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EARLY STUDY ON THE APPLICATION OF NEXCERA ULTRA LOW THERMAL EXPANSION CERAMIC TO SPACE TELESCOPES

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I. INTRODUCTION

Optical mirrors for space telescopes, which require high precision and high thermal stability, have commonly been made of glass materials such as ultra low expansion glass (e.g. ULE®) or extremely low expansion glass-ceramic (e.g. ZERODUR® or CLEARCERAM®). These materials have been well-known for their reliability due to their long history of achievements in many space applications.

Currently, ultra low thermal expansion ceramic NEXCERA™ is regarded a promising material essential for ultra-lightweight and thermally-stable optics for future optical missions that require extremely high observation performance. NEXCERA is a cordierite-based polycrystalline ceramic and has been developed by Krosaki Harima Corporation, one of the leading companies of advanced ceramics in Japan.

NEXCERA has a high specific stiffness, extremely low coefficient of thermal expansion (CTE) and excellent long term stability. In the previous paper, the long term dimensional stability of NEXCERA was reported as 0.01 ± 0.01 ppm over 13 months [1]. The excellent polishing characteristics and new development of material composition suitable for mirror applications were also reported in a recent paper. This material was polished to a precise mirror surface using Magnetorheological Finishing (MRF) technology and provided the best surface roughness of less than 1nm RMS [2]. For these reasons, NEXCERA has been used not only as structural components such as calibration tools and primary standards but also as optical reflecting mirrors in the precision metrology field requiring high accuracy and stability.

In the previous study, the NEXCERA mirror of 340 mm in diameter was successfully slimmed down to 5.4 kg (Areal density : 60 kg/m^2) with a precise flatness of less than $\lambda/10$ [3]. In order to apply NEXCERA to large scale space optics, further weight reduction is one of the technical issues to be solved. This paper presents the results of a prototype of an ultra-lightweight mirror substrate using advanced manufacturing technologies.

II. NEXCERA MATERIAL PROPERTIES

Ultra low thermal expansion ceramic NEXCERA is a cordierite ($2MgO\text{-}2Al_2O_3\text{-}5SiO_2$) based ceramic and has advanced material properties to meet severe requirements of space applications. Its key properties are a high specific stiffness (140 GPa / 2.55 g/cm^3) [2] and high long term stability (0.01 ppm / 13 months) [1] combined with an extremely low CTE (< 0.03 ppm/K) at room temperature [2]. Its high stability against thermal disturbance and secular change allow it to be applied to optical components in earth orbiting satellites.

Figure 1 shows the comparison between NEXCERA, low expansion glasses, CFRPs, Invar alloys and other advanced ceramic materials in terms of CTE and specific stiffness. As shown in Fig. 1, NEXCERA has the same CTE as low expansion glass materials and higher specific stiffness than these glasses.

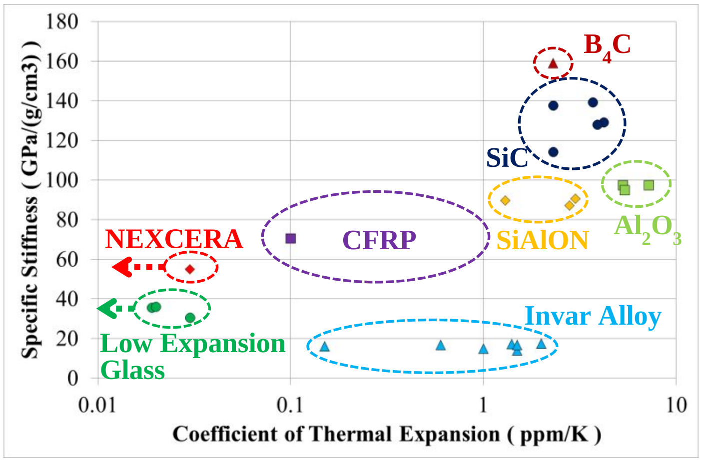


Fig. 1. CTE and specific stiffness of NEXCERA compared with other materials

The principle properties of NEXCERA and typical glass materials that have been applied to space optics are shown in Tab. 1. The density, CTE and specific heat properties of all these materials are almost at the same degree. On the other hand, NEXCERA has two major advantages in its mechanical properties for space applications.

The specific stiffness of NEXCERA is about one-and-a-half times higher than that of glass materials. This means that this material has a competitive advantage in good balance between lightweight and high rigidity over glass materials. Another advantage of NEXCERA property is higher thermal conductivity that is highly beneficial to homogenize a temperature distribution against thermal cycle loads on orbit. Although the strength of NEXCERA seems to be higher than that of other materials, it's important to note that the strength of glass and ceramics is not a material property like the Young's modulus and dependent on the microstructure of the surface, the area of the surface exposed to tensile stress, the rate of stress increase and the environmental media [5].

Tab. 1. Principle properties at room temperature of typical materials applied to space optics.

Properties	NEXCERA N117B [2]	ZERODUR Class 0 [4]	CLEARCERAM -Z HS [6]	ULE 7972 Standard [7]
Density ρ [g/cm^3]	2.55	2.53	2.55	2.21
Young's modulus E [GPa]	137	90.3	92	67.6
Specific Stiffness E/ρ [GPa/(g/cm^3)]	53.7	35.7	36.1	30.6
Poisson's ratio ν	0.31	0.24	0.25	0.17
Bending Strength [MPa]	220	Refer [5]	122	49.8
CTE [ppm/K]	± 0.03	± 0.02	± 0.02	± 0.03
Thermal conductivity [W/(mK)]	4.2	1.46	1.54	1.31
Specific Heat [J/(gK)]	0.78	0.80	0.77	0.77

III. PROTOTYPING AN ULTRA-LIGHTWEIGHT MIRROR MOCK-UP

As the first step in this study, a prototype model of a mirror substrate made of NEXCERA was designed to have good balance between being ultra-lightweight and highly-rigid. A smaller mock-up with almost the same scale for rib patterns and thickness was extracted from the former design and partially manufactured. This first step has permitted to investigate and to validate the actual manufacturing capability.

A. Design of the Ø 1.8m Mirror Demonstrator

Japan Aerospace Exploration Agency (JAXA) has designed an ultra-lightweight and highly-rigid mirror of 1.8 meters in diameter to conceptual design study of future optical telescopes for high-resolution earth observation. The features of this mirror demonstrator are as follows:

- Extremely low thermal deformation due to thermal environment on low earth orbit
- Extremely high rigidity with a closed-back structure (diffusion bonding)
- A triangular pattern of very thin ribs (1.7 mm thick)
- Sub-ribs (1.3mm thick and 8 mm high located in 150 mm deep from rib opening surface)
- Concave optical face (2.0 mm thick)

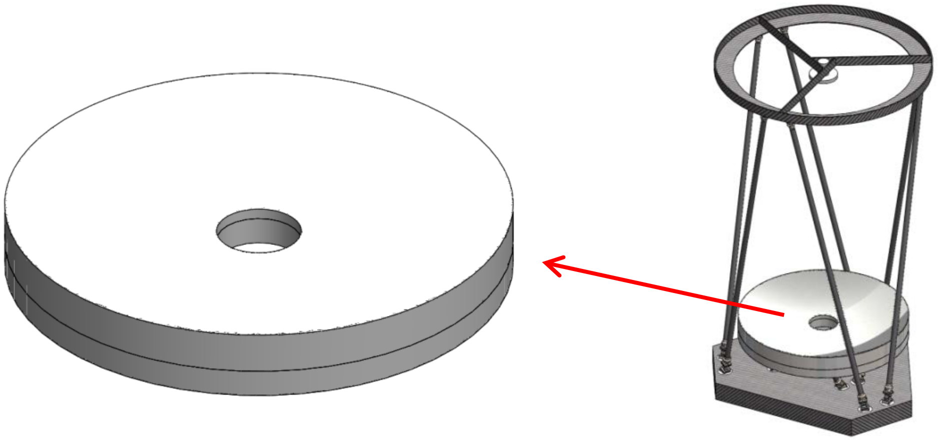


Fig. 2. CAD Model of the Ø 1.8m Mirror Demonstrator

Figure 2 shows the CAD model of the mirror demonstrator and conceptual drawing of telescope system. The telescope components except the main mirror, such as optical bench, truss assembly, spider arm and secondary mirror shown in Fig. 2, are tentative imaginary drawings. The diameter and edge height of the main mirror is 1.8 m and 300 mm, and the mass is less than 102 kg leading to the areal density of less than 40 kg/m^2. Although the mass seems to be heavier than that of similar recent studies, it's important to note that the mass was calculated under an extremely high-rigid configuration with a closed-back structure. The mass of only the optical face body under an open-back configuration was estimated to be 58 kg leading to the areal density of less than 23 kg/m^2. This value compares favourably with that of other recent ultra-lightweight mirrors.

Figure 3 shows the manufacturing sequence of the mirror substrate with a closed-back structure. Its key technology is diffusion bonding using hot isostatic pressing (HIP) that makes it possible to directly form a joint without any adhesive agent. The strength of the boundary face bonded by appropriate HIP condition is known to have the same adequate mechanical strength as monolithic materials. A high-precision CNC machining technology for dimensionally accurate rib patterns of both bodies and surface matching of both rib opening surfaces is also important to avoid defective bonding in the HIP process and suppress thermal residual stress after bonding.

Figure 4 shows the results of the eigenvalue analysis of the mirror under free boundary conditions. Despite the low mass and large size, the first eigen frequency was above 450 Hz and the first out-of-plane vibration mode was at 700 Hz. This means the mirror has a sufficiently high-rigidity allowing a decoupling with large vibration of launchers during launch and micro vibration from spacecraft driving mechanisms on orbit. A micro vibration on orbit due to driving mechanisms has been a major issue for high-resolution observations, and space optics for these purposes should be designed not to be affected by harmful micro vibration.

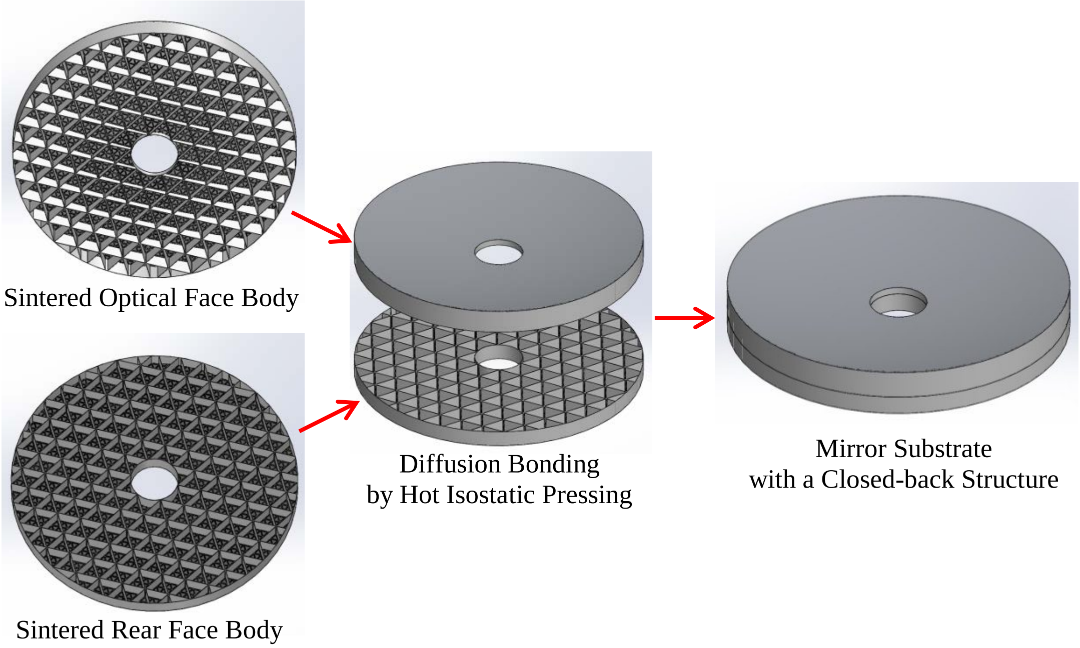
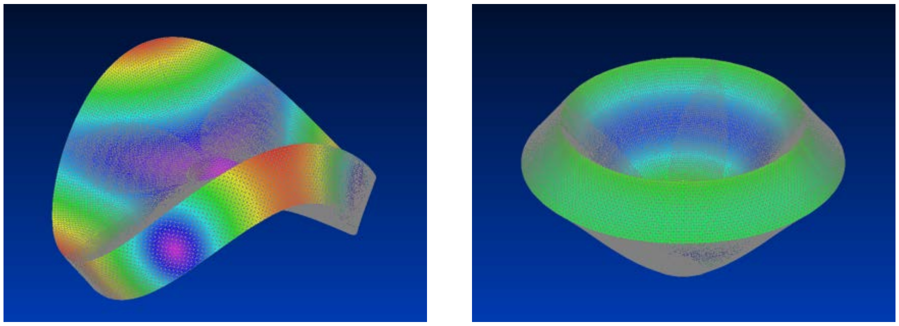


Fig. 3. Schematic of manufacturing sequence of the mirror substrate with a closed-back structure



Mode 1: 456 Hz Mode 2: 706 Hz

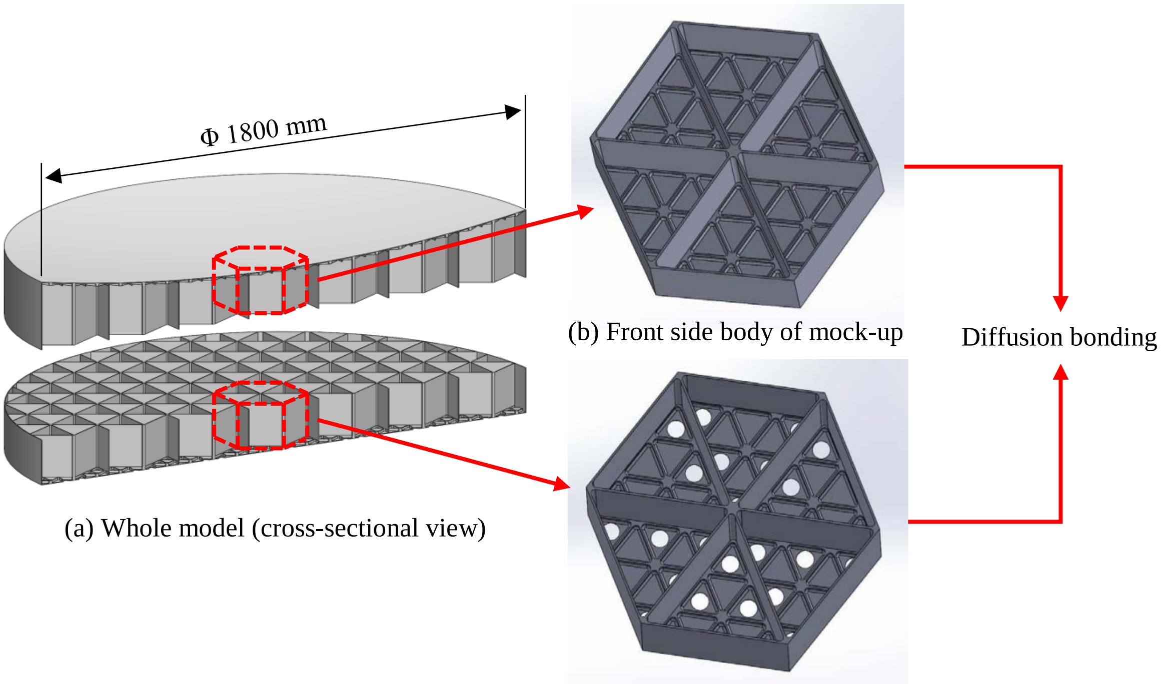
Fig. 4. Eigen frequency of the Ø 1.8m Mirror Demonstrator

B. Prototyping of the Smaller Mock-up

The smaller mock-up with almost the same scale for rib patterns and thickness was extracted from the former design and partially manufactured. The features of this mock-up are as follows:

- A unit cell of the rib pattern
- Diffusion bonding front side body and rear side body
- Hexagonal outline, 230 mm between opposite corners
- A triangular pattern of very thin ribs (1.7 mm thick for 150 mm deep)
- Sub-ribs (1.3mm thick and 8 mm high located in 150 mm deep from rib opening surface)
- Flat optical face (2.0 mm thick)

The CAD model of the mock-up is shown in Fig. 5, and the manufacturing sequence is presented in Fig. 6. The geometry of the optical face was changed to a flat surface to simplify this prototyping and select a focus on the technology for ultra-lightweight mirror substrate. The front side body and rear side body were manufactured separately, and then diffusion bonded using the HIP process. The manufacturing process of NEXCERA product is able to use near net shape forming before sintering, meaning it's possible to considerably shorten machining time relative to hollowing from sintered bulk materials which is a commonly-used machining process to lighten glass mirrors.



(a) Whole model (cross-sectional view)

(b) Front side body of mock-up

(c) Rear side body of mock-up

Fig. 5. CAD model of the smaller mock-up

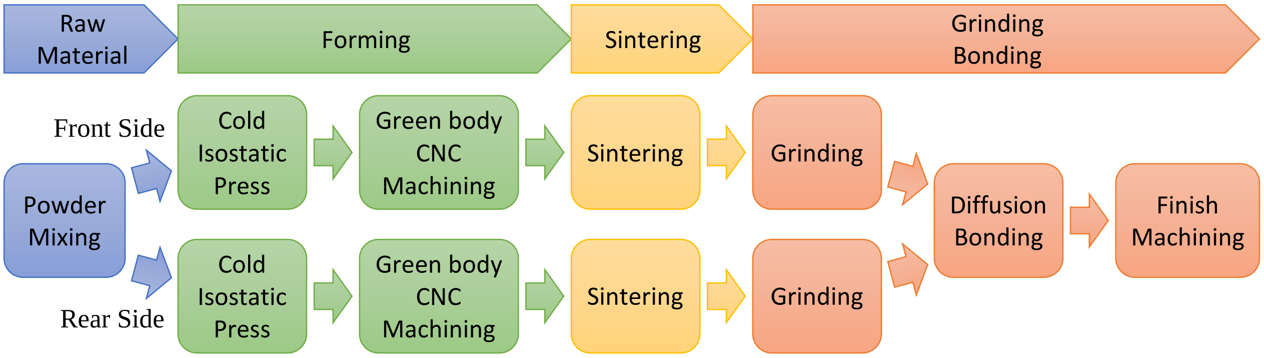
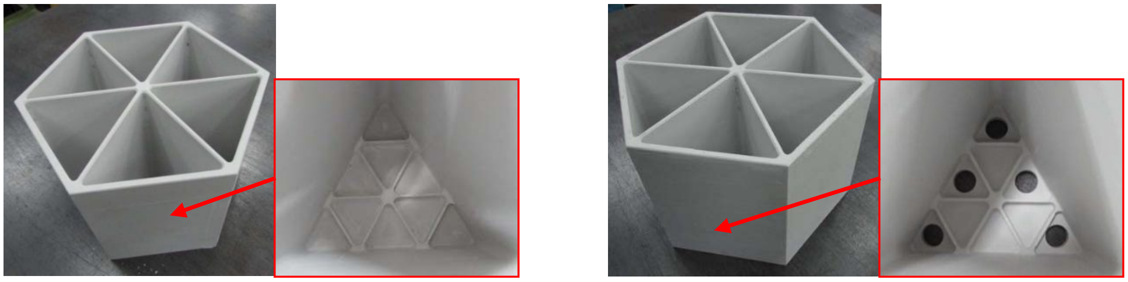


Fig. 6. Manufacturing sequence of the mock-up

Each green body was machined from a block of raw material that was pressed from powder to the desired-shape block using cold isostatic press (CIP). The technical challenging issues of green machining were very thin ribs, small radius at each corner (R3 mm for 150 mm deep), sub-ribs located in the deep place (150 mm deep from narrow opening). Despite the difficulty in green machining, the process conditions such as tool shape, cutting feed rate, order of processing and so on were optimized through trials and errors, and finally both bodies were successfully manufactured as shown in Fig. 7.

Each body was then sintered as shown in Fig. 8, and then ground to final rib geometry before diffusion bonding as shown in Fig. 9. The thickness of ribs was further reduced to a target thickness of 1.7 mm from this grinding process. That is because there are limitations to reduce the thickness of green body using CNC machining due to its low strength and ease of chipping before sintering like chalk. The grinding process conditions were also optimized to achieve both processing reliability and machining efficiency through trials and errors. According to the process conditions confirmed through this prototyping, the thickness of ribs of NEXCERA mirror substrate could be much thinner less than 1.7 mm for 150 mm deep ribs.

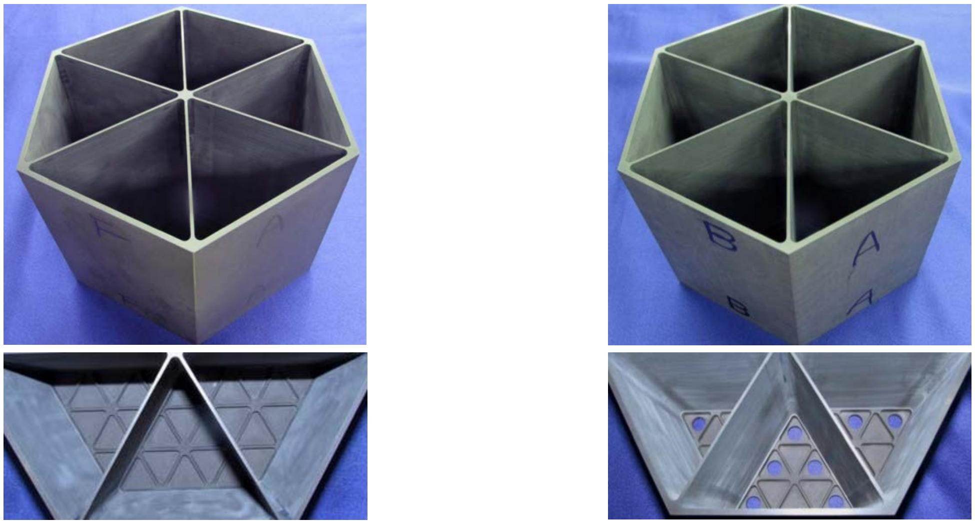


(a) Front side body (b) Rear side body

Fig. 7. Green bodies after near net shape CNC machining

(a) Front side body (b) Rear side body

Fig. 8. Sintered bodies before grinding process



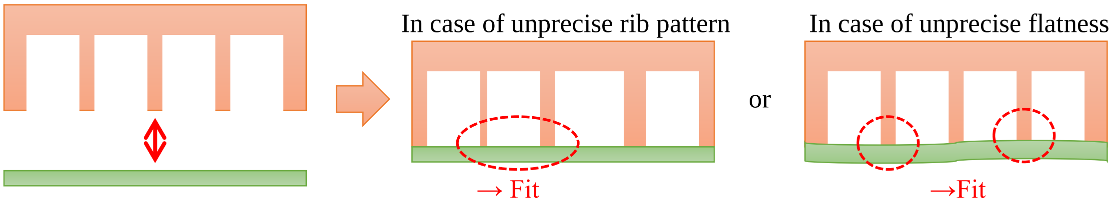
(a) Front side body (b) Rear side body

Fig. 9. Sintered bodies after grinding process

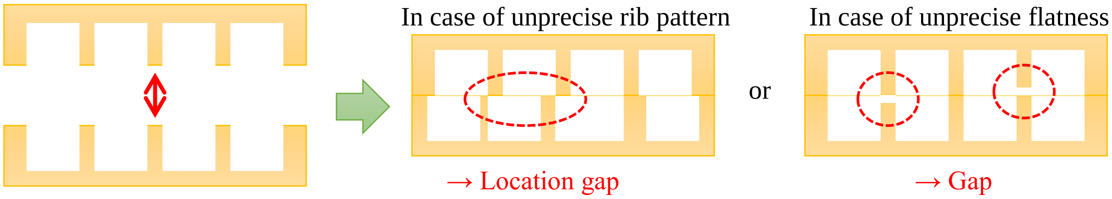
Figure 10 illustrates two configurations of bonding to form light-weighted closed-back structures of mirror substrates. Configuration (a) have been generally applied, because the bonded face sheet could be fit comfortably into the other rib opening surface during the HIP process due to its flexibility, and bonding defects are less likely to occur and the reliability is relatively high. Although configuration (b) is much more difficult than configuration (a), configuration (b) makes it possible to form taller and more rigid closed back structures. A high-precision machining is necessary under configuration (b), because the rigid rib couldn't be fit into another rib opening surface during the HIP process due to their high stiffness as shown in Fig.10. At this prototyping, we dared to try difficult configuration (b) for the validation of diffusion bonding technology. Despite the difficulty in bonding configuration, the diffusion bonding process was successfully conducted as shown in Fig. 11. The many holes of the rear face serve as an air way in the HIP process. The important points of successfully diffusion bonding are high-precision machining of rib patterns and the flatness of both rib opening surfaces.

Finally, all measurements were checked in conformity with the drawing and non-destructive inspection of bonding face was conducted by two inspection techniques, ultrasonic flaw detection and X-ray computed tomography scanner. We can mention in particular,

- Rib thickness: between 1.63 and 1.79 mm (target @ 1.70 ± 0.1 mm)
- Optical face thickness: between 1.90 and 1.94 mm (target @ 2.00 ± 0.1mm)
- Weight: 2.39kg (target 2.26kg)
- Bonding defects were not detected at all by ultrasonic inspection or X-ray CT inspection

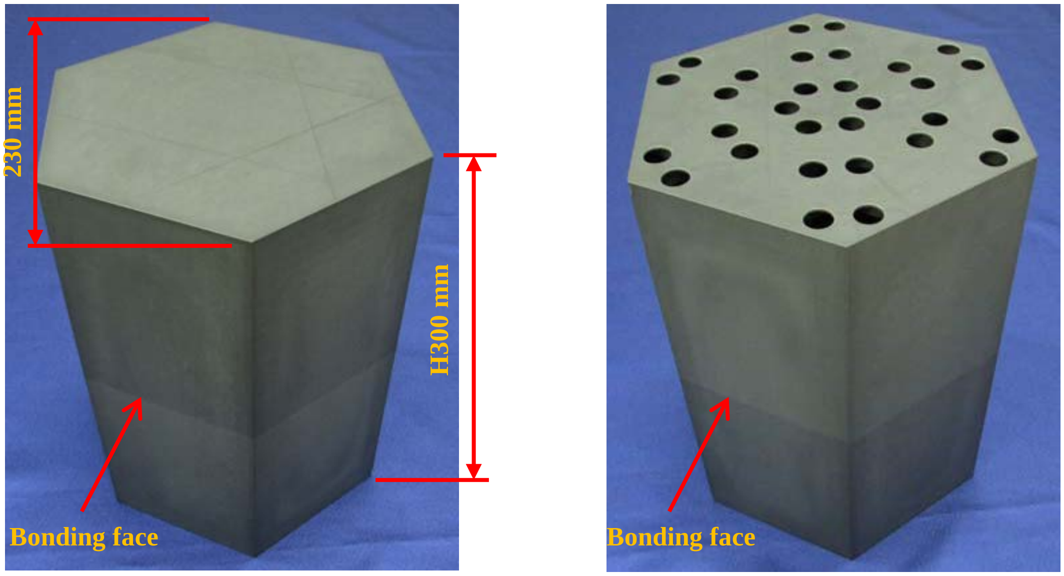


(a) Bonding rib edge to face sheet



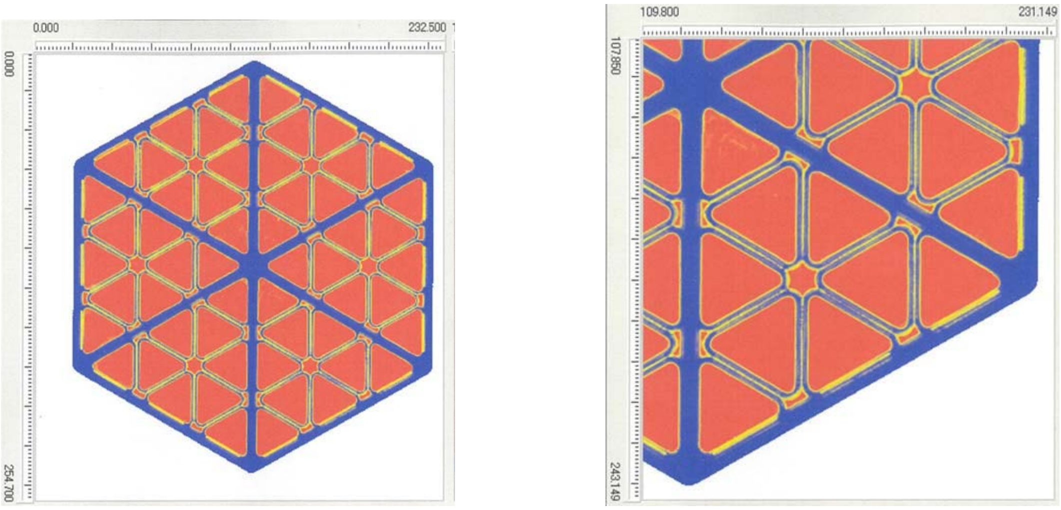
(b) Bonding rib edge to the other rib edge

Fig. 10. Configurations of diffusion bonding and influences of machining errors



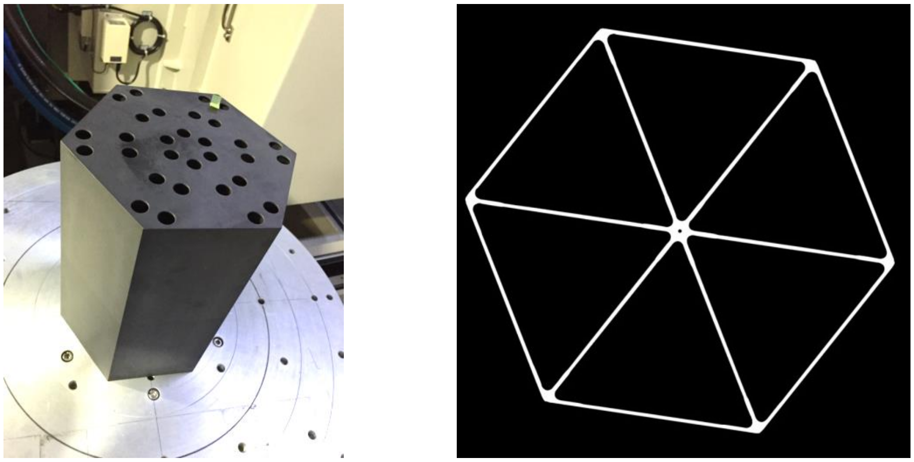
(a) Front side (b) Rear side

Fig. 11. Diffusion bonded body after HIP process and finish machining process

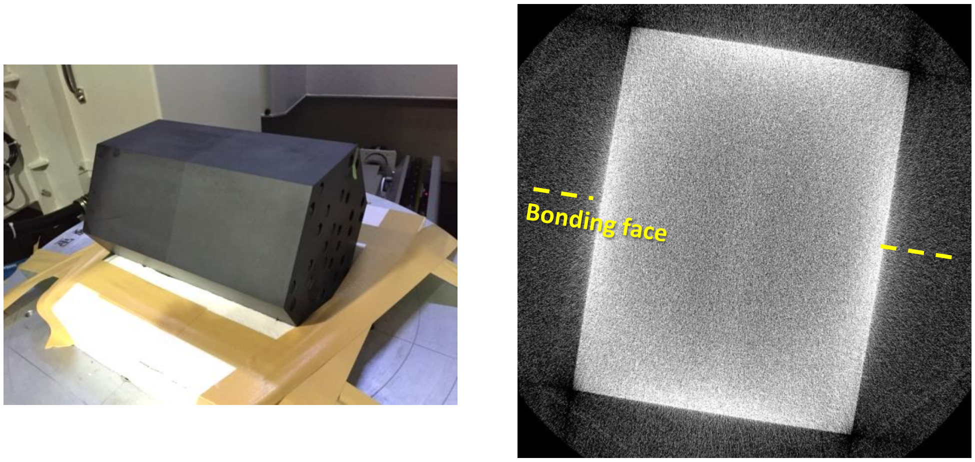


(a) Whole area (b) Enlarged view

Fig. 12. Results of the ultrasonic inspection



(a) Transverse cross section (bonding face)



(b) Vertical cross section (rib wall)

Fig. 13. Results of the X-ray CT inspection

IV. CONCLUSIONS

An ultra-lightweight and high-rigid prototype model of the NEXCERA mirror substrate was designed, and partially manufactured as the first step in this study. The dimensions and rib arrangements were conservatively designed for the highly-rigid primary mirror of 1800 mm in diameter and 300 mm in height in a conceptual optical telescope. The substrate had a closed-back structure to achieve sufficient rigidity and stability for large scale space optics.

The smaller mock-up with almost the same scale for rib patterns and thickness was extracted from the former design and partially manufactured. The mock-up consisted of a front side body and rear side body that were bonded using diffusion bonding technology. Each body has a hexagonal outline, 230 mm between opposite corners and 150 mm in height. These bodies were formed and sintered separately, and then the rib walls were ground thinly to the process limitation of 1.7 mm thickness. The ground bodies were then bonded to form a closed-back structure, and the outer shape of bonded bodies was finished by the grinding thereafter. The top plate was ground thinly to 2 mm thickness. Finally, all measurements were checked and there were no problems in particular. Bonding defects were not detected at all by ultrasonic inspection or X-ray CT inspection, in spite of difficulties in this bonding configuration.

According to the design parameters confirmed through this prototyping, NEXCERA mirror substrate could be much lighter less than 40 kg/m^2 with highly-rigid closed-back structures or less than 23 kg/m^2 with open-back structures. As a result of this work, it is expected that NEXCERA mirror will be applied to large scale space optics that require a combination of ultra-lightweight, high-precision, high-rigidity, high-thermal-stability and high-long-term-stability.

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