Surface modification on a silicon carbide mirror for space application

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Silicon carbide (SiC) is a promising candidate for large-scale mirrors due to its high stiffness and thermal stability. However, it is very challenging to obtain a super smooth surface for high precision optical telescopes due to the intrinsic defects of SiC. In this letter, a super smooth surface with a roughness lower than 1 nm and a surface profile of $\lambda/50$ is achieved by depositing a uniform and dense silicon surface modification cladding by plasma ion assisted deposition (PIAD) on a lightweight concave reaction bonded (RB) SiC mirror, followed by a polishing procedure. Characterization data from the high resolution optical microscope, WYKO profilometer, Zygo interferometer, and nanoindentation are further discussed. The thermal shock resistance test indicates that the surface modification cladding is very stable and shows firm adherence. A reflectance of over 98% in the visible light region is obtained on the spectrometer after being coated with the silver-enhanced coatings.

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Space telescopes are desirable for high resolution and high light collection efficiency. This leads to the fabrication of primary mirrors with large aperture[1−3]. These mirrors must also maintain a precise surface profile when exposed to severe space environments during operation, which require high stiffness and great thermal stability. In addition, weight is always a key factor for space shuttles.

Silicon carbide (SiC) is an ideal blank mirror material with attractive physical and mechanical performance[4]. To date, the HERSCHEL space project has achieved the largest SiC mirror with a 3.5-m diameter and a weight of only 240 kg. As a comparison, the glass primary mirror of the Hubble space telescope is 828 kg with a diameter of 2.4 m. In Fig. 1, the thermal stability (thermal conductivity/CTE) versus specific stiffness (elastic modulus/density) of several widely used for space-borne mirrors is illustrated. A higher thermal stability ensures less mirror distortion. It is a common notion that a higher specific stiffness translates to more lightweight efficiency. In general, the reaction bonded (RB) SiC delivers the best performance.

Owing to the intrinsic defects of SiC mirrors formed during the fabrication process, there is difficulty in meeting the critical specifications of a reflecting telescope when used in visible light regions. Different from the thick (>100 μm) surface modification claddings of chemical vapor deposited (CVD) SiC and sputtering silicon[5−7], in the present work, a thinner (< 20 μm) silicon surface modification cladding was deposited on a large monolithic RB SiC mirror via the plasma ion assisted deposition (PIAD) technique. Thinner surface modification cladding can reduce the stress and processing time, resulting in a much reduced RB SiC mirror distortion.

In Fig. 2, microsteps could be clearly observed by atomic force microscopy (AFM). Since silicon is much softer than SiC, during the polishing process, the quantity of silicon was more easily grinded than SiC, resulting in increased roughness.

Beckmann's scalar scattering theory has proven the relationship between the roughness and the reflecting scattering loss[8]

$$S_{\mathrm{R}} = R_0 \left(\frac{4\pi\sigma n_0}{\lambda} \right)^2, \quad (1)$$

where R_0 is the reflectance of an ideal optical surface without scattering, σ is the root mean square (RMS) roughness, n_0 is the refractive index of the incident medium, and λ is the wavelength.

Equation (1) demonstrates that scattering is highly correlated with the surface roughness. The testing result of the WYKO profilometer of a bare RB SiC sample after polishing is shown in Fig. 3. A significant scattering of about 0.34% (σ=R_{q}, λ=632.8 nm) occurs. Recent results indicate that the primary limitation of the SiC optical system performance is the poor surface quality, not necessarily the profile control.

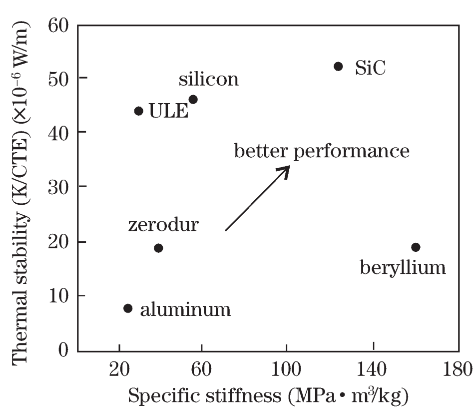

Fig. 1. Thermal stability versus specific stiffness of some blank mirror materials.

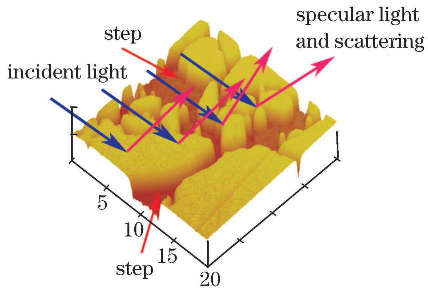

Fig. 2. Scattering occurs when light incidents at the bare polished surface of RB SiC.

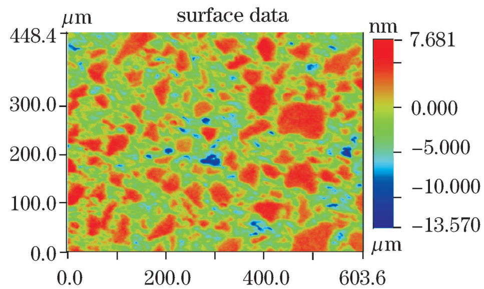

Fig. 3. Testing result of the WYKO profilometer of bare RB SiC sample after polishing.

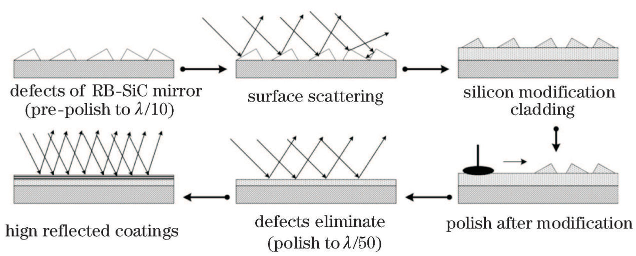

Fig. 4. Surface finish and coatings flow chart.

Silicon surface modification claddings were deposited from the polycrystalline silicon material by an E-gun in a vacuum chamber with a diameter of 2.5 m. Before depositing, the RB SiC mirror and samples were cleaned with acetone and alcohol, respectively, in an ultrasonic bath for 15 min. A Veeco Mark II plasma source was used for the coating process. Pure argon (99.999%) was introduced into the plasma source as working gas. The pressure of the chamber was kept at 6×10^{-3} Pa. Cladding thickness was controlled by an IC/5 crystal controller. A new surface finish process was developed. The overall flow is described in Fig. 4.

Since the monolithic RB SiC mirror was over 600 mm in diameter, it was difficult to perform the tests. Therefore, most tests, except for the surface profile test, were conducted using a 26×26 (mm) control sample.

Surface topographies were tested by a Mitutoyo MF-A-1010 optical microscope in 500× reflection mode. Figure 5(a) shows the photomicrograph of a RB SiC sample without surface modification. The boundary between silicon and SiC, due to the bimetallic effect, can be clearly observed. After coating the silicon surface modification cladding, the RB SiC sample can be more precisely polished, as shown in Fig. 5(b). The surface is very dense and uniform, and without boundary and pinholes.

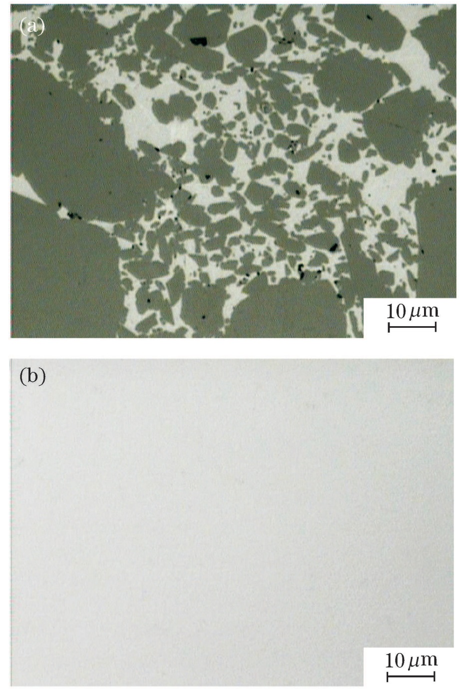

Fig. 5. Photomicrograph of polishing (a) without the surface modification cladding, (b) after coating the surface modification cladding.

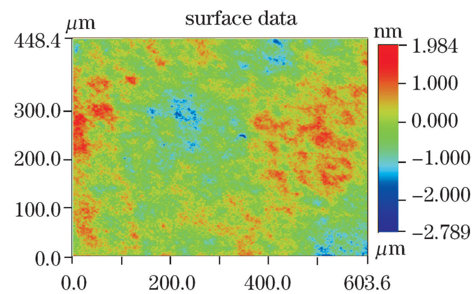

Fig. 6. Testing result of the WYKO profilometer of RB SiC sample after polishing the silicon surface modification cladding.

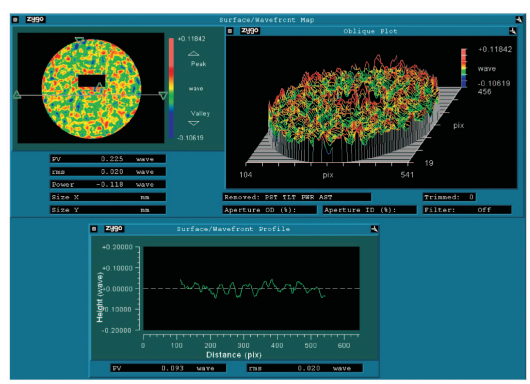

Fig. 7. Two-dimensional, three-dimensional, and surface profile images of the polished silicon surface modification cladding on a large RB SiC mirror.

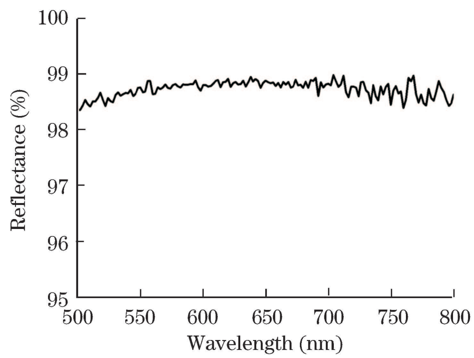

Fig. 8. Reflectance testing result after depositing high reflecting coatings.

Table 1. Testing Results of Hardness (H) and Modulus (E)

No. of Points	H Average Over Defined Range (GPa)	E Average Over Defined Range (GPa)
1	11.279	138.845
2	11.331	138.416
3	10.947	137.715
4	11.034	136.681
5	10.931	137.142
6	11.036	137.64
7	11.311	138.053
8	11.239	138.159
9	11.331	138.789
10	10.936	137.584
11	11.411	138.902
12	11.331	138.832
13	11.079	137.67
14	11.087	136.863
15	11.041	137.288
Average	11.155	137.905

The roughness of the RB SiC mirror surface with the silicon surface modification cladding was measured by a WYKO profilometer. From Fig. 6, it can be seen that the testing area achieves a perfect surface and fine roughness. Compared with the bare polished surface, the roughness greatly decreased from 2.94 nm (R_q) to 0.53 nm (R_q). According to Eq. (1), the scattering loss is only 0.01%, which is 34 times less than that in the traditional techniques.

Surface profile was characterized by a ZYGO interferometer. Figure 7 shows the silicon surface modification cladding after polishing. A good surface profile of $\lambda/50$ (λ=632.8 nm) is achieved. Since the silicon surface modification cladding was single-phased, the bimetallic effect was avoided during polishing.

Hardness and modulus were measured by nanoindentation. The testing parameters were 15 points, 500 μN, and 6-mm length. The hardness of the silicon surface modification cladding was a key factor when machining the space mirror. Testing results, as shown in Table 1, indicate that the hardness and modulus of the silicon surface modification cladding were quite similar to those of the bulk silicon. As the silicon polishing technique had been extensively studied, no difficulties were encountered when polishing the accurately smooth surface.

The thermal shock resistance process was performed by putting the sample into liquid nitrogen (77 K) for 15 min and then by transferring it into boiling water for another 15 min. This procedure was conducted five times. No peeling or cracks was observed on the silicon surface modification cladding.

Reflectance was measured by a Lambda 900 UV/Vis/NIR spectrometer after silver enhanced coatings were deposited onto the mirror surface. A high reflectance of over 98.5% is obtained in the visible light region (500–800 nm), as shown in Fig. 8.

In conclusion, several results have been achieved from this cladding deposition and polishing technique. A very thin silicon surface modification cladding with a thickness of only 20 μm was obtained, as compared with the conventional 100 μm. The fabricated silicon surface modification cladding achieved a combination of greatly improved mechanical, thermal, and optical properties. A super smooth surface with a roughness of 0.53 nm (R_q) and a surface profile of only $\lambda/50$ was observed. A high reflectance of over 98.5% in the visible light region (500–800 nm) was obtained.

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