Silicon Carbide Optics for Space Situational Awareness and Responsive Space Needs

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1. ABSTRACT

Over the past 10 years the application of Silicon Carbide (SiC) materials to space based imaging systems has expanded. The aerospace community has long recognized the technical, cost, and schedule benefits associated with the material, and adoption of the technology is facilitated as more successful flight systems are demonstrated. SiC provides a number of technical advantages, as a result of superior material properties. The material can also be manufactured using near-net-shape fabrication processes which provide significant cost and schedule advantages compared with competing material technologies. These technical and manufacturing advantages make SiC uniquely well suited to address the needs associated with Space Situational Awareness (SSA) and Responsive Space (RS) applications. The material has a low coefficient of thermal expansion, and a high thermal conductivity, allowing visible quality imaging in the presence of stressing, and changing, thermal loads. The material's specific stiffness is high, approximately 70% of Beryllium, allowing stiff, lightweight optical systems to be produced. Passively athermal systems have been produced, demonstrating the ability of the material to provide visible quality imaging, without the need for actively controlled focus adjust mechanisms. In addition, SiC structural elements do not outgas, and have no issues with moisture absorption, allowing rapid on-orbit data acquisition. From the manufacturing perspective the material offers dramatic schedule benefits, these come primarily from L-3 SSG's near-net-shape manufacturing process which allows complex, lightweighted optical and structural elements to be produced without the need for costly/time-consuming machining processes. These schedule advantages become more dramatic as the aperture of the system increases, and/or as the number of units increases. In this paper we provide an overview of the technical and manufacturing advantages associated with SiC, provide background with respect to the material's flight heritage, and illustrate the advantages that can be obtained in applying the material to SSA and RS mission scenarios.

2. INTRODUCTION

Silicon Carbide (SiC) has long been recognized as an excellent material choice for space-based remote sensing applications [1]. In Fig. 1 we present a plot of thermal stability (thermal conductivity/CTE) versus specific stiffness (modulus of elasticity/density) for a number of different materials. SiC has a high degree of specific stiffness and can be used to produce very lightweight and stiff structures. An examination of Fig. 1 will show that SiC, depending on the specific material form, can have between 70% to 90% of the specific stiffness of Beryllium. SiC has excellent thermal stability showing a factor of 1.5x to 3.0x improvement over low expansion glasses. SiC also has excellent optical properties, and different forms have been demonstrated to support visible, and even EUV quality surface figures and finishes [2]. This combination of material advantages makes SiC an excellent material candidate for space optical instruments. Reaction bonded (RB) SiC, in particular, is attractive for these applications since its slip-cast fabrication process allows the production of aggressively lightweighted optics without the need for expensive and time consuming post-machining. This near-net-shape manufacturing process makes RB SiC a low-cost alternative to other SiC materials and/or Beryllium.

L-3 SSG's RB SiC material has been described in previous work [3]. RB forming processes have been used to produce very large, lightweight SiC optics, at very low cost. In Fig. 2 we show a typical rib supported primary mirror which has been produced with L-3 SSG's near-net-shape RB SiC manufacturing process. L-3 SSG has applied the slip casting manufacturing process to a wide range of optical component and system applications.

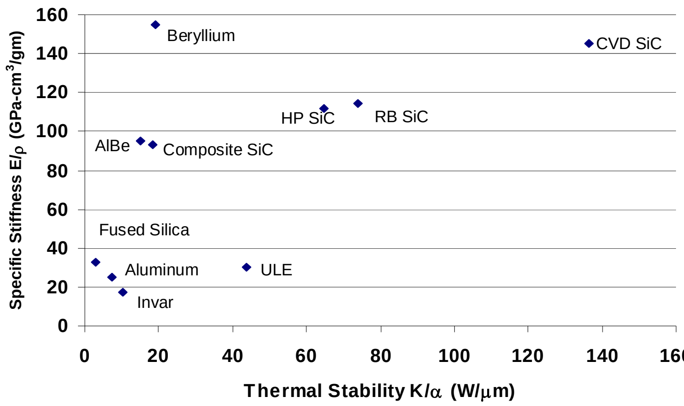

Fig. 1. Specific Stiffness versus Thermal Stability for Different Materials [1]

Fig. 2. Typical RB SiC Mirror Substrate (as cast, no machining)

3. SIC FLIGHT HERITAGE

The first all SiC flight telescope developed by L-3 SSG was used for NASA's New Millennium Deep Space-1 mission [4]. The MICAS (Miniature Infrared Camera and Spectrometer, Fig. 3) instrument was launched over 10 years ago and the successful operation of the system laid the ground work for follow on SiC systems which L-3 SSG has produced for a wide range of applications [5,6,7]. The most recent flight success is the all SiC Long Range Reconnaissance Imager (LORRI) which was produced for NASA's New Horizons mission to Pluto and the Kuiper belt [7]. The LORRI telescope is an all-RB SiC, 21 cm aperture, Ritchey-Chretien system with a narrow field-of-view (0.29°). SiC was selected as the optimal material for the LORRI telescope, given the mission's stressing thermal environment (operation from 148K to 313K), and demand for long term dimensional stability (LORRI will take > 12 years to reach the Kuiper belt). The RB SiC LORRI telescope is shown in Fig. 4. The SiC system weighs 5.8 kgs. The optical system consists of two aspheric SiC reflectors and a lens cell which have been aligned to obtain a system level wavefront error of 0.15 λ RMS (λ = 633 nm). The system launched in 2006 and has been used to obtain imagery of Jupiter and Saturn as its flight trajectory takes it out to the edges of the solar system.

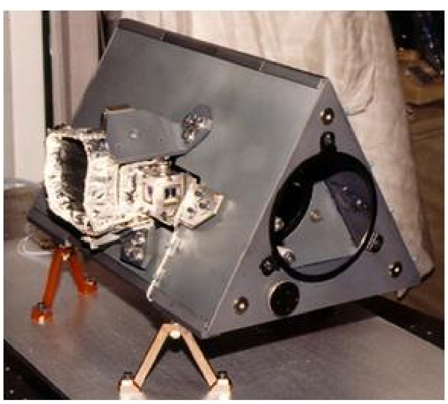

Fig. 3. MICAS SiC Instrument

Fig. 4. All RB SiC LORRI Imaging Telescope

4. SIC FOR RESPONSIVE SPACE NEEDS

One of the major benefits associated with the RB SiC material is the near-net-shape manufacturing process which allows lightweighted mirror substrates and complex metering structures to be produced with very little post-machining. The resulting schedule advantages obtained during substrate fabrication are dramatic, this is particularly true for large (> 1 meter) optics. L-3 SSG is in the process of scaling the RB SiC manufacturing process to large apertures. In Fig. 5 we show one of the first lightweighted mirror substrates (1.4 meters point-to-point) to be produced in the new, large furnace which has recently been installed at L-3 SSG's Ceramics Facility. Substrates at this size have been produced with a series of furnacing operations which are accomplished in a matter of weeks.

Compare this to state-of-the-art low expansion glass or Beryllium mirrors, at the same size, which can take many months, often exceeding a year for substrate fabrication [8].

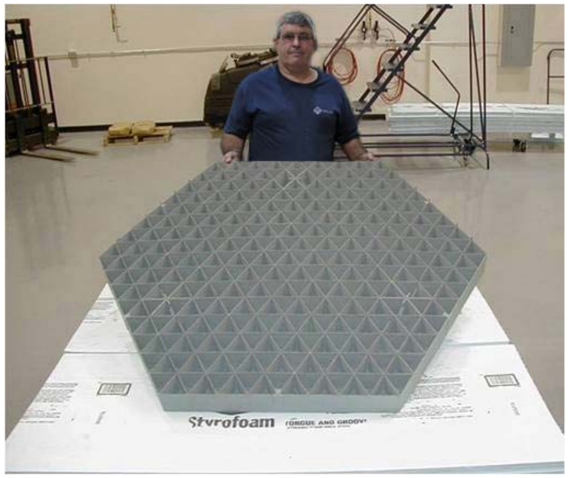

Fig. 5. 1.4 Meter SiC Segment In-Process at L-3 SSG's Ceramics Facility

Polishing of SiC optics has been a challenge, primarily due to the material's slow removal rate. For smaller optics L-3 SSG has addressed this issue by applying a thin Silicon cladding to the SiC optical component. The cladding greatly facilitates optical finishing of the SiC, being ductile enough to be diamond turned, and readily post-polished. In Fig. 6 we show an interferogram obtained from a challenging, off-axis parabolic optical surface (see Fig. 7). This piece has been Si clad, diamond turned, and subsequently post-polished by L-3 SSG's Tinsley Laboratories group to 0.012 waves [1].

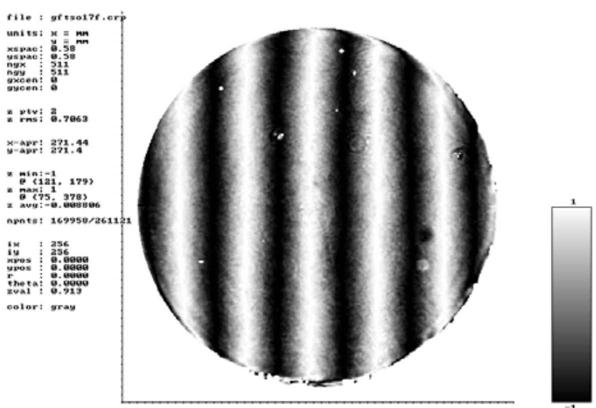

Fig. 6. Interferogram from Silicon Coated SiC Aspheric Optic (0.012 λ RMS)

Fig. 7. Photo of Silicon Coated SiC Aspheric Finished Optic

Silicon cladding and diamond turning can only be applied to mirrors which are approximately 1 meter in size, or smaller. Larger optics, like the one depicted in Fig. 5, require polishing of the SiC material itself, this can be an issue, this is particularly true with RB SiC, due to the material's two-phased (Si/SiC) microstructure [1]. These two materials have different hardnesses, as a result they remove at different rates using traditional polishing processes. This two-phased microstructure typically limits the surface roughness which can be achieved in the RB SiC material [3]. L-3 SSG-Tinsley is developing a new polishing process which allows the material removal rates of the silicon and SiC regions to be controlled independently, resulting in visible quality surface finishes [9]. In Fig. 8 we show the results achieved on a 0.5 meter pathfinder (12 Angstroms RMS (10x objective), the newly demonstrated process continues to be refined in preparation for polishing of the large 1.4 meter mirror segment shown in Fig. 5. The polishing time associated with the RB SiC finishing process will not be able to compete with the rapid turn around times associated with Si cladding and diamond turning, however, the schedule advantages gained during fabrication of the SiC substrate itself are sufficient to make the technology attractive from the standpoint of rapid turnaround, response space requirements.

5. SIC BENEFITS FOR SPACE SITUATIONAL AWARENESS

SiC optics also provide critical benefits for SSA mission scenarios. Dorland et. al. have described a compact (15 cm aperture) optical system for space astrometry can be used for SSA observations of objects in a GEO environment (J-MAPS) [10]. The thermal environment experienced by a sensor making SSA observations, can vary greatly depending on the solar angle of the SSA sensor, in reference to the space object of interest. SiC was selected as the optimal material for the J-MAPS telescope, in order to minimize the effects of thermal gradients, and to provide an Optical Telescope Assembly (OTA) which has a good CTE match to the CMOS Si focal plane array [10]. In order to demonstrate the benefits of SiC L-3 SSG has developed an optical/mechanical/thermal model of a notional 15 cm aperture RB SiC optical system, similar in geometry (and optical sensitivities) to the J-MAPS system (Fig. 9). The system was modeled from a GEO orbit, with a worst case scenario condition of direct solar loading of the primary mirror. The resulting thermal gradients are mapped onto a structural model which yields mechanical displacements which are in turn converted into wavefront errors [11]. In Fig. 10 we have summarized how the wavefront error of the primary mirror varies as a function of solar loading angle for a number of candidate optical materials. The RB SiC mirror shows 5x – 10x less deformation than what would be expected with aluminum or beryllium mirror substrates, approaching what would be expected from a low expansion glass primary (0.06 waves RMS peak error for SiC as compared to 0.02 waves RMS peak for ULE), while providing the low mass, high stiffness benefits associated with SiC, and the fast production times associated with the RB SiC slip casting process.

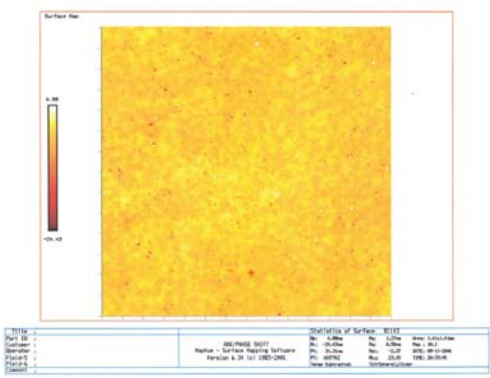

Fig. 8. Surface Finish: 1.2 nm RMS

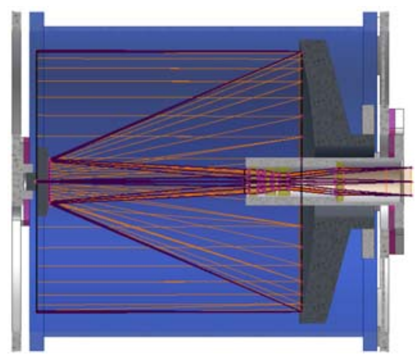

Fig. 9. 15 cm Aperture On-Axis SiC Telescope Model

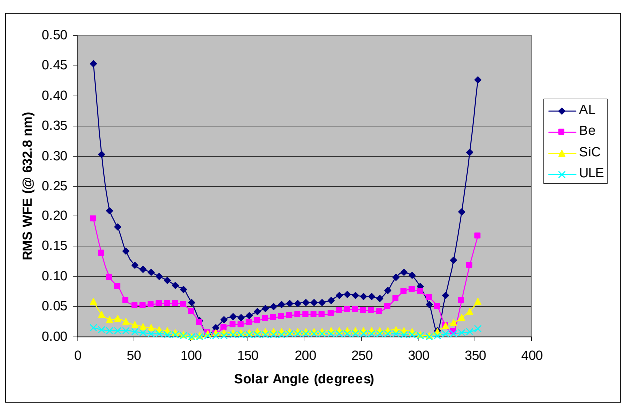

Fig. 10. RMS Wavefront Errors (primary mirror only) as a function of solar loading angle, for different primary mirror materials

6. SUMMARY

Interest in SiC as an opto-mechanical material continues to expand as more space flight successes are demonstrated. The material property advantages associated with SiC, and the specific manufacturing advantages associated with L-3 SSG's RB SiC make it ideally well suited for responsive space and SSA applications.

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