Hybrid Al/SiC Composite Optics for IFE Applications

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I. Introduction

Inertial Fusion (IFE) optics presents a unique challenge. Ghoniem [1] provides a mirror design for such an application. The surface has been chosen to be metallic, because dielectric materials exhibit great sensitivity to the effects of ionizing radiation. The leading high reflectivity candidate materials are aluminum, magnesium, silver, gold and copper. To select between these metals the following criteria were used:

1) high reflectivity in the wavelength of interest
2) effects of radiation on absorptivity
3) surface temperature rise during the laser pulse
4) thermal fatigue resistance
5) radiation effects on surface deformation

Although silver has excellent reflectivity, neutron induced microclusters are expected to distort the mirror's surface. Near surface collision cascades in silver will be very dense, because of the high electronic stopping power of silver. On the contrary, copper is excluded on the basis of its high neutron induced swelling, particularly when it is pure. The higher fatigue strength of aluminum results in a smaller mirror size, when it is compared with magnesium. In addition, the neutron induced swelling rate of commercial grade aluminum is lower than that of magnesium. For the above reasons aluminum has been chosen as the material for the surface of the mirror.

The structural support of the mirror is a SiC composite. The SiC composite is chosen for the following reasons:

1) Very low neutron induced deformations by thermal and irradiation creep mechanisms in the temperature range 500-700 K.
2) For porosity of approximately 10-15%, no neutron swelling is to be expected and thus the mechanical deformations of the mirror's surface are minimized.
3) SiC is a low activation material, so the choice of SiC will allow passive safety, and allow land burial of the mirror at the end of life.

Several attempts were made to deposit thin Al coatings on SiC substrates. Tillack [2] has studied the response of such coatings under pulsed beam conditions and has found low threshold damage.
A potential solution to this problem is to make a hybrid structure.

The use of Al mirrors for IFE applications is greatly limited by the very high thermal expansion coefficient (CTE) of aluminum. As a result, UV quality mirrors made with Al are limited to very small size and extremely large weight. On the other hand, thin PVD coatings on Al undergo rapid damage.

II. Experimental

1. Approach

The thin Al-coating limits the durability of short-pulse laser optics.

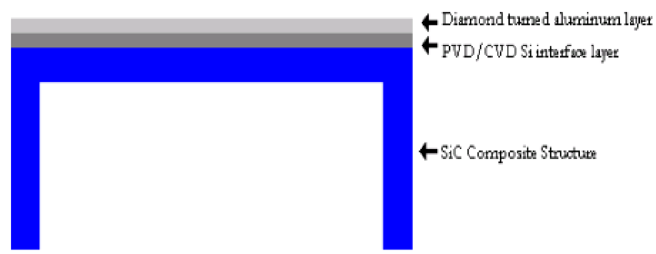

Figure 1. Current Design Concept for Al/SiC.

MER has proposed a highly innovative solution to this problem, Figure 1. The baseline structure is made of high thermal conductivity, high purity SiC-SiC composite. Subsequently, either CVD or PVD Si is deposited as the optical quality layer. The Si coating is ground and polished to a few microns P/V. At this stage, a very thin (2 – 3 mils thick) aluminum foil is attached to the Si surface via brazing. The final optical quality of the mirror is accomplished via diamond turning. In addition, the backplate (SiC/Al) can be constructed to balance the thermal performance.

The use of this approach has a significant advantage over pure Al. The fundamental issues with large Al-optics are associated with its very high CTE and the resulting thermal distortions.

2. SiC-SiC Composite Structure

The SiC-SiC composites were made in two forms:

i) 2.5 cm x 2.5 cm x 0.1 cm coupons

ii) 4" hexagonal structures

Tyranno SA 5HS fabrics were used. A thin 0.2 µm interfacial carbon coating was applied. A polysilazene resin was used as the binder. The coupons/structures were molded at 185^{o}C. Subsequently, a high temperature pyrolysis was employed followed by a re-infiltration and a re-pyrolysis. As a result, a β-SiC matrix was formed.

3. CVD Si

A 50 µm thick coating was applied on the surface of the SiC-SiC composite by CVD.

4. Al/Si Joining

The thin Al-foil was joined on the top of the CVD-Si coating at a temperature of 560^{o}C.

5. Diamond Turning

Initial results on testing Al-optics for IFE applications suggest the use of diamond turning for optical fabrication.

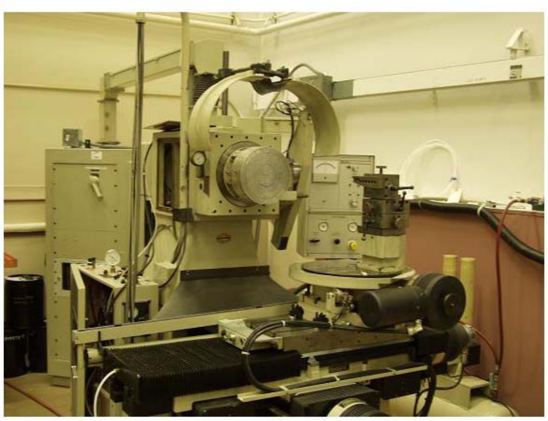

Figure 2. Diamond Point Turning Machine.

The diamond turning machine, shown in Figure 2 is used. It has up to 81 cm operating diameter. Optomechanical mounting is the key factor. For the small 4" mirror, the mounting support shown in Figure 3 will be used. The key issue is the alignment of the surface with respect to the diamond tool. First, the back surface of the structure is ground to under 20 µm accuracy parallel to the mirror surface. Secondly, the mirror is attached to the plate by maintaining the parallel plane accuracy. The process parameters include coolant type, cutting speed, and the geometrical design of the cutting tool. The print-through problem is controlled by filling the honeycomb back structure with a high elastic modulus filler.

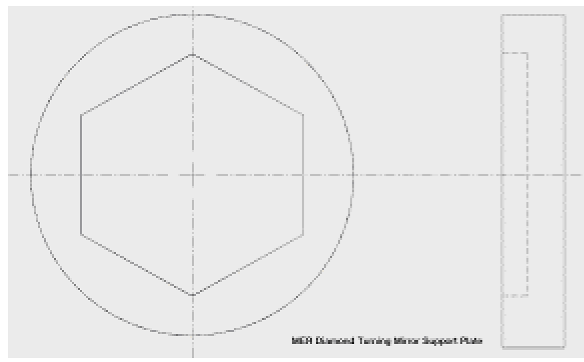

Figure 3. 4" Mirror Diamond Turning Support.

In addition, several 1"x1" coupons were diamond turned, and subsequently tested under laser beam conditions.

6. Laser Testing

Testing was performed using a 420-mJ Lambda Physik Compex 201 laser operating at 248 nm and a repetition rate up to 10 Hz. The pulse duration was approximately 25 ns. Figure 4 shows the arrangement of the experiment. The beam is polarized with a cube beam splitter and then attenuated using a half waveplate and second cube. It is important to maintain a high degree of polarization; leakage of p-polarized light will cause the absorbed energy to increase significantly. Low-power operation using the attenuator is used primarily to clean and precondition surfaces, because the laser itself has a limited range of energy output.

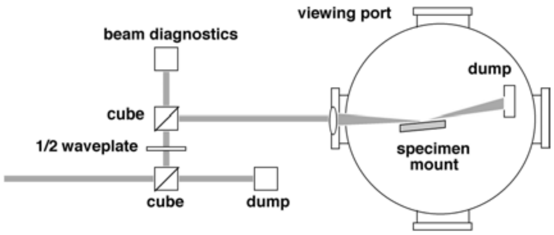

Figure 4. Experimental Setup for Mirror Damage Studies.

The rectangular beam (7×22 mm) is passed through a plano-convex lens (fl=155 mm) to create a trapezoidal footprint on the mirrors with fluence increasing with distance (see Figure 5). This provides a range o fluences for each test; damage usually occurs at the high-fluence side of the specimen. The angle of incidence varies only a fraction of a degree from one end of the footprint to the other.

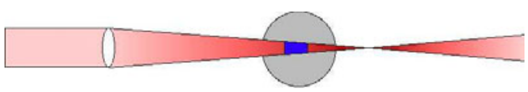

Figure 5. Focal Geometry and Beam Footprint.

All tests were performed at an 85˚ angle of incidence. The laser fluence we quote here represents the energy density passing normal to the beam. At 85˚, the footprint on the mirror is about 11 times larger than the area across the beam. Since the reflectivity of Al for s-polarized light at 248 nm is approximately 99%, the absorbed energy (5 mJ/cm^2) is approximately 1000 times lower than the incident laser energy (5 J/cm^2).

Initial experiments performed in air resulted in chemical reactions at the surface due to the high photon energy. Therefore, all experiments reported here were performed at 10^{-6} torr pressure.

The testing protocol included several single-pulse cleaning shots followed by 1 Hz operation at increasing fluences for several hundred shots each, and then extended operation at 5 Hz and the maximum fluence. Shot counts up to 100,000 were obtained. Proper preconditioning is especially important for thin films, which can be easily damaged by laser absorption in surface impurities.

The mirror surfaces were monitored by video imaging of the fluorescence from the surface.

7. Optical Evaluation

A Wyco 2000 was used to assess the mirror microroughness.

III. Results and Discussion

1. SiC/Al Joining

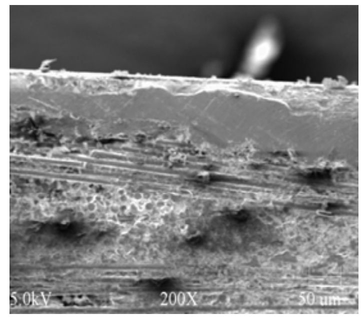

Figure 6. Aluminum Foil Diffusion Bonded to SiC Structure.

The joining of aluminum foil to the Si/SiC mirror structure was the key task in the reported period. Ten 1” x 1” x 0.1” SiC-SiC composite coupons were fabricated with high quality Si-optical surface. The bonding of Si to aluminum was achieved via solid state reaction (no additional metallic impurities to address the survivability under a fusion environment). The processing conditions include time, temperature and pressure.

Figure 6 shows the very well bonded thin (50 µm thick) aluminum foil bonded to the Si optical surface.

The process conditions were optimized to address the large CTE mismatch between aluminum and silicon carbide. The reaction between silicon and aluminum provided for a strong bonding. In addition, the process conditions were optimized to prevent recrystallization.

2. Diamond Turning

Several 1”x1” SiC-SiC/Al coupons were initially diamond turned. Good surface quality was achieved. Section four describes the laser testing on the 1”x1” diamond turned coupons.

Figure 7. 4” Al-facesheet Diamond Turned.

In addition, 4” SiC-SiC/Al optics was diamond turned. Figure 7 shows the 4” diamond turned optics initially attained using Al-foil bonded to the composite structure.

The key success was the elimination of the print-through problem. This problem arises due to structural stiffness differences between the rib section and the composite sheet in between. The solution to this problem was found to be two-fold:

i) The SiC slurry provides the load transfer between the structure and the facesheet.

ii) The back-structure was loaded with lead to increase the structural stiffness.

3. Optical Evaluation

Subsequently, initial surface characteristics were accessed using Wyco 2000. About 16 nm initial surface roughness was achieved. The as-diamond turned surface quality will be further improved by better control of the initial alignment.

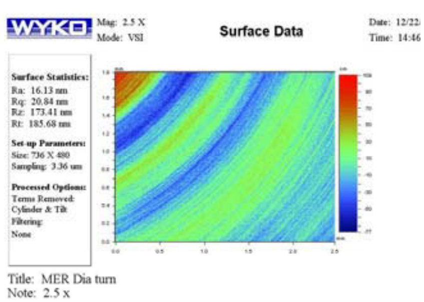

Figure 8. Microroughness of a Polished Diamond Turned Al Disk.

4. Laser Testing

Several 1”x1” coupons were tested. First the standard set of cleaning shots (at reduced fluence), and finally 10,000 shots at a peak of 5 J/cm^2 with 248 nm light were performed.

For example, Figure 9 shows the visible fluorescence from the first cleaning shot at low power. This is normal. Dirt and minor defects are removed as the laser fluence gradually ramps up.

Figure 9. Visible Fluorescence From First Cleaning.

In Figure 10, two spots are highlighted. These are apparently outside he footprint --- one below the beam and one at the lowest fluence region (the laser enters from the right and increases in fluence to the left). The chamber is washed with light during the pulse and any scattering sights (from dirt or defects) can produce visible fluorescence. Already in the first low-power shot (Figure 9), we can see these white spots. An approximation of the beam footprint in white is also drawn (Figure 10).

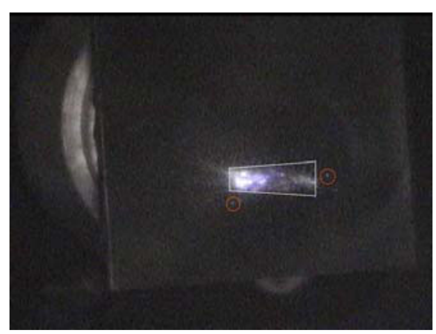

Figure 10. Visible Fluorescence at Full Laser Power.

Figure 11 was obtained later in the test, while shooting at 10 Hz and peak laser intensity (5 J/cm^2). Notice the fluorescence under the footprint is decreased, and the two white spots are clearly visible. These spots are outside of the beam footprint and so are unaffected by the testing. They continue to scatter visible light.

Figure 11. Decreased Fluorescence at Long Exposure Time.

During post-test examination using an optical microscope, no signs of damage were found. Based on the fluorescence signature, it appears that the surface may be improving during testing. These results showed a great improvement over the thin Al coating on the CVD SiC substrate.

IV. Summary

1. Solid-state diffusion joining of Al-foil to SiC mirror was demonstrated.

2. Diamond turning of Al-foil attachment to the SiC mirror was demonstrated.

3. 4” SiC/Al mirror was diamond turned without any print-through.

4. 1”x1” SiC-SiC/Al optics showed excellent performance under pulse-laser conditions.

V. Reference

1. N.M. Ghoniem and A. Elazab, “Thermo-mechanical Design of the Grazing Incidence Metal Mirror of the Prometheus-IFE Reactor”, Fusion Engineering and Design, **29,** pp. 89 – 97, 1995.

2. M.S. Tillack, J. Pulsifer and K. Sequois, “UV Laser-Induced Damage to Grazing Incidence Metal Mirrors,” Proc. *Inertial Fusion Science and Applications 2003*, Monterey, CA, pp. 810-814, Sept. 2003.