1 Introduction
A quick and extensive survey using space satellites has become increasingly important, for example, to rapidly assess the damage of disasters such as major earthquakes, tsunamis, or hurricanes. The interest in an astronomical observation in more detail has also increased to research mechanisms of the universe. With a growing need for data from satellites, the observation performance required for satellites has been increasing to an ever-greater extent. In particular, the angular or spatial resolution of an observation is one of the key specifications used to determine satellite performance and based on the minimum angle or distance at which points can be distinguished as individuals. Moreover, it describes the ability of any image-forming device such as an optical or radio telescope, or a camera, to distinguish small details of an object. Actually, it also depends on various optical parameters, but according to the “Rayleigh criterion”, the angular resolution can be easily estimated from the wavelength of the light and the diameter of the aperture: $\sin \theta = 1.22 \frac{\lambda}{D}$, where $\theta$ is the angular resolution, $\lambda$ is the wavelength of the light, and $D$ is the diameter of the optical aperture [1]. It can be seen that the greater the diameter of the optical aperture, the greater the resolution, because another parameter, namely wavelength $\lambda$, is strictly defined by the nature of the observations made for the satellite mission. The spatial resolution is also inversely proportional to the diameter of the optical aperture. Generally, the characteristic of a first lens or main mirror of an optical system is the dominant factor used to determine the overall performance. Additionally, a reflecting telescope is commonly used for space telescopes to get a really good view of ground objects or collect low-intensity lights from far-distant stars or galaxies. Therefore, one effective solution involves enlarging the aperture diameter of the main telescope mirror. Figure 1 plots the relation between the aperture diameter of the main mirror and the observation resolution on the ground compared with world’s major earth observation satellites. This plot is edited from only publicly available information rather than accurate data because details about actual satellite performance are generally sensitive and confidential information. It may also depend on other parameters such as the altitude of the satellite orbits or the size of the field of view, but it can be seen that telescopes with a large main mirror can distinguish fine details of ground objects. That means space telescopes have increasingly large mirrors so they can see ever finer details of ground objects or stars.

Of course the larger the aperture diameter of the main mirror, the heavier the weight. However, the maximum weight of satellites is limited by the launch capacity of transportation vehicles. The main mirror is the key element of all satellite instruments and influences the construction feature of whole satellite structures and their weight, meaning the mirrors must effectively balance the need for a large aperture and to remain lightweight. Optical telescope mirrors, which require surface roughness of several nanometers, are commonly made of glass or ceramic such as ultra low expansion glass (ULE®), zero expansion glass ceramic (ZERODUR®) and silicon carbide (SiC).
These materials can easily attain sufficiently precise surface by optical polishing, but it’s difficult to reduce the weight due to the material properties and fabrication process. To ensure effective balance between high rigidity and light weight, the rear side of mirrors made of these materials is commonly hollowed out from bulk material by machining and rib structures are constructed as shown in Figure 2.

Although this was successful in reducing weight by more than 90% relative to the bulk material, the percentage remains limited due to the processable thickness of the rib wall. Areal density is an important factor in space mirror technology to evaluate the achievement of weight saving. It’s desired to make as low as possible with keeping adequate stiffness. As an example, areal density of the primary reflector of the HERSCHEL telescope was 21.8 kg/m$^2$ [2]. It was composed of 12 SiC segments brazed together and the segment was lightweighted with rib structures in the rear face. In other examples, the Advanced Mirror System Demonstrator (AMSD) for James Webb Space Telescope (JWST) successfully demonstrated the ability to manufacture Φ 1.3 m ULE mirrors with areal densities of 18 kg/m$^2$. While AMSD achieved a significant weight reduction of ULE mirrors with the development of a qualified manufacturing process, when it came time to insert these mirrors into the JWST architecture, it was discovered that they would not survive the launch loads because they were not stiff enough. It was necessary to add 10 kg/m$^2$ of mass, bringing their areal densities up to 28 kg/m$^2$ [3]. These previous studies suggest that it’s difficult to reduce the weight of space telescope mirrors any more with traditional materials.

In contrast, carbon fiber reinforced plastics (CFRP) are ultra-lightweight with low density. CFRP are also superior in terms of the fabrication of thin-wall structures by stacking thin prepreg layers and using honeycomb core sandwich structures, and have successfully reduced weight by more than 95%. Since the CFRP density is lower than that of other typical materials used for space telescope mirrors, CFRP sandwich structures have a great advantage in terms of weight saving. As an example, Composite Optics, Inc. designed and fabricated a Φ 2 m all-composite mirror to demonstrate that a large CFRP mirror could meet the requirement of space telescopes in terms of lightweight, surface precision and thermal stability. After fabrication and testing, the actual areal weight of the mirror was 10 kg/m$^2$, and the figure accuracy was 2.3 μm RMS (root mean square) at room temperature [4]. We also fabricated a Φ 0.3 m CFRP sandwich mirror composed of CFRP skins and CFRP honeycomb core as shown in Figure 4 and achieved the areal density of less than 9 kg/m$^2$ in a previous study [5]. Furthermore, because this demonstrated mirror was designed to have more than sufficient rigidity for its size, it’s possible to make the mirror much lighter.
Additionally, CFRP have a high specific stiffness and their coefficient of thermal expansion (CTE) can be tailored sufficiently low over a wide temperature range, as shown in Figure 5 and 6, making them widely applicable for structural members of satellites. Their excellent properties are also suitable for components requiring high accuracy such as reflectors and telescope structures. Table 1 compares the CFRP properties with other candidate materials for space telescope mirrors. Since the focus on this paper is on mechanical and thermal aspects of CFRP mirrors, only the relevant properties are included in Table 1. The data for the CFRP were obtained from the measurement of CFRP quasi-isotropic laminated plates composed of the same materials as the demonstrated CFRP mirror. Other data except for CFRP were obtained from references. All values in this table are estimated at room temperature and vary depending on the details of the materials or ambient environments. Table 1 clearly shows that SiC offers higher rigidity and conductivity compared with other materials. However, it exhibits one or two orders of magnitude higher thermal expansion which is detrimental to dimensional changes brought about by temperature variations in operating environment. Not as higher as SiC, CFRP also have high rigidity and conductivity, and not as lower as ULE or ZERODUR, CFRP also have low CTE. It’s notable that CFRP have no serious weak point in

![Fig. 5. Critical properties for mirror materials.](image)

![Fig. 6. CTE versus temperature curves for typical materials used for space telescope mirrors [4].](image)

<table>
<thead>
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<tbody>
<tr>
<td>Density ( \rho ) (10^3 kg/m^3)</td>
<td>Low</td>
<td>1.68</td>
<td>2.71</td>
<td>2.21</td>
<td>2.53</td>
<td>3.16</td>
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<tr>
<td>Elastic Modulus ( E ) (GPa)</td>
<td>High</td>
<td>116</td>
<td>68.3</td>
<td>67.6</td>
<td>90.3</td>
<td>420</td>
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<td>Specific Stiffness ( E/\rho ) (10^6 m)</td>
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<td>2.57</td>
<td>3.12</td>
<td>3.64</td>
<td>13.6</td>
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<tr>
<td>CTE ( \alpha ) (ppm/K)</td>
<td>Low</td>
<td>&lt; 0.49</td>
<td>22.7</td>
<td>0 ± 0.03</td>
<td>0 ± 0.05</td>
<td>2</td>
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<tr>
<td>Thermal Conductivity ( k ) (W/m/K)</td>
<td>High</td>
<td>46.1 (In-plane)</td>
<td>156</td>
<td>1.31</td>
<td>1.46</td>
<td>190</td>
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<td>Thermal Stability ( k/\alpha ) (10^6 W/m)</td>
<td>High</td>
<td>94.1</td>
<td>6.87</td>
<td>&gt; 43.7</td>
<td>&gt; 29.2</td>
<td>95</td>
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<tr>
<td>Formability of Large Scale Mirrors</td>
<td>Good</td>
<td>Good (Integral mold)</td>
<td>Medium (Braise, Weld)</td>
<td>Medium (Fusion, Frit)</td>
<td>Medium (&lt; 4.5m)</td>
<td>Medium (Braise, Bond)</td>
</tr>
<tr>
<td>Weight Reduction</td>
<td>Good</td>
<td>Good (Sandwich)</td>
<td>Medium (Machining)</td>
<td>Medium (Machining)</td>
<td>Difficult (Machining)</td>
<td>Difficult (Machining)</td>
</tr>
<tr>
<td>Formability of Precise Surface</td>
<td>Good</td>
<td>Difficult</td>
<td>Medium</td>
<td>Good</td>
<td>Good</td>
<td>Good ~ Medium</td>
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<td>Status</td>
<td>Routine</td>
<td>Under Development</td>
<td>Routine</td>
<td>Routine</td>
<td>Routine</td>
<td>Flight Proven</td>
</tr>
</tbody>
</table>
fundamental properties. Additionally, their thermomechanical properties can be tailored to the desired values with the appropriate choice of fiber type, resin chemistry, volume fractions, and lay-up orientation. For these reasons, CFRP have a lengthy track record in applications for structural members of many satellites such as truss elements and structure panels which is required to be mechanically rigid and thermally stable.

In addition, other important aspects such as formabilities of large scale and precise surfaces are summarized in the lower part of Table 1. Although CFRP have superior fundamental properties, the practical use of CFRP mirrors as optical elements for space telescopes remains unachieved to date, except for developing models [4] [5]. The reasons include the fact that the surface accuracy has not met stringent requirements and the dimensional stability against space environments has not been sufficiently validated [9] [10]. For example, the surface accuracy required for visible or near-infrared light space telescopes is measured in nanometers. However, CFRP surfaces have micro asperities known as fiber print-through caused by chemical and thermal shrinkage while curing as shown in Figure 7. The surface roughness is usually at least a few hundred nanometer RMS when fabricated as is, and too rough for optical telescope mirrors. The thermal stability of the mirror surface is also stringently required at nanometer level in space environments. In particular, mirrors for infrared light telescopes are cooled to cryogenic temperature to reduce radiation noise from the mirror itself, meaning that thermal stability from room temperature to cryogenic temperature is critical issue to validate the surface precision.

In this study, we fabricated CFRP mirrors and made experimental discussions in terms of the formability of precise surface and the thermal stability in space environments.

2 Experimentation

2.1 Design of Demonstrated CFRP Mirrors

We developed all-composite mirrors to demonstrate validity of CFRP mirrors for dimensionally accurate and thermally stable structures. The specimens used in this basic experimental study were comprised of simple flat sandwich panels with CFRP skins and CFRP flex cores.

The prepreg sheets used for the face skins were composed of YSH-60A and NM31 manufactured by Nippon Graphite Fiber (NGF). YSH-60A is a pitch based graphitized carbon fiber and has a moderately high elastic modulus. NM31 is a cyanate ester resin and has properties of low moisture absorption, superior micro-crack resistance and small cure shrinkage relative to epoxy resins. The resin content of the prepreg sheets was designed so that the CTE of CFRP quasi-isotropic laminates could be near-zero. The layup configuration for the face skins was 16 plies with a quasi-isotropic stacking sequence of \([0/ +45/ 90/ -45]_{2s}\).

The cores for sandwich panels were UltraFlex® manufactured by Ultracor, Inc. It’s available a honeycomb core with distinctive cell geometry as shown in Figure 8, and provides similar or higher...
mechanical properties than comparable hexagonal cores of equivalent density. Moreover, it has excellent flexibility and exceptional formability into curvatures. That means it has a great advantage in fabrication of concave or parabolic mirrors relative to hexagonal cores. While the specimens in this study were flat panels, we chose not hexagonal cores but UltraFlex with a view to development into actual concave or parabolic figure of reflectors or mirrors. The cores were made of plain-cloth prepreg mono-sheet composed of high modulus pitch carbon fiber YSH-50A (NGF) and cyanate ester resin RS-3 (TenCate). The fiber direction was 45° to the core height, the core size was 3/8” and the density was 32 kg/m³ (2 pcf). The areal density was 1.3 kg/m² with 40 mm thickness. The dimensions of the specimens were 150 × 150 × 43 mm, with the thickness of each skin was 1.5 mm and the core height was 40 mm. The areal size was decided to be able to easily fabricate and evaluate in a low cost way with laboratory-based experimental installations. The thickness of the face skins and the core height were designed to have sufficient rigidity and survive assumed launch loads for more than a meter scale mirrors.

2.2 Fabrication Process

For fabrication of the face skins, unidirectional prepreg sheets were stacked in the quasi-isotropic configuration on a layup tool made of synthetic fused silica which was polished to improve the surface flatness to less than λ/10 (λ is 632.8 nm which is the wavelength of measurement for surface quality assurance). The tool material was selected to reduce thermal distortion of the CFRP laminates in the cooling phase of cure cycle by equalizing both CTE of the laminates and the layup tool. In addition, the surfaces of the cured CFRP skins were expected to have smoothness by replicating the smoothness of the tool. In this experiment, the laminates were sandwiched between same tools with an additional tool placed on the top of the laminates as shown in Figure 9, because thermal symmetry throughout curing process is very important to avoid overall figure errors such as astigmatism, coma, and spherical aberration [12]. The stacked laminates were cured at 175 °C for 2 hours in an autoclave. The back face skins were also cured in the same configuration and conditions.

Pre-cured front and back skins and flex cores were bonded using film adhesive of epoxy resin (AF191, 3M™) on the same tools and symmetrically stacked configuration in an autoclave.

2.3 Replication Process

After sandwich adhesive bonding, the surfaces of the front face skins were coated by thin resin layer as in the replica method using the same polished tool [13]. This is a common approach that is well documented. An additional resin layer is covered micro roughness and mitigated the magnitude of fiber print-through, and results in better surface quality. The steps of the replication process in this study are sketched in Figure 10: First, the surface of the layup tool was polished to the desired smoothness (usually less than λ/10) and mold release agent was spread on the tool, whereupon appropriate amount of epoxy resin for the replica coat, which was degassed in a vacuum, was spread thinly and uniformly over the mold release agent. A pre-cured honeycomb sandwich panel was carefully adhered to the epoxy resin to avoid any air or dust particles infiltrating into the
boundary face, and the resin was cured at room temperature. After bonding cure, the coated mirror was demolded. Generally, the mirror surface is finally overcoated with aluminum or gold to enhance the surface reflectivity and with SiO₂ or MgF₂ to prevent damage and oxidation of aluminum by vacuum evaporation. In this study, both reflection and protection coatings were not applied in order to estimate the thickness of resin layer by a technique of transparency film thickness measurement as mentioned in the next paragraph.

2.4 Measurement of Surface Profile

The surface profiles of the specimens were measured at critical phases of the fabrication and replication processes for follow-up evaluation of the surface profiles during the processes. For precise evaluation, we used a non-contact 3D optical surface profiler (NewView™ 7300, Zygo) based on white light interferometry. The field of view and spatial sampling interval could be compatibly selected with the appropriate choice of objective and zoom lenses. Measurements conditions are shown in Table 2. Moreover, high pass or low pass filtering separated surface profiles into waviness, roughness, and high frequency components. These techniques made it possible to classify the surface errors by spatial factors and error causes [13]. Measurements were executed at 9 points on the surfaces in 3 × 3 reticular pattern of 25 mm wide. The average and dispersion of 9 point data of each measurement condition were evaluated.

Thickness of a resin layer is generally measured from a cross-sectional observation. While this is a direct and accurate measurement, this way is undesirable because the specimen is cut off and destroyed. Therefore, we estimated the thickness by non-destructive method using a technique of transparency film thickness measurement. The Z-axis stage was controlled to come into focus on the top and bottom boundary faces of the resin layer and each stage position was read out from an ultra

Fig. 10. Schematics of the replication process.

Table 2. Measurement conditions of surface profiles.

<table>
<thead>
<tr>
<th>Field of view</th>
<th>Sampling interval</th>
<th>Observed surface profile</th>
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<tbody>
<tr>
<td>0.4 mm × 0.4 mm</td>
<td>0.6 μm</td>
<td>Roughness</td>
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<tr>
<td>1.25 mm × 1.25 mm</td>
<td>1.4 μm</td>
<td></td>
</tr>
<tr>
<td>4 mm × 4 mm</td>
<td>4.4 μm</td>
<td></td>
</tr>
<tr>
<td>12.5 mm × 12.5 mm</td>
<td>14 μm</td>
<td></td>
</tr>
<tr>
<td>40 mm × 40 mm</td>
<td>60 μm</td>
<td></td>
</tr>
<tr>
<td>100 mm × 100 mm</td>
<td>60 μm</td>
<td>Figure accuracy</td>
</tr>
</tbody>
</table>

Fig. 11. Measurement apparatus.
precision linear encoder. Then, the thickness was calculated from the differences of the stage positions. The estimated results by this method were in excellent agreement with the measurement results from a cross-sectional observation in a previous study.

2.5 Thermal Test Configuration

The thermal test configuration is shown in Figure 13 and 14. This configuration was a small laboratory-based experimental system in a low cost way and designed for fundamental optical tests in thermal vacuum environments. One of the specimens coated by replica method was placed at a fixture in a vacuum chamber. The chamber was located on a high performance vibration isolation system which attenuated vibrations from surrounding disturbance sources in all six degrees of freedom by high precision air springs. The thermal environment of the chamber was cooled and heated by a shroud that supported both liquid nitrogen and temperature controlled heaters. The L-shaped fixture to support the specimen was made of copper to homogenize a temperature distribution with high heat transfer and attached to the temperature controlled stage in the shroud. The specimen was not securely fixed but flexibly supported from the fixture to prevent mutual influence of the thermal deformation due to the CTE.
mismatch between the specimen and the fixture. Thermocouples were installed at the four corners on the front and back skins to monitor multipoint temperatures and thermal gradients of the specimen. The surface accuracy throughout thermal test was measured using a laser interferometer (GPI-XP™, Zygo) and the light source was a He-Ne laser which wavelength was 632.8 nm. The measurement area was confined to the central of $\phi$ 100 mm of the specimen due to the aperture diameter of the interferometer. It was located on the same vibration isolation system with the chamber. This equipment layout was important to diminish measurement errors occurred by the relative displacement between the interferometer and the chamber due to vibrations from surrounding disturbance sources. The plane wave laser was irradiated to the specimen surface through the quartz window of the chamber and the surface accuracy was calculated from the observed interferogram patterns. The chamber was evacuated to $1 \times 10^{-4}$ Pa and the thermal condition was planned to cool to 120 K and then heat to 360 K which were easily achieved with liquid nitrogen and heaters. Surfaces were measured every 30 K and the thermal environment in the shroud was temporarily kept at a constant temperature throughout each measurement to prevent thermal disturbance and transiently thermal deformation.

3 Results and Discussions

3.1 Fabrication of Demonstrated CFRP Mirrors

Figure 15 shows photographs of a demonstrated CFRP mirror at three steps of the fabrication and replication processes. It’s obvious that the surface after replica coating was fairly became smooth with a clear reflection image on the surface. The weight was measured 157 grams after replica coating, so that the areal density was 7.0 kg/m². The breakdown of the areal density was as follows: front and back skins were 5.6 kg/m² in total (each skin was 2.8 kg/m²), the flex core was 1.3 kg/m², film adhesive for sandwich bonding was 0.1 kg/m² and replicated resin layer was less than 0.1 kg/m².

3.2 Surface Profile

The surface profiles measured at critical phases of the fabrication processes are shown in Figure 16. The horizontal axes of these graphs are the size of the field of view and vertical axes are the averaged surface accuracy measured at the 9 points on the surface. The contour figures shown in these graphs indicate the surface maps illustrated surface figures or micro roughnesses which are typically observed in each measurement condition.

After fabricating face skins as shown in Figure 16 (a), the overall saddle shapes or spherical shapes were observed at wide measurement areas over 10 × 10 mm. The figure accuracy became larger with increase in the measurement areas and seems to be proportional to the area size. In this zone, the surface profiles were determined by the magnitude of overall figure errors. In case the overall figure errors were simple shapes such as astigmatism, coma, and spherical aberration, it was possible to estimate the magnitude of the errors for large scale mirrors by extrapolating the graphs to the large areas. In the middle areas of 1 to 10 mm square, the overall figure errors made little impact on the surface accuracy relative to the wide areas. Instead the surface accuracy was determined by the streaky patterns. These patterns were observed in fiber directions, not only of the outermost layer but also of the second and third layers. The peak-to-peak amplitude of the patterns was about $\pm$ 0.5 µm and the spatial pitch was 0.2 to 0.5 mm or sometimes several mm. It was considered to be fiber tow print-through in terms of the pattern directions and pitch. In the smallest

(a) CFRP skins.  
(b) After sandwich bonding.  
(c) After epoxy resin coating.  
(Without reflection coating.)

Fig. 15. Photographs of a demonstrated mirror at critical phases of fabrication process.
measurement area of $0.4 \times 0.4$ mm, where area size was smaller than the width of fiber tow, only streaky pattern in the fiber direction of the outermost layer was observed. The amplitude of the pattern was about $\pm 0.1$ µm and the pitch was 5 to 10 µm. It was considered to be individual carbon fiber print-through because the pattern pitch was corresponding to the diameter of the single carbon fibers.

After sandwich bonding as shown in Figure 16 (b), the overall shapes were changed compared to the skins in a greater or lesser degree, but the averaged magnitude of the surface figure errors were almost same. It was thought that the changes of overall figure errors were occurred by the mutual influence of the slight differences in the figure errors of both front and back skins. In contrast, surface errors due to fiber tow and individual carbon fiber print-through in the middle and small areas were nearly-unchanged compared to the skins.

The surfaces became fairly smooth after the replica process as shown in Figure 16 (c). Although the fiber tow patterns in the middle areas did not solved completely, the magnitude of the patterns was fairly mitigated. The individual carbon fiber print-through was completely covered and diminished. The surface roughness could be controlled to within several nm RMS, and the figure accuracy was improved to 0.2 µm RMS at the measurement area of $100 \times 100$ mm. The thickness of replicated resin layer was estimated about 95 µm and its dispersion was about 4 µm by the non-destructive method.

Fig. 16. Surface profiles of a demonstrated CFRP mirror at critical phases of fabrication processes.

Fig. 17. In-focus image of the top and bottom boundary faces of the resin layer.
3.3 Stability under Thermal Test

Figure 18 shows a series of changes of interferogram patterns during thermal test. The actual temperature profile and characteristic surface maps calculated from each interferogram pattern are shown in Figure 19. While the thermal condition was planned to cool to 120 K, cooling operation was actually stopped on the way at 160 K because some belt-like irreflexive zones were observed in the interferogram patterns. As a consequence, these were found to be cracks on the resin layer by an observation after thermal test. Temperature gradients in each skin and between both skins were less than 3 K, meaning the thermal environment was well managed by the shroud.

As shown in Figure 18 and 19, a spherical figure error which was convex upward and streaky patterns due to fiber tow print-trough in the direction of 0°, ±45° and 90° were observed initially. Initial surface

![Fig. 18. Changes of the interferogram patterns during thermal test.](image1)

![Fig. 19. Temperature profile and thermal deformation during thermal test.](image2)
accuracy was 0.1 μm RMS. The fiber tow print-through gradually changed for the worse by cooling from room temperature. In addition, low contrast fringes and high fringe densities of interferogram patterns made it difficult to calculate clear surface maps while cooling. Although they were not clear, it was found that the overall figure errors were included spherical shapes and saddle shapes while cooling. In contrast, the streaky patterns were decreased and reverse saddle shape was occurred while heating in the latter half of the test. A plot of the surface figure error versus temperature is shown in Figure 20. It was found that the surface was relatively stable at a temperature from 240K to 360K, and thermally induced figure error was 0.1 μm RMS at 240K in the first cooling process. The error took a sharp turn for the worse at 240K and it was finally degraded to 2.5 μm RMS at 160K.

The results suggest that the streaky patterns due to fiber tow print-through were caused by chemical and thermal shrinkage of the matrix resin of CFRP while curing process and the thermal residual stress caused by the shrinkage was relaxed with coming close to curing temperature. Therefore, the streaky patterns were almost diminished and fine contrast fringes of interferogram patterns were obtained in the latter half of the test. Additionally, it was thought that the overall figure errors were occurred by the mutual influence between the front skin, back skin and honeycomb core as a bimetallic effect because the saddle shape was occurred in the reverse direction at cooling and heating processes. Moreover, thermal stress was increased with decreasing temperature which means increasing the difference from curing temperature, and result in making cracks on the surface while cooling in the first half of the test. The changes of the surface figures were not repeated at same temperatures both of cooling and heating.
processes in the cold condition because mechanical balance of the surface was changed due to the cracks. Figure 21 shows cracks occurred at 160K and remained on the resin layer after the test. With the detailed measurements, the cracks were stuck out upward from the surface and the height was 2 μm to 4 μm as shown in Figure 22. In addition, surface profile measured after thermal test was obviously degraded as shown in Figure 23. Although the overall shape was seemed mostly unchanged except for the cracks, the surface accuracy in the middle and narrow area was degraded an order of magnitude relative to initial state. In these areas, the surface accuracy was determined by the fiber tow print-through and single carbon fiber print-through. That means these print-thorough were affected by the thermal environments to a greater extent and thermal deformation observed at the short bandwidth less than 100mm was residual after thermal test.

4 Conclusions

In this study, ultra-lightweight and high-accuracy CFRP mirrors for space telescopes were fabricated using the improved fabrication process with the thermally symmetrical configuration. The areal density was achieved 7.0 kg/m², and figure accuracy at 100 mm square and micro roughness was improved to 0.2 μm RMS and 6.2 nm RMS with replicated coating. The measurement system for thermal test with a vacuum chamber and a He-Ne laser interferometer was constructed and the demonstrated mirror was tested at cryogenic temperature. Thermal induced figure error was 0.1 μm RMS at 240K and 2.5 μm RMS at 160K. High-frequency thermal deformation was found to be coincided with fiber tow print-through. These streaky patterns degraded the contrast of fringes of interferogram patterns and made it difficult to calculate clear surface maps. The cracks were occurred at 160K and remained on the surface after thermal test. The direction of all cracks was coincided with the direction of outermost layer. A residual thermal stress between carbon fibers and matrix resin caused by chemical and thermal shrinkage while curing process have the great impact on thermal stability of the CFRP surface. The relaxation of the residual thermal stress and reduction technique of the fiber print-through were residual issue for future works to further improve surface accuracy and thermal stability of CFRP mirrors.

References