimization, in NetFabb. Figure 19d depicts the optimum Star lattice.

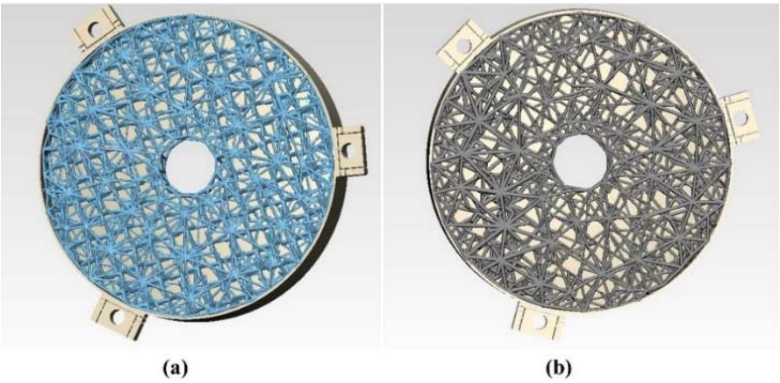


Figure 18. (**a**) Uniform lattice infill space mirror, (**b**) Non-uniform lattice after optimization.

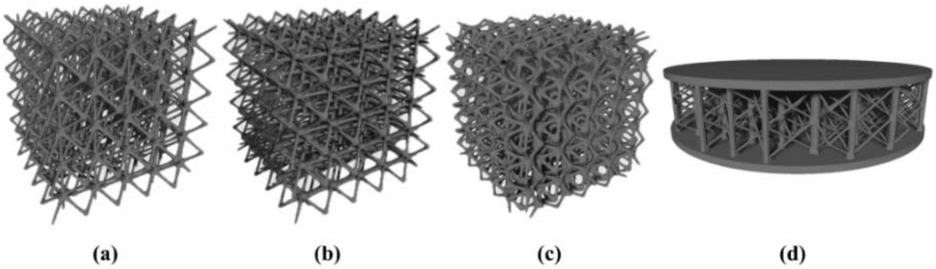


Figure 19. (**a**) Star lattice (BCCz), (**b**) Tetra, (**c**) Icosahedron, (**d**) A 3D-representation of the optimized Star lattice structure.

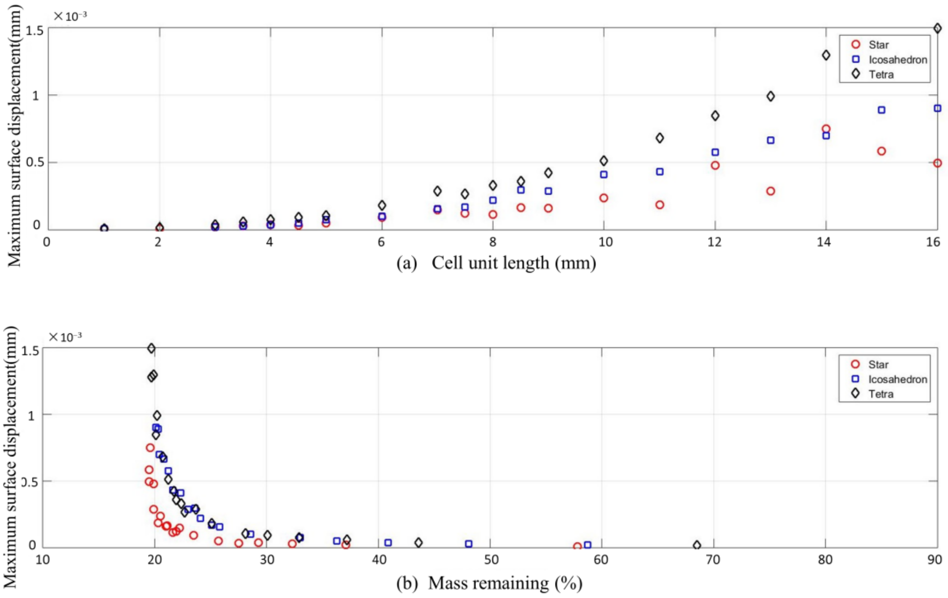


Figure 20. (**a**) The change in maximum displacement with unit cell length for the three lattice geometries, (**b**) The change in maximum displacement as a function of mass remaining percentage.

4.3. Voronoi Cells

Over millions of years of natural evolution, nature has developed extensive high-performance structures, and Voronoi structure or Voronoi media exists widely in nature (Figure 21a–c) [5,65]. For example, Voronoi scaffolds shown in Figure 21d are inspired by bone. Ref. [66] Voronoi tessellation is a space division technique developed by mathematician G.F.Voronoi in 1905. This method produces regions called "cells" from a set of points called "seeds", and it has the characteristic property that any point within a cell will be closer to the cell's seed than any other point in the space [67,68]. Voronoi cells offer an element of randomization in the structure which is the primary difference between the lattices and Voronoi cells. If the seeds were distributed in a regular pattern, a Voronoi pattern would be a regular grid structure. However, a random Voronoi structure can be obtained by adding a random component to the seed placement, which has unique advantages and characteristics different from other structures.

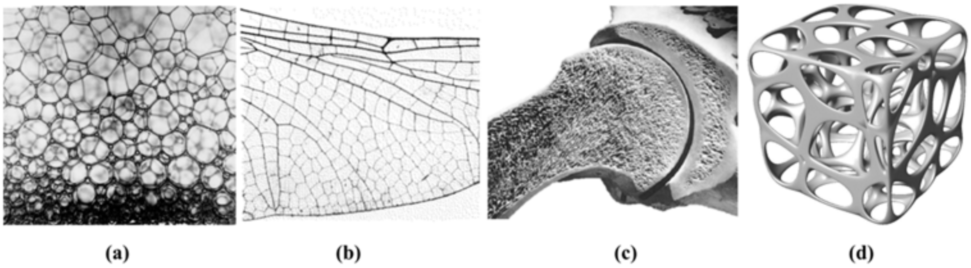


Figure 21. (**a**–**c**) Examples of Voronoi cells, (**d**) Bio-inspired models.

Previous scholars have found that Voronoi structures perform excellently in mirror design. As shown in Table 7, in the research of Joni Mici et al. [61], Voronoi designs achieved the greatest volume loss among eight schemes. Meanwhile, Voronoi mirrors showed significant improvements, compared with the traditional design, in thermal displacement, thermal strain, and displacement under pressure. Furthermore, Voronoi structures provide more degrees of freedom for structural optimization so the optimized design can achieve better performance [34].

Table 7. Volume comparison among different structures.

Model	Volume	Volume Reduction
Titanium Solid	299.23 cm^3	0%
Titanium Skin	53.18 cm^3	82%
Regular Voronoi—1000 pts	110.65 cm^3	63%
Delaunay—1000 pts	231.97 cm^3	22%
BCC A (0.75 mm center—1.5 mm ring)	206.69 cm^3	31%
BCC B (1.5 mm center—0.75 mm ring)	152.30 cm^3	49%
Voronoi A (0.75 mm center—1.5 mm ring)	141.50 cm^3	53%
Voronoi B (1.5 mm center—0.75 mm ring)	99.96 cm^3	67%

Voronoi can be divided into 2D and 3D manufacturing types according to the spatial distribution. A 3D-Voronoi structure, which could be regarded as a similar foam core structure (Section 4.1), could own similar advantages. At the same time, a 3D-Voronoi structure can be controlled and adjusted by algorithms instead of completely random foam so it's more suitable for engineering applications.

Enrico Hilpert et al. [69–71] from Fraunhofer Institute, systematically studied the mirrors filled with a stochastic 2D-Voronoi foam. As shown in Figure 22a,b the density distribution of the foam is based on static load cases. As shown in Figure 22c Voronoi cells from Poisson disk sampling for the nearest-neighbor distance, which assumes smaller minimal values than in the surrounding area in the three areas. As a result, the mass could be reduced significantly, meanwhile, the stiffness is increased, resulting in a significant increase in the specific stiffness.

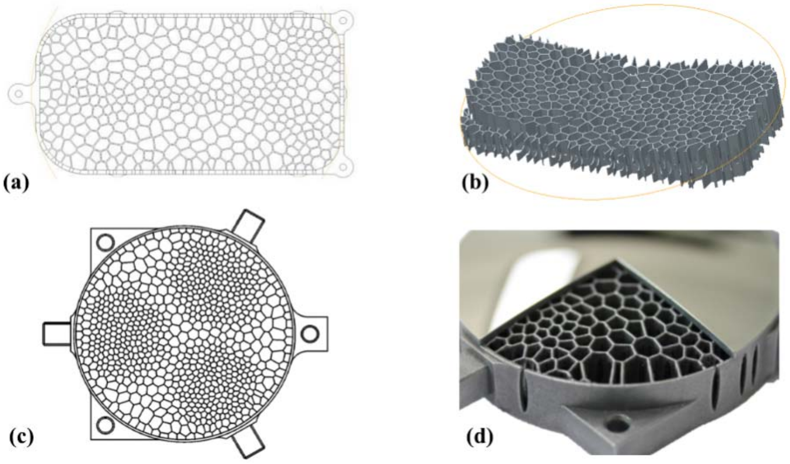


Figure 22. (**a**) Mirror lightweighted by Voronoi foam, (**b**) Internal lightweight structure, (**c**) Optimized mirror light-weighted by Voronoi foam, (**d**) Diamond-turned mirror with 2D-Voronoi structure.

Figure 23a shows an open 3D-Voronoi structure with 1000 points generated using Lloyd's algorithm [72] inside of the topology-optimized mirror shape [61]. Changing the number of cells (structural members) as well as the size of the structural members will affect stiffness under load. Thermal variations under operational loads during processing could also alter structural properties. The follow-up research on these 3D-Voronoi structures ought to be continued, which will promote the innovation of the mirror design.

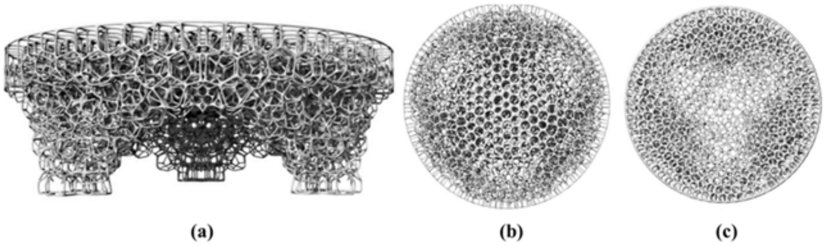


Figure 23. (**a**) A Voronoi-based structure for mirrors, (**b**) Thickness varies from 0.75 mm at the circumference to 2 mm in the center, (**c**) Thickness varies from 2 mm at the circumference to 0.75 mm in the center.

5. Future Trends

As we all know, the designing and manufacturing criteria for space mirrors are lightweight and high stiffness. The traditional lightweight mirror structures of web and arch design have played an important role in the past decades and have been widely used. With the development of the aerospace industry and the improvement of relevant technical requirements of space optical systems, a variety of design and optimization methods have been applied to the field of lightweight design for mirror core structures. In recent years, especially after the rapid development of metal 3D printing, irregular structures, represented by lattice and Voronoi, which show multifaced outstanding performance and greatly increase the freedom of mirror design, will play an important role in the future [5]. Looking back at the development history of the recent dozens of lightweight design and optimization of space mirrors (Figure 24), the design level has been continuously improved while the manufacturing technology has been constantly iterative so that innovative structures have been continuously manufactured with complex surface shapes and complex mechanical geometric shapes, which are characterized by lightweight, high strength/stiffness relative to weight and aesthetics.

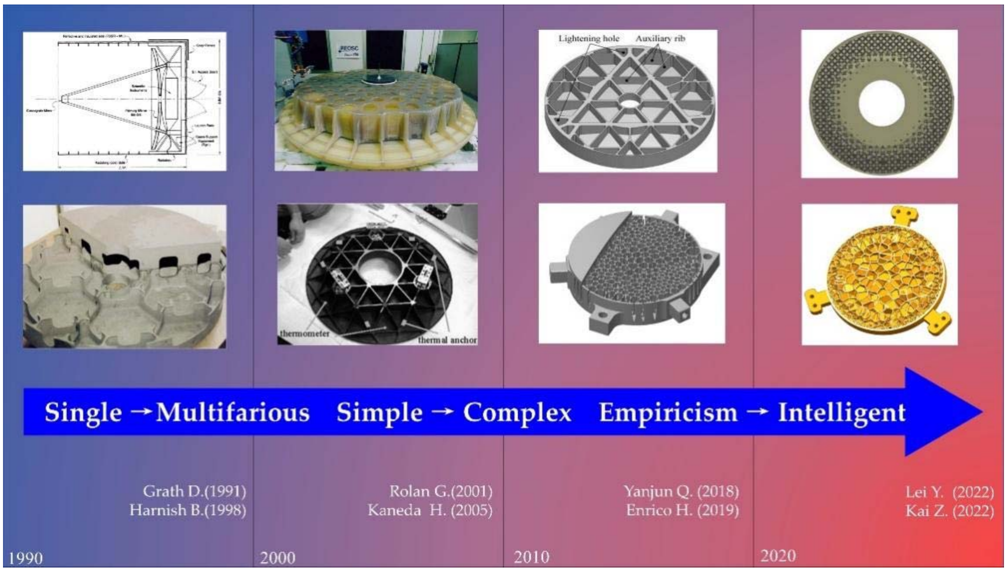


Figure 24. Typical lightweight mirror designs at different development stages in recent decades [8,9,40,70,73–76].

Therefore, future work and trends of optimizing the design of reduced-weight mirrors may focus on the following four topics:

(1) Explore and develop the application of 3D printing in the field of mirror manufacturing, including extending the usable materials, perfecting the printing technology to enable the fabrication of more refined bio-inspired structures, etc. With the rapid development of this technology, the mirror with complex geometries could be manufactured successfully [77]. The future priorities to introduce AM-made mirrors are developing a reliable and traceable process chain from design and development via manufacturing, post-processing, assembly, and integration to verification and final inspection [78,79].

(2) Topology optimization technology will continue to play an important role in the field of lightweight mirror design. Especially for mirrors manufactured by AM, they will be occasionally affected by process parameters, material properties, and structures during processing. Future related research will endeavor to develop an effective model to accurately predict product performance and simulate a more accurate polishing, or diamond turning, environment with the intention to realize the integrated design of the material, process, structure, and performance [31,44].

(3) Lattice and Voronoi, unconventional structures realized by 3D printing technology, show excellent weight reduction and mechanical properties, will become a significant direction with a good development prospect. It's a promising idea to use the combination of topology optimization, lattice, and other methods to improve structures synergistically, then reasonable tools and indicators should be used to verify the structural performance. Mirrors with complex structures are limited by some factors, such as the accuracy of AM, lack of mature structural algorithms, and tough post-processing, which will be a promising issue and possess extensive engineering application prospects [79].

(4) Scientific and technological problems can be solved via the investigation of natural structures and materials. For example, the honeycomb structure, constantly used in lightweight mirrors, is inspired by the bee honeycomb. Biomimicry can be used to improve mirror structures by learning naturally excellent structures. Artificial intelligence (AI) and machine learning could also facilitate the design of bio-inspired structures [80].

6. Conclusions

The present review introduces a series of advances in the structural design of space mirrors mainly including traditional machining structural design, topology optimization, and special designs such as lattices and Voronoi structures. Meanwhile, the application and performance of different designs are compared for reference. With the continuous development of design technologies and AM, more mirrors with innovative structures and excellent performance will be put into practical engineering applications in the future.

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