Evaluation of segmented and brazed mirror assemblies

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Abstract

Direct Sintered Silicon Carbide (SSiC) is a promising material for mirror optics due to its low density, high stiffness and high thermal stability. In order to make large mirror optics (over 1 meter diameter), processing limitations to create monolithic structures of this size class require that smaller segments need to be fabricated and then joined in a post sintering operation. Fabrication of segmented Ø300mm lightweighted concave mirrors to demonstrate different fabrication methods is presented here. The mirrors are comprised of 6 radial segments joined by means of silicon braze technology and are coated with a SSiC Chemical Vapor Deposition (CVD) layer for improved surface finish to reduce straylight scatter. Evaluation of conventional pitch lap polishing of brazed and coated optic surfaces has shown no degradation to surface figure and surface roughness.

Keywords: Sintered Silicon Carbide; Ceramic Joining, Silicon Braze, CVD SiC; Segmented Mirrors

1.0 Introduction

Technical challenges exist to demonstrate large scale optics greater than Ø1.2 meter in diameter that are made from SSiC for visible and infrared (IR) applications. Typically the ability to make large monolithic SSiC structures would require large processing facilities; a cold iso-static press, depending on shrinkage during sintering, would need to have the capability to press a green body larger than Ø1.6m – currently there are no known U.S. facilities that exist for this size. Further, very few sintering furnaces capable of firing a green body exist to accommodate this class of optics. Large, uncoated SSiC optic structures have been successfully fabricated by Boostec, Inc. by braze joining a radial array of smaller sintered segments; most notably the Ø3.5m Herschel Space Telescope primary mirror and Ø1.5m Aladin LIDAR primary mirrors (see figure 1). Whereas the Herschel Telescope is being deployed to observe the far IR sub-millimeter wavelengths (80 to 670um), CoorsTek's goal is to demonstrate processing capability that will result in large scale SSiC optics capable of observation in the Visible and near IR wavelengths of the spectrum.

Figure 1 – Large, segmented un-coated SSiC primary mirrors; the Ø3.5m Herschel primary mirror on the left and the Ø1.5 Aladin primary mirror on the right.

Improvement in surface finish is required to reduce porosity and straylight scattering for the shorter target wavelengths can be accomplished using SSiC CVD cladding over the base direct sintered silicon carbide material. A Ø300mm mirror with a spherical optic surface with a radius of curvature (R.O.C) = 2.5m was selected for demonstration. The mirror is a brazed assembly comprised of 6 radial segments. Target thicknesses for the mirror web and facesheet thickness are nominally 2.25 mm following CVD coating. The resultant Aerial Density is 25kg/m^2.

2.0 Fabrication Issues & Development

Standard processing of monolithic SSiC optic structures follows a basic process flow: silicon carbide powder, coated with a polymeric binder, is isostatically pressed in excess of 1000 atmospheres to form a green ceramic billet. The billet is pressed to be oversize by 15% to 20% to accommodate shrinkage during sintering. The green billet is machined using 3 and 5 axis milling centers to a near net shape for as many of the optic features as possible. A guiding principle in ceramic design for optics is to maximize the amount of green-machined features that can remain in the as-sintered state; this will minimize the amount of post-sintering machining required with benefits in cost and processing time reduction. Following sintering, dimensional characterization of the resultant shrinkage is performed. Tolerance control of as-fired features is typically less than ±0.5% of a given dimension with a ±0.10 mm minimum tolerance. Post-sintering diamond machining however is necessary to achieve the closer tolerances and surface finish required for the optical surface and the mounting features.

Two different process paths were investigated in the fabrication of these mirror assemblies:

- **CVD before Brazing:** in this process the individual sintered segments are SSiC CVD coated prior to being braze joined into an assembly. In this process the braze line is apparent on the coated mirror surface after the mirror is ground and polished. The advantage of this process for developing large optics (>Ø1m) is that the CVD reactor size only needs to be large enough to accommodate the individual segment rather than the whole assembly. Disadvantages of this process are occultation caused by the exposed braze line and a more arduous and lengthy processing path with additional grinding steps and increased risk. CVD thickness control of the finished optic is more difficult to maintain due to the number of assembly steps that follow cladding of the individual segments.

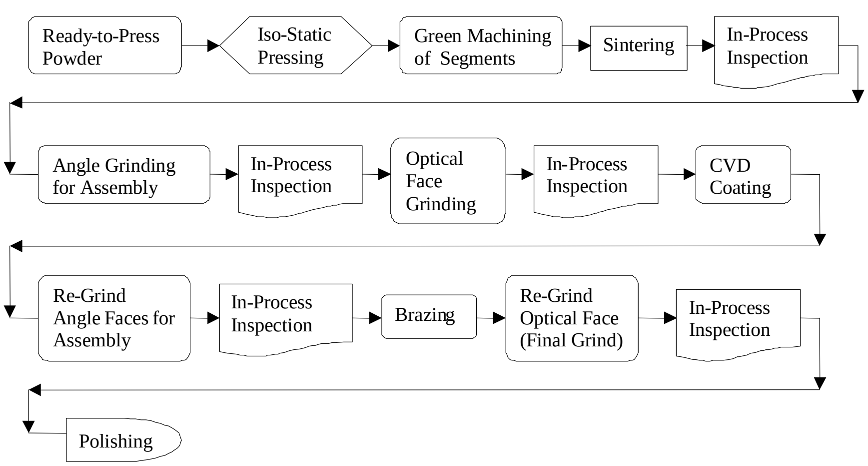

Figure 2 - CVD Before Braze process path

- **Brazing before CVD:** in this process the individual sintered segments are first brazed into an integral assembly (see figure #3). The brazed assembly is then coated with Pure SSiC CVD. The braze line should not be apparent on the coated mirror surface after the mirror is ground and polished in this process. The disadvantage of this process is the size of the CVD reactor that is required to accommodate the large, assembled optic. Advantages of this manufacturing path include an optical surface free from optical discontinuities (braze lines) and a processing path that is less complex and poses less risk from processing.

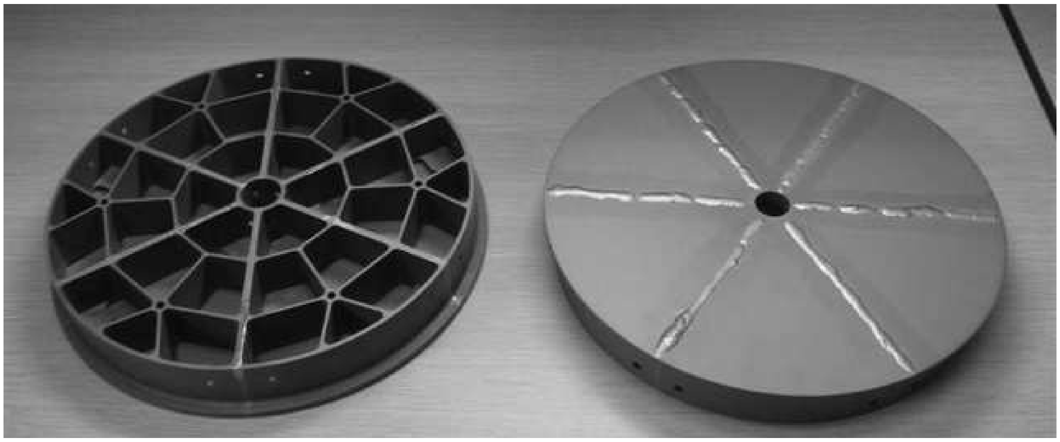

Figure 3 – Brazed mirror assembly before optical face grinding and CVD

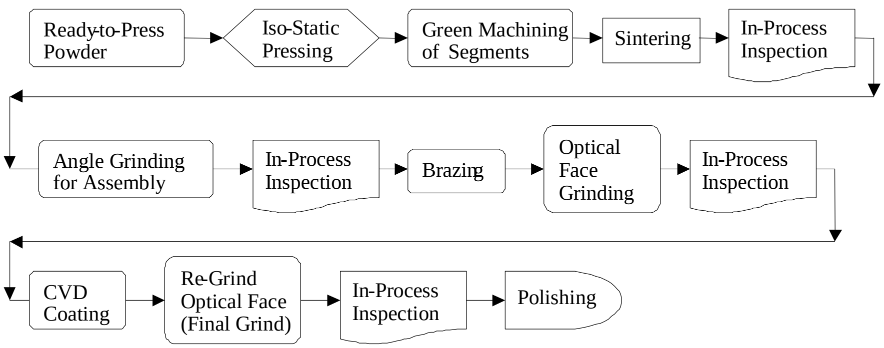

Figure 4 - Braze Before CVD process path

Common processing of the individual sintered segments was performed through iso-press, followed by green machining and sintering. Routine processing continues after sintering in a surface grinding operation that defines the mating surfaces. The assembly requirements prior to braze for the individual six segments requires that the included 60° mating angle for the individual segment sides be diamond ground with a high degree of precision (see figure 5). Such precision is critical to braze integrity and the resulting braze line thickness. From this point forward processing differs for each development path.

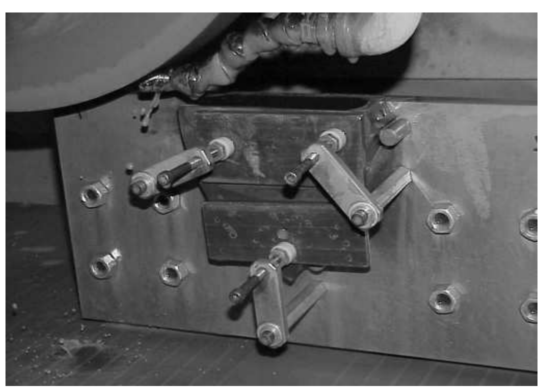

Figure 5 - Surface grinding of a mirror segment mating surface

2.1 Sub-Scale Process Development

Initial braze joining and SSiC CVD coating development was accomplished through the preparation of 50mm x 100mm x 8mm thick test coupons. The coupons have a brazed butt joint that combines two separate 50 mm squares. Two brazed coupons were over-coated with SSiC CVD, the remainder of plates were left uncoated. The coated and uncoated coupons were processed fully through conventional pitch lap polishing at Rapt Industries, Livermore, Ca, to evaluate the potential impact of the brazement on surface finish and surface figure control. Target polish specifications included were flatness under a 1/10 wave Peak to Valley (P-V) using a 633nm light source and surface roughness less than 1 nm RMS.

2.2 Processing of CVD Before Braze Segmented Ø300mm Mirrors

For this processing path, following the initial mating surface diamond machining, the individual segments are assembled and clamped in a grinding fixture, which is in turn affixed to a rotary table (see figure 6) for diamond machining of the optical face. The form profile control of this machining operation was measured to be less than 20um with respect to the specified R2.5m spherical shape. Once this machining operation is complete, the parts are cleaned and detailed. SSiC CVD coating was then deposited on the parts to a coating thickness of 0.50 mm. To avoid edge effects of the coating at the braze lines, the mating surfaces are left un-masked and are coated as well. Regrinding of these mating surfaces is then required to meet the assembly fit for the subsequent brazing operation.

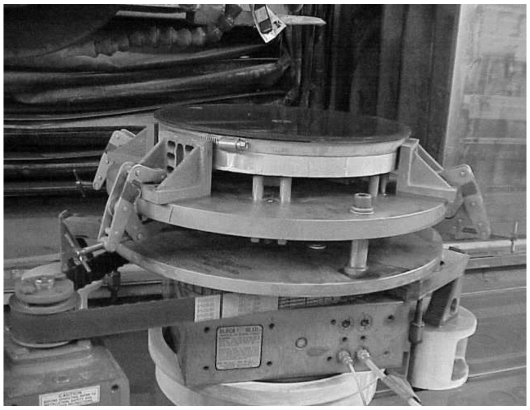

Figure 6 - Assembled mirror optical face grinding operation

Brazing of the assembled segments at the Boostec facility is performed. The brazing process, developed by Boostec, utilizes a doped Silicon compound with a coefficient of thermal expansion (CTE) closely matched to their base SSiC material. The brazing process creates a very thin, uniform joint. Braze thickness is less than 50 um and in most cases less than 10 um. The strength of the braze joint has been demonstrated to be greater than 50 Mpa. It is desireable to have the braze joint as thin as possible. When the braze thickness is less than 10 um, the strength of the braze joint is comparable to that of SSiC material alone (See figure 7). A segmented, brazed Ø1.35m demonstrator version of the Herschel primary mirror (also fabricated by Boostec) was cryogenically tested at 100°K, and exhibited no appreciable change in wave front error (WFE), compared to the WFE noted at ambient temperature.

Once brazing is complete and the excess braze material is removed, the optic surface can then be reground and polished.

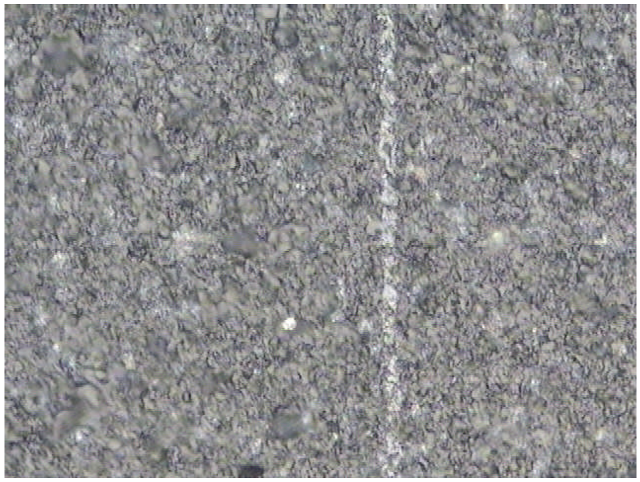

Figure 7 – 7 um Wide braze joint of lapped SC30 test plates

2.3 Processing of Braze Before CVD Segmented Ø300mm Mirrors

In this process path, following the initial mating surface diamond machining procedure, the individual segments were brazed at the Boostec facility. The brazed assemblies were returned to CoorsTek for grinding of the optical face and OD flange in a rotary table machining operation. The form profile control of this grinding operation was again measured to be less than 20um with respect to the specified 2.5m R.O.C. Once this grinding operation was complete, the parts were cleaned and detailed prior to CVD SSiC coating at the CoorsTek Arkansas facility.

Further process development was needed to introduce a low temperature SSiC CVD coating cycle that would allow CVD coating of the brazed mirror assembly without degradation or creep of the brazement. Typical SSiC CVD coating cycles operate at temperatures up to 1600 C, above the melting points of the eutectic and pure silicon constituents of the braze material (see figure 8). The low temperature SiC CVD coating was applied at a temperature well below the braze liquidus at a thickness of 0.50mm. Following coating, regrinding of the clad optical surface was performed prior to polishing.

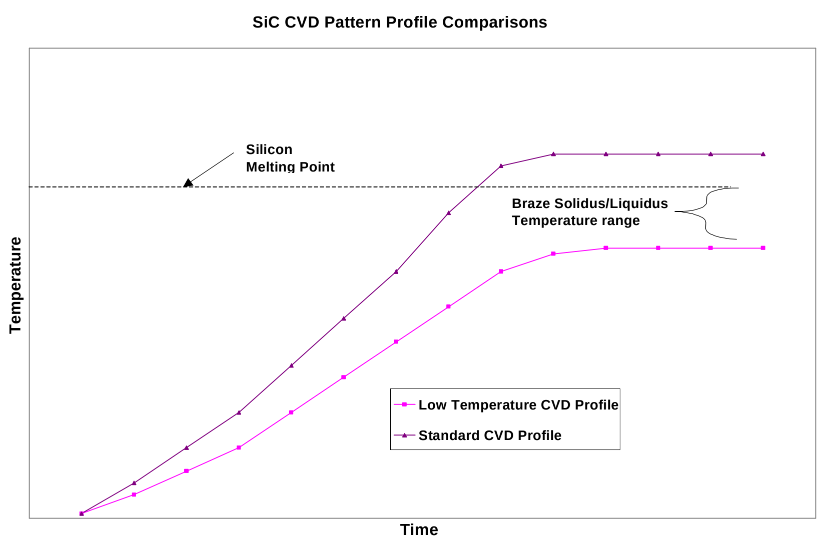

Figure 8 – Pure SSiC CVD profile development

3.0 Results

Processing of the brazed mirror assembly and coating of the brazed mirror blank utilizing the low temperature SSiC CVD cycle prior to polishing was successful, indicating that the low temperature process was stable with respect to the braze joint. No surface discontinuities in the unpolished optic surface are discernible at this time. Spectroscopic examination of SSiC CVD coated co-processed graphite samples showed no transport of the braze compound species to the CVD reactor surfaces removing concerns of contaminating the reactor vessel.


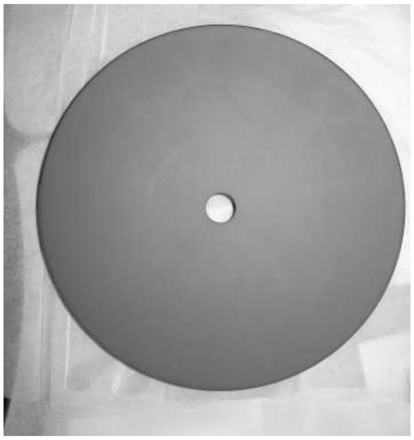

Figure 9 – Braze Before CVD segmented mirror assembly after SSiC CVD coating prior to polishing.

Processing of the sub-element coupons was performed through conventional pitch polishing at Rapt Industries. Specifications were met for surface figure at 0.091 waves P-V (coated) and 0.081 waves P-V (un-coated). No large period or local error as measured on a Zygo New View 5000 white light interferometer was found in the area of the CVD directly over the braze line (see figure10). Surface finish for the CVD coated sample exceeded the specification and was measured at 4.54 Angstroms Rms (figure 11).

For the uncoated brazed sample, conventional polishing of the test plate and braze joint caused preferential removal of the softer silicon braze line resulting in the hollowing out of a 10 nm deep trench (figure 12). The polished surface discontinuity caused by the exposed braze line may have negligible impact on optic performance, due to the narrow width of the line and shallow depth of the preferential removal.

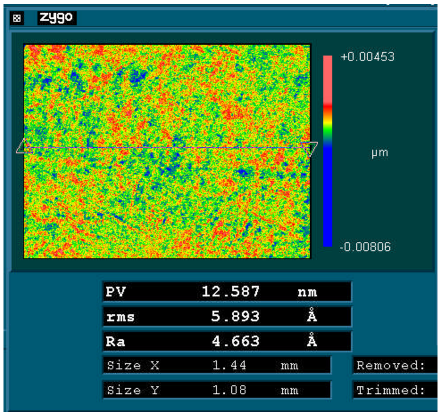

Figure 10 - Test Plate – CVD over Brazed SC30 50mmx50mmx8mm Sections using a 5X objective.
This above image shows a 1.44 mm x 1.08 mm patch of the CVD surface directly over the braze– no evident discontinuities.

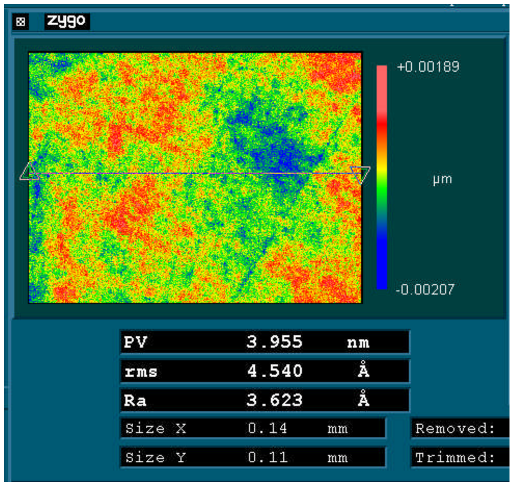

Figure 11- Test Plate – CVD over Brazed SC30 50mmx50mmx8mm Sections using a 50X objective
This image shows a surface roughness evaluation in the same region - image size is 0.14 mm x 0.11mm.

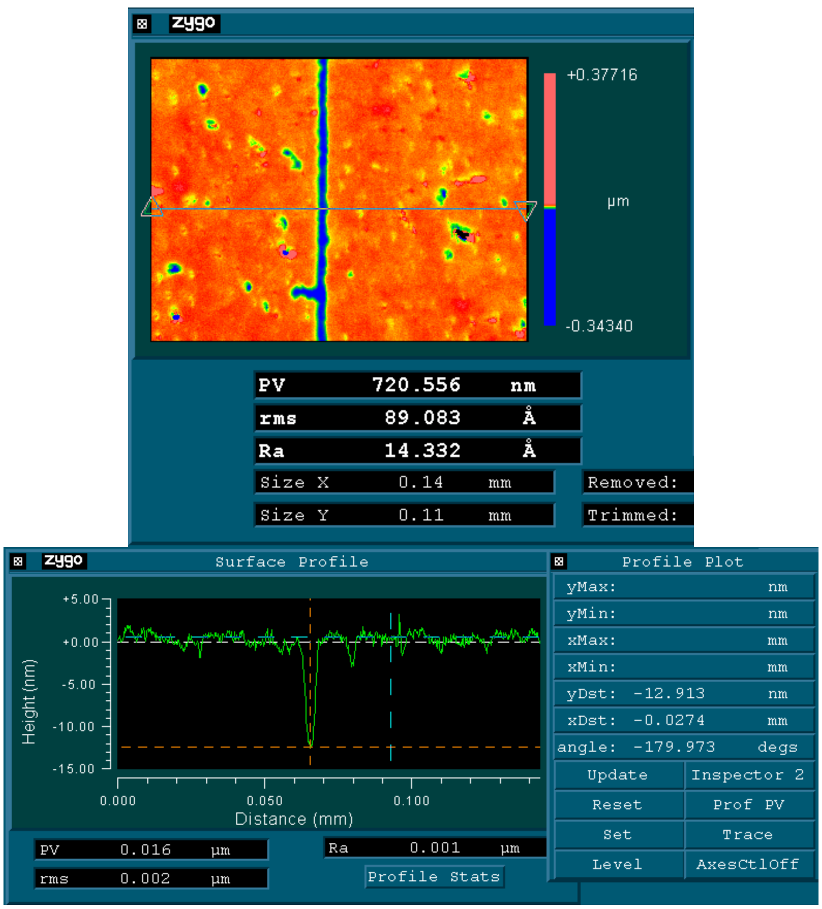

Figure 12- Uncoated Test Plate –Brazed SC30 50mmx50mmx8mm Sections using a 50X objective
This image shows a 50X magnification for surface roughness evaluation of the braze seam and surrounding SC30 plate - image size is 0.14 mm x 0.11mm. From the line traces in the bottom image it was found that the braze is ~10 nm under the surrounding SC30 surface for this polished surface of a typical braze seam.

4.0 Conclusion

Demonstration of two processes capable of fabricating meter class or larger segmented mirrors for visible and near IR applications has been presented. An individual mirror segment can first be SiC CVD coated and then brazed, or several segments can first be brazed and then SiC CVD coated. The processing choice will depend on the intended application, equipment availability and capacity. While significant effort remains to further demonstrate polishing of SSiC CVD clad segmented and brazed mirror assemblies, we are very encouraged by the promising results that we have demonstrated on the Ø300mm segmented mirror and polished test coupons.

The ability to use SiC CVD as a coating for the visible and near IR spectrum has also been demonstrated. This coating has been polished to 1/10th wave using conventional polishing techniques. The SiC CVD can be applied over a silicon braze joint yielding no measureable discontinuity in the optic surface at the joint. The SiC CVD can also be applied prior to the braze joining process, then polished. This route yields a slight polishing discontinuity

Acknowledgements

Our sincere appreciation is given to the technical teams at Boostec, Inc; and Rapt Industries for the strong support they have provided. Many thanks is extended to all Coorstek personnel in Hillsboro and Arkansas who have helped further this internal development program.