Optical and Optomechanical Ultra-lightweight C/SiC®* Components

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Abstract

Optical and optomechanical structures based on silicon carbide (SiC) ceramics are becoming increasingly important for ultra-lightweight optical systems that must work in adverse environments. At IABG and Dornier Satellite Systems (DSS) in Munich, a special form of SiC ceramics carbon fiber reinforced silicon carbide (C/SiC®) has been developed partly under ESA and NASA contracts. C/SiC® is a light-weight, high-strength engineering material that features tunable mechanical and thermal properties. It offers exceptional design freedom due to its reduced brittleness and negligible volume shrinkage during processing in comparison to traditional, powder-based ceramics. Furthermore, its rapid fabrication process produces near-net-shape components using conventional NC machining/milling equipment and, thus, provides substantial schedule, cost, and risk savings. These characteristics allow C/SiC® to overcome many of the problems associated with more traditional optical materials. To date, C/SiC® has been used to produce ultra-lightweight mirrors and reflectors, antennas, optical benches, and monolithic and integrated reference structures for a variety of space and terrestrial applications. This paper describes the material properties, optical system and structural design aspects, the forming and manufacturing process including high-temperature joining technology, precision grinding and cladding techniques, and the performance results of a number of C/SiC® optical components we have built.

1. Introduction

Several different SiC-type ceramic manufacturing processes have been developed around the world in recent years, usually with the goal of developing structures and components that provide high stiffness at low mass, high thermo-mechanical stability, and high isotropy combined with a low coefficient of thermal expansion (CTE). Due, however, to the inherent brittleness of traditional, monolithic, powder-based SiC ceramics and their tendency to shrink during sintering processing, hardware made of SiC has been limited to relatively low structural complexity and medium-sized components, and relatively large wall thicknesses. In seeking to overcome these deficiencies, ESA and NASA have supported the development of a new ceramic engineering material carbon fiber reinforced silicon carbide (C/SiC®). Due to its unique manufacturing process, C/SiC® permits the construction of:

- extremely complex and large three-dimensional precision structures,
- wall thicknesses as thin as 1 mm, and
- open- and closed-back structures for lightweight mirrors, optical benches, and actively-cooled antennas.

*: C/SiC® is registered in Germany as a trademark of IABG and ECM

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The C/SiC® manufacturing process (see Figure 4) is simple and straightforward and makes use of standard milling, turning, and drilling techniques. The size of the structures and mirrors that can be manufactured is limited only by the scale of the available production facilities, the largest of which currently is 3 meter in diameter and 4 meter in length (Figure 7) [1-2].

2. Material properties

The C/SiC® material was developed as part of an extensive study of available materials undertaken within the Phase-A study of ESA's Meteosat Second Generation (MSG) SEVIRI instrument and the dedicated development effort of the Ultra-Lightweight Scanning Mirror (ULSM) project, and the NASA-funded demonstration of the ultra-lightweight potential of C/SiC® mirror technology for the Next Generation Space Telescope (NGST). C/SiC's main features and advantages are as follows:

- Very broad operating temperature range (4 to 1570 K)
- Low specific density (2.65 g/cm^3)
- High stiffness (up to 269 GPa) and bending strength (210 MPa)
- Low coefficient of thermal expansion (CTE: 2.0 x 10^{-6} K^{-1} at room temperature and near zero below 100 K)
- High thermal conductivity (~ 135 W/mK)
- Good electrical conductivity (2 x 10^{-4} Ohm.m)
- Isotropic characteristics of CTE, thermal conductivity, mechanical properties, etc.
- Very high chemical, corrosion, and abrasion resistance
- No aging or creep deformation under stress
- No porosity
- Fast and low-cost machining
- Short manufacturing times
- Considerable flexibility in structural design
- Ultra-lightweight capability (small wall thickness and complex stiffeners)

One of the material's most advantageous features for space-borne, opto-mechanical instruments is the combination of high stiffness, low CTE, and good thermal and electrical conductivity, in contrast to traditional optical materials (Table 1). These advantages are even greater at cryogenic temperatures, where the CTE of C/SiC® is low, but its thermal conductivity is still high. Figure 1 shows the 4-point-bending strength versus deflection of C/SiC®. The CTE tests (Figures 2 and 3) were carried out by Composite Optics, Inc. (COI), on four C/SiC® specimens between room temperature and approximately 12 K. The specimens' dimensions were 6" x 1.75" x 0.196". The four specimens were cycled twice from room temperature to approximately 12 K and back to room temperature. The measurements were of strain versus temperature (Figure 2), from which the CTE versus temperature was derived (Figure 3). The average error associated with any data point was approximately ± 2 microstrains [3-7].

Physical Properties	**Units**	**C/SiC®**	**Zerodur**	**Be I-70A**
CTE @ RT	10^{-6} K^{-1}	2.0	0.05	11.0
Thermal conductivity, k	W/m K	135	1.64	194
Specific heat, c	J/kg K	700	821	1820
Young's Modulus, E (mean value)	GPa	250	90.6	289
Steady-state thermal distortion	E k/a	16875	1248	1693
Dynamic thermal distortion	E k/(a c)	24.10	1.52	2.80

Table 1: C/SiC's physical properties compared with those of other optical materials.

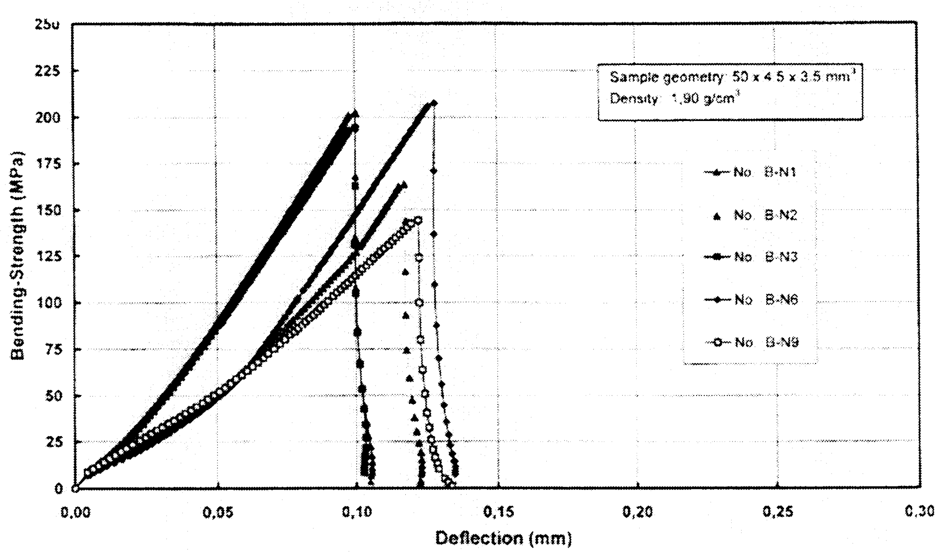


Figure 1: 4-point-bending strength versus deflection of C/SiC® at room temperature.

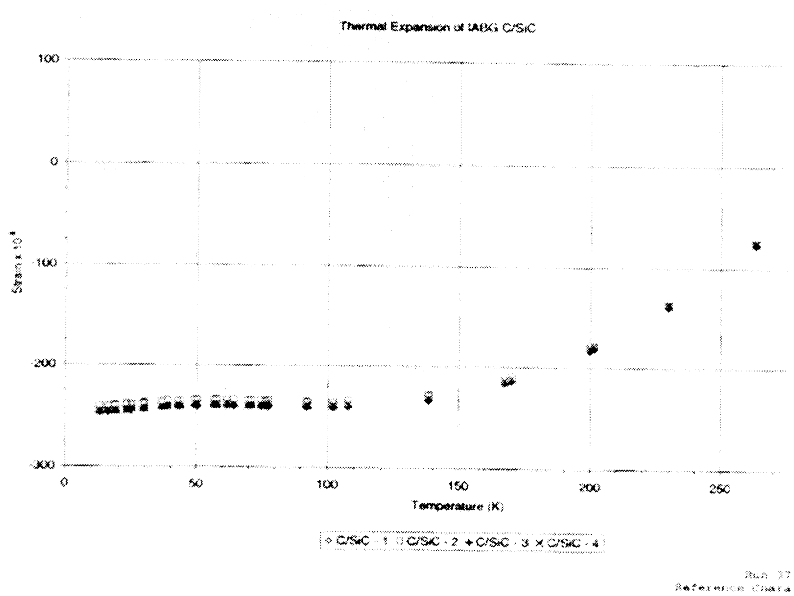


Figure 2: Strain versus temperature behaviour of cycled C/SiC® (temperature range: 12-300 K).

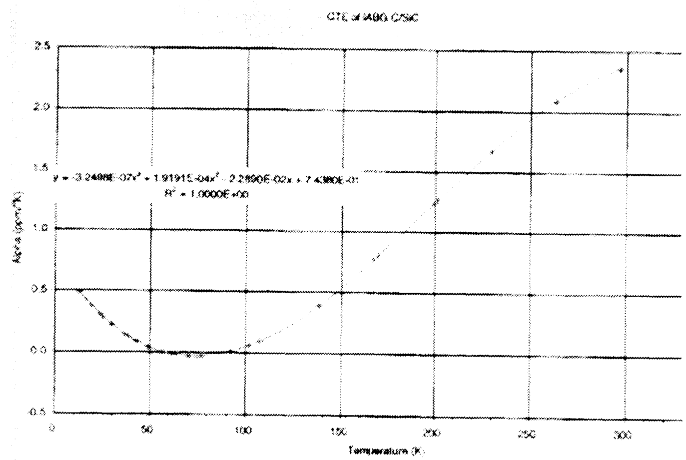


Figure 3: CTE versus temperature of C/SiC® (temperature range: 12-300 K).

3. The C/SiC® Manufacturing Process

In Figure 4 we present the principal steps of the manufacturing of C/SiC® optical components. The raw material used is a standard porous, rigid, carbon/carbon felt (C/C) made of short, chopped, randomly oriented carbon fibers (i.e., the felt is isotropic on scales of about one mm and larger, Figure 5). The random orientation of the fibers is clearly discernable in the figure. The fibers are molded with phenolic resins at high pressure to form a carbon fiber reinforced plastic (CFRP) blank, which can be produced in various sizes. During a pyrolization/carbonization heat treatment at up to 1000 °C, the volatiles outgas and the phenolic matrix reacts to a carbon matrix (C/C-felt). The short carbon fibers are randomly oriented in the C/C felt and, hence, an isotropic mechanical and thermal behavior is achieved. A graphitization process in inert atmospheres (by heat treatment at temperatures up to 2100 °C) reduces the chemical reactivity of the carbon fibers with liquid silicon. This process has a decisive influence on the physical and mechanical properties of the C/SiC® composite. The C/C-felt compound, called "greenbody," has a density between 0.65 and 0.75 g/cm^3 and is sufficiently rigid for standard NC milling to virtually any shape [8-10].

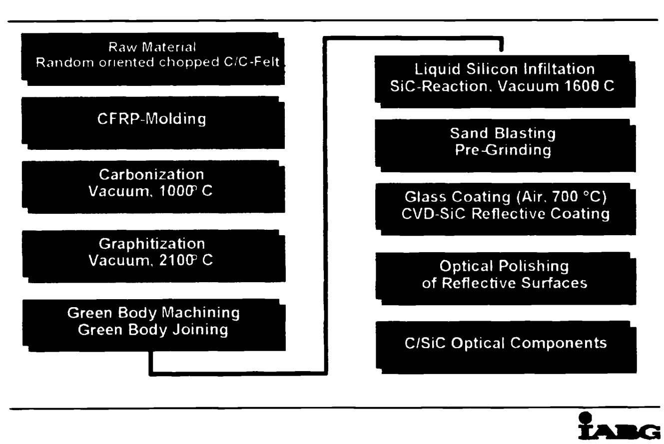


Figure 4: Manufacturing process of C/SiC® optical components.

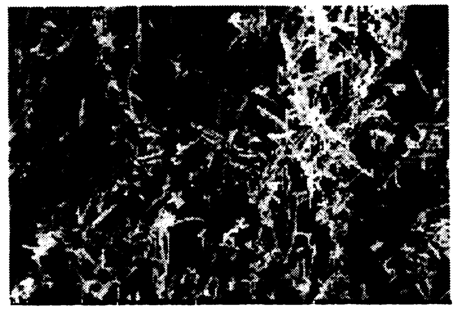


Figure 5: REM microphotograph of the greenbody chopped C/C fiber material.

4. Greenbody Machining (Milling)

As demonstrated in the ULSM mirror program (Section 9.1), very complex structures of virtually any shape can be formed from a single greenbody by standard computer-controlled milling. Figure 6 shows the milling of the ULSM mirror, which has a rather sophisticated support rear structure, including cutouts, milled from a single block of greenbody. Ribs of 1 mm can be milled with a standard tolerance of ± 0.1 mm. This versatility and speed in milling (the milling of C/SiC® greenbodies is similar to the milling of wood) are among the most significant advantages of this advanced engineering material, as it drastically reduces the forming costs and enables the manufacture of truly ultra-lightweight mirrors, reflectors, actively-cooled antennas, and other complex precision structures. Only a vacuuming provision is required to keep the carbon dust off the machine electronics, drive, and rails. It can also be machined to form struts and tubes without the need to machine support structures in another material [11]

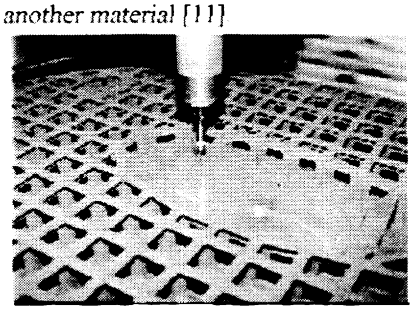


Figure 6: Milling operations on the 85 cm x 55 cm x 6 cm ULSM greenbody C/C blank.

5. Ceramic Infiltration Process

Upon completion of the milling, the greenbody structure, along with a sufficient supply of silicon, is mounted in a high-temperature furnace and heated under vacuum conditions to temperatures at which the metallic silicon changes into the liquid phase (about 1405 °C). Capillary forces in the porous blank wick the molten silicon into the structure. Subsequently, the temperature is increased to up to 1800 °C, and the liquid silicon reacts with the carbon matrix and the surfaces of the carbon fibers to form a silicon carbide matrix in a conversion process. The rate at which silicon and carbon react and, in particular, the degree to which the carbon in the carbon fiber surfaces reacts need to be carefully controlled to (a) limit the rate of heat released during the exothermic conversion process and (b) retain sufficient carbon fiber material for reinforcement of the resulting C/SiC® material. To accomplish both goals, we developed an optimized, computer-based infiltration process control for different-sized infiltration chambers. Our largest facility can process mirrors of up to 3 meters in diameter and large three-dimensional structures, such as optical benches (Figures 16 and 17), up to 2 meters in diameter and 4 meters in length (Figure 7) [12-14].

The density of the infiltrated C/SiC® composite is typically 2.65 g/cm^3. The unique advantage of our infiltration and conversion processes is that there is no noticeable shrinkage between greenbody and the resulting C/SiC® structure i.e., the processing is "near-net-shape". After controlled cool-down (the thermal treatment duration is typically 24 hour from cold to cold), the C/SiC® structure is carefully examined. The C/SiC® structure is then machined with suitable diamond tools to achieve the required interface (e.g., mirror adaptation and mounting) and surface quality [15-16].

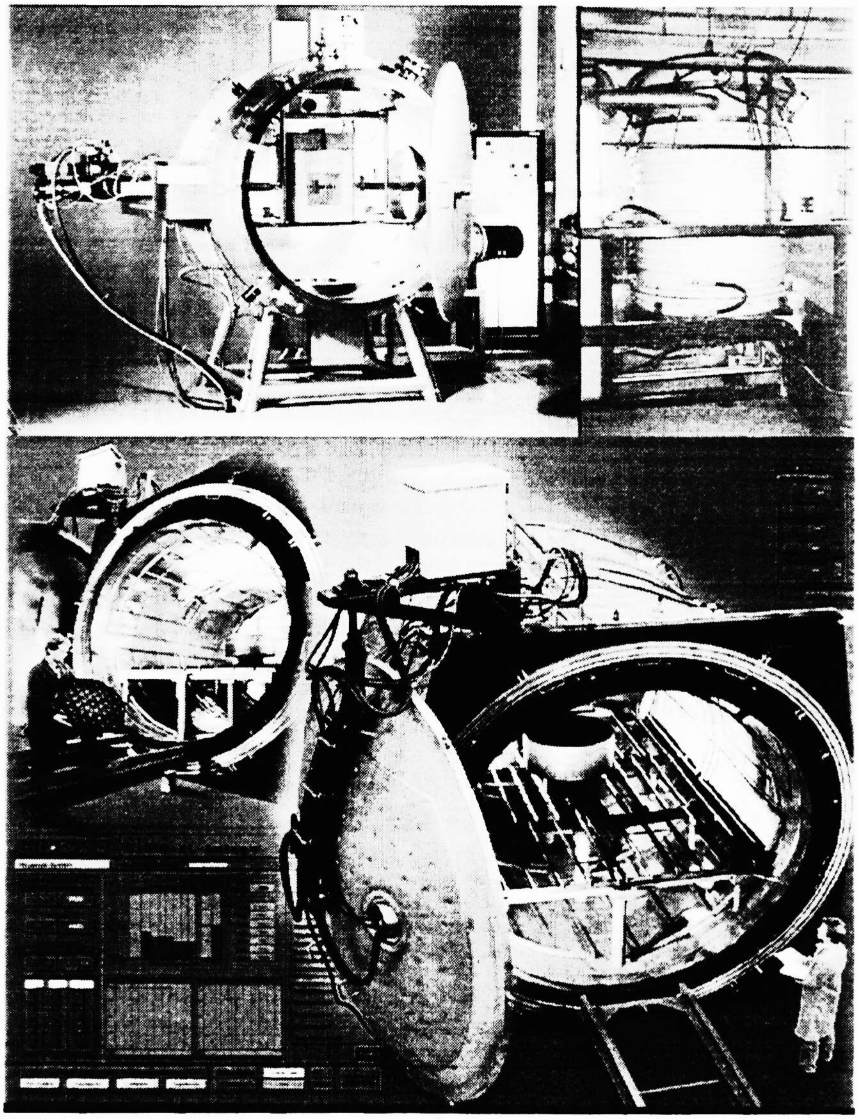


Figure 7: The three high temperature vacuum process facilities at IABG in Ottobrunn, Germany. The interior of the largest of the facilities has useable dimensions of 2 m x 3 m x 4 m.

6. Grinding and Polishing

The infiltrated mirror blank is ground to the required surface figure. As the carbon fiber content contributes to the micro-roughness of the surface, applications at near-infrared, visible, and X-ray wavelengths require that the optical surface be cladded and polished.

Several cladding materials and deposition techniques have been tested. The most promising candidates to date are monolayer-chemical-vapor-deposited (CVD) SiC, SiC-Si slurry cladding, and directly bonded glass. Plasma vapor deposited (PVD) silicon surfaces are also being evaluated. In selecting the most suitable cladding material, thermal expansion coefficient matching between the cladding and C/SiC®, allowable thermally induced surface errors, and machinability have all to be taken into account. The differential thermal expansion, the Young's modulus of the surface cladding, and the cladding thickness have to be optimized to keep bi-metallic bending effects in the mirror to a minimum.

Although the CVD-SiC cladding on the mirror blank is a good candidate in terms of material properties matching, it is difficult to achieve high optical quality due to SiC's exceptional hardness. Too high a pressure on the polishing tool causes a "print through" effect, whilst insufficient pressure increases polishing times and limits the optical performance. Polishing can, however, be improved by an additional ion-beam polishing step (Figure 8). A C/SiC® mirror with a directly bonded float glass coating is shown in Figure 9a.

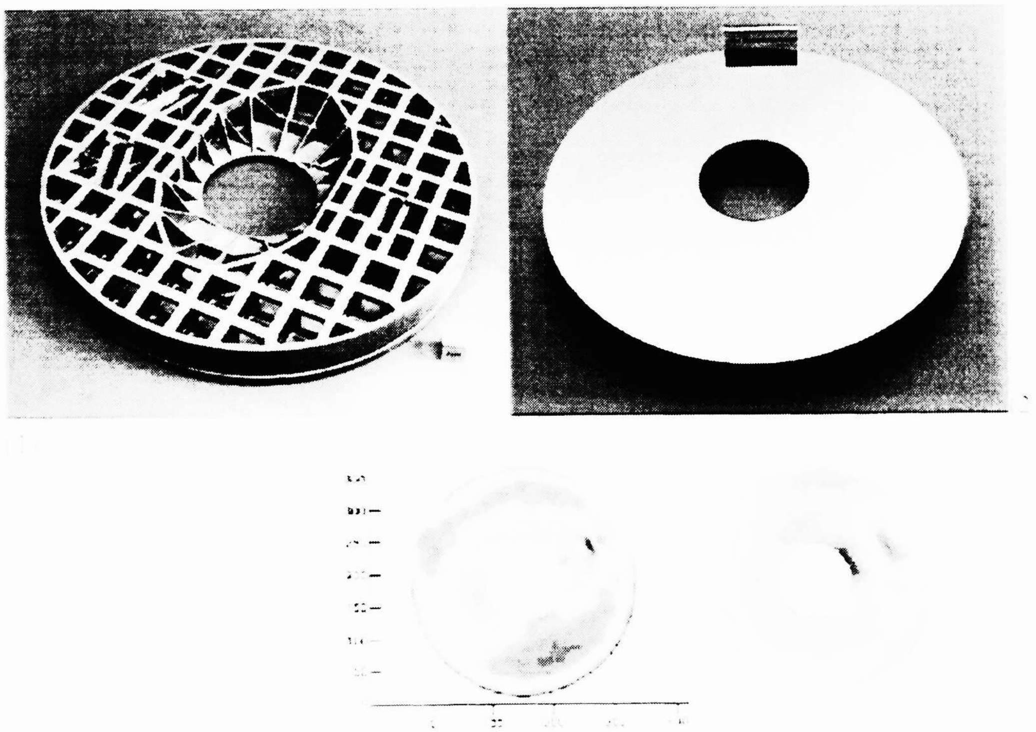


Figure 8: ULSM optical test mirror rear side (1) and front side (2) before and after ion-beam polishing (3).

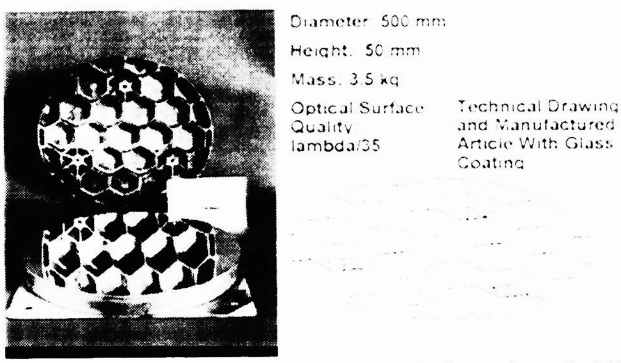


Figure 9a: MSG primary C/SiC® mirror (diameter: 500 mm) with float glass cladding.

Our newest cladding technique is based on a slurry containing microscopic SiC grains that is applied to the pre-ground C/SiC® mirror surface and heat-treated in the presence of liquid silicon. The result is a near-homogeneous SiC surface layer, containing a small percentage of silicon, whose thermal and mechanical properties closely match those of the underlying C/SiC® substrate. The bonding of this cladding to the substrate is excellent due to the covalent bonding between them (see Figure 9b). The slurry technique is still under development with the goal of maximizing the homogeneity of the SiC-Si cladding, upscaling to meter-class optics, and optimizing the cladding thickness for best optical polishing results and cladding weight.

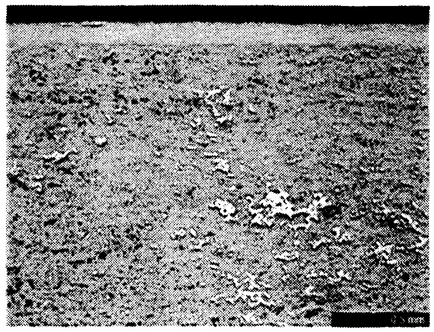


Figure 9b: Microstructure of optical grade C/SiC® with SiC slurry cladding (cross section).

7. Ion-beam Polishing

After polishing the mirror by classical means, the optical surface is locally treated by ion-beam polishing (i.e., plasma etching) to reduce the local errors in the surface figure and achieve high optical performance. This process was developed by the Institut für Oberflächen-Modifikation in Leipzig for the 440 mm-diameter optical test mirror for the ULSM program. Figure 8 shows the interferograms before and after the ion-beam treatment. Plasma etching improved the mirror's rms surface figure error from 123 to 39 nm. (The mirror's surface micro-roughness is discussed in Section 9.1).

8. Joining Technology

In comparison to most traditional SiC technologies, C/SiC® has another big advantage that is of considerable benefit in the manufacture of large mirrors and complex monolithic structures, namely the capability of joining sub-components either in the greenbody stage or fully Si-infiltrated C/SiC® segments to form the final structure. This joining technology allows one to manufacture monolithic mirrors and structures larger than the available greenbody C/C felts. It also makes it possible to assemble lightweight mirrors with closed-back structures (Figure 10) and complex three-dimensional instrument structures. The joining process starts with the gluing together of either greenbody parts prior to Si-infiltration or fully Si-infiltrated C/SiC® segments, using a special chemical adhesive developed at IABG. The segments can also be joined at their mechanical interfaces with C/C-bolts, screws or other fittings. During the subsequent Si-infiltration, the adhesive resin reacts to carbon so that a C/C-material is generated that has the same percentages of carbon, as well as the same porosity, as the rigid carbon felt. The infiltration process and the reaction with liquid silicon lead to a monolithic structure whose three material constituents (i.e., unreacted carbon fibers, SiC, and Si) and, hence, mechanical and thermal properties are the same everywhere, including at the joints, as those of the bulk C/SiC® ceramic composite material itself. This is ideal, for example, for athermal telescopes with mirrors and structures all made of C/SiC®, and assures uniform thermo-mechanical properties throughout the assembly. The sizes of C/SiC® structures that can be assembled by joining are only limited by the existing infiltration facilities.

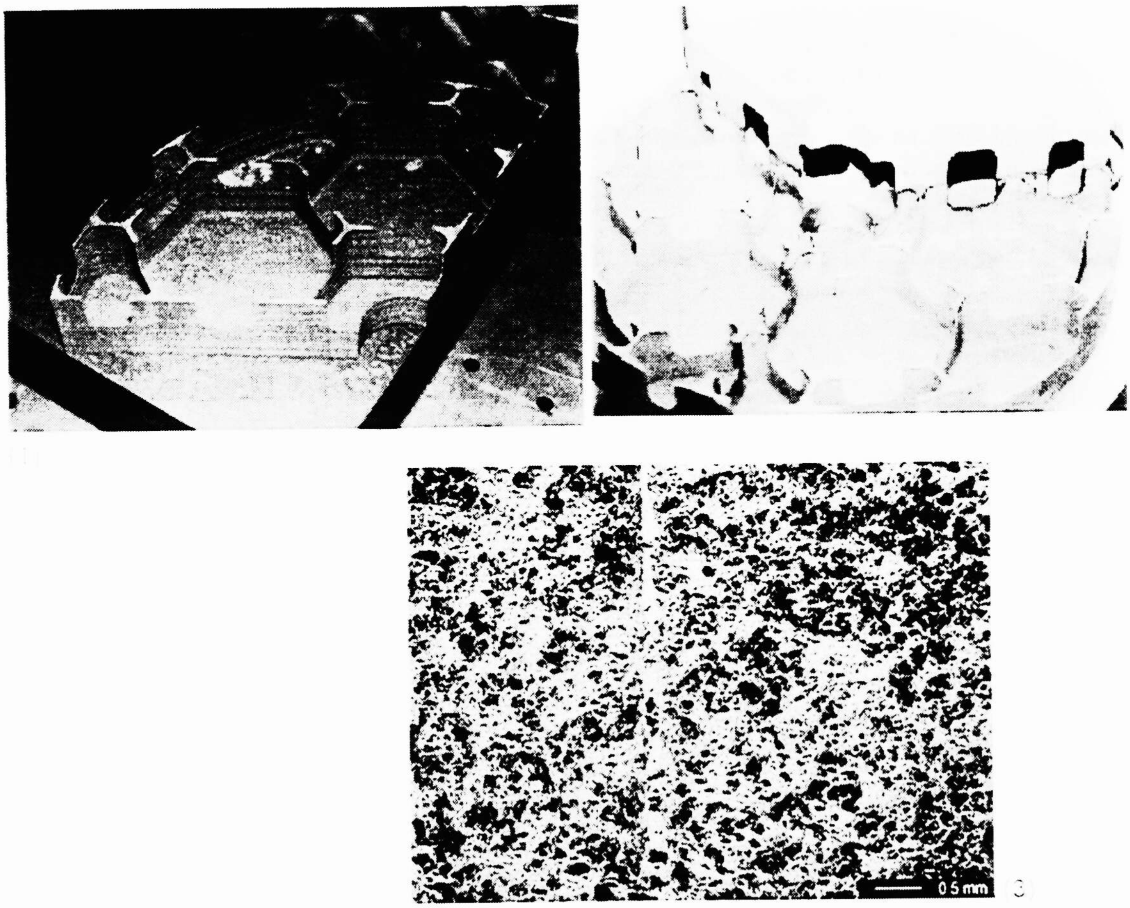


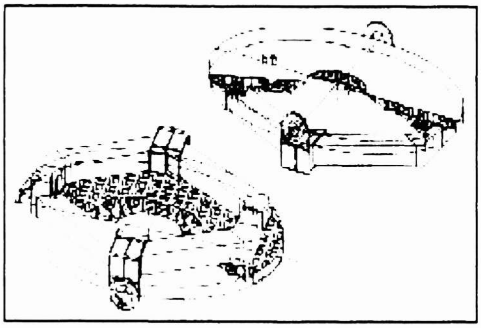
Figure 10: Ultra-lightweight closed-back C/SiC® structure with a diameter of 45 cm, made from six medium sized pieces (1). The pieces were joined in the greenbody state into a single, monolithic C/SiC® unit and then infiltrated (2). The interface microstructure of joined optical grade C/SiC® segments (cross section) is shown in (3).

9. Optical and Optomechanical C/SiC® Applications

9.1 Ultra-Lightweight Scan Mirror (ULSM): C/SiC® was selected as the candidate material for the Ultra-Lightweight Scanning Mirror (ULSM) of the SEVIRI instrument on ESA's Meteosat Second Generation (MSG) spacecraft. This mirror is designed for very stringent thermo-mechanical stiffness and optical requirements, yet still have an ultra-low mass. Operating in a geostationary orbit on a spacecraft rotating at 100 rpm, the mirror is exposed to both solar irradiation and the intense cold of space and, due to its 45° inclination to the spin axis, to a maximum mechanical loading of 3.2 g at the mirror tips, acting in opposite directions.

The mechanical design of the elliptical ULSM and one of the polished mirror blanks are shown in Figure 11. The mirror's backing structure contains square "pockets" 40 mm across. The individual ribs are only 1.2 mm thick, with each containing a large cutout for structural efficiency and to improve the mirror's thermal properties, especially under vacuum conditions.

The optical surface of the ULSM was successfully cladded with a CVD-SiC layer and polished to better than the specification of 60 nm rms surface figure error (see Section 7) and less than 2 nm rms surface micro-roughness. There was no measurable performance degradation after assembly with the isostatic mounts and the CFRP frame (Figure 12). The ULSM mirror has since undergone mechanical and long-term thermal cycling load tests, as well as extreme temperature tests, without showing any deformation of the optical surface. Radiation-hardness tests on the bulk material and the reflective coating were also performed successfully using a small test mirror.



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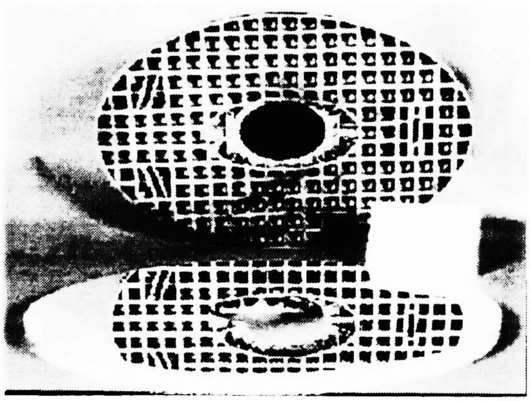

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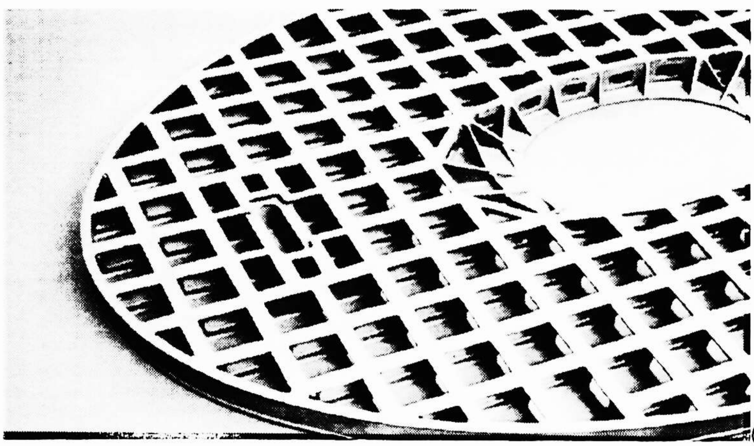


(3)

Figure 11: Design (1) and hardware (2) of the 85 cm x 55 cm Ultra Lightweight Scanning Mirror (ULSM), and rear side (3). The mirror weighs just 7 kg and has an areal density of about 26 kg/m².

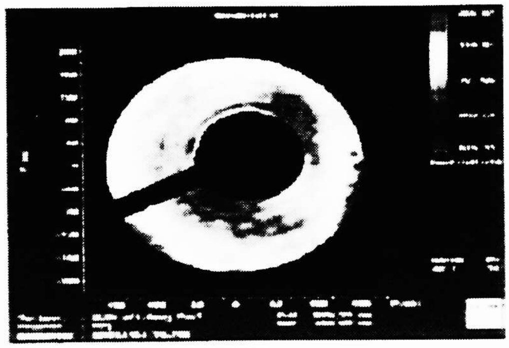


Figure 12: Interferogram of the assembled 85 cm x 55 cm ULSM C/SiC® mirror.

9.2 ATLID Telescope: Another example of a highly efficient C/SiC® optical structure is the Atmospheric Lidar Experiment (ATLID) parabolic mirror (F 0.9, aperture 63 cm). In the stiffening structure (Figure 13), material was removed in a trade-off between stiffness and mass, including consideration of the isostatic mounts. The triangular grid pattern with a rim thickness of only 1 mm and with internal cutouts is among the most complex ceramic structures of such size ever built. The mirror was designed to have a first eigenfrequency of greater than 400 Hz and a structural safety margin of 3.9 at 60 g static load [17].

After fine-machining and lapping to 8-micron rms figure accuracy, the mirror surface is cladded with a 150-micron CVD-SiC layer. Sample polishing tests showed good homogeneity and demonstrated that a surface micro-roughness of less than 1 nm rms can be achieved. The „as built" mass of the mirror is just 6.2 kg equivalent to an areal density of about 20 kg/m^2.

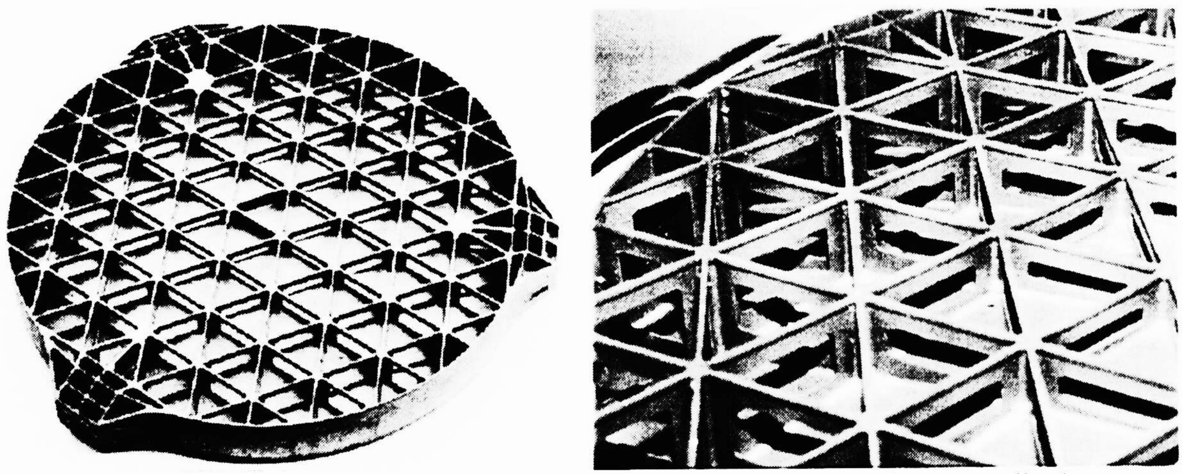


Figure 13: Rear side of the 63-cm parabolic C/SiC® mirror for the ATLID telescope application.

10. Ultra-Lightweight Potential

Figure 14 shows the design and deformation plot of the first eigenmode (1300 Hz) of the 500-mm ultra-lightweight, subscale demonstration mirror for the NGST project, designed to an areal density of 8 kg/m². The completed C/SiC® mirror, with triangular and cathedral ribs, diameter of 500 mm, height of 55 mm, and rib thickness of 1 mm is shown in Figure 15.

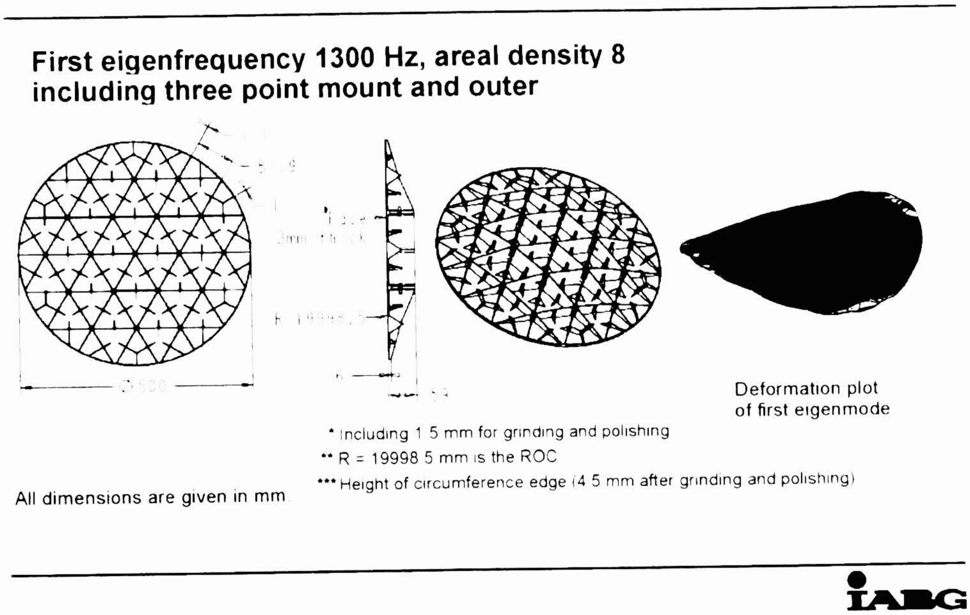


Figure 14: Design and deformation plot of first eigenmode of the 50-cm NGST ultra-lightweight demonstration-mirror (ULWM).

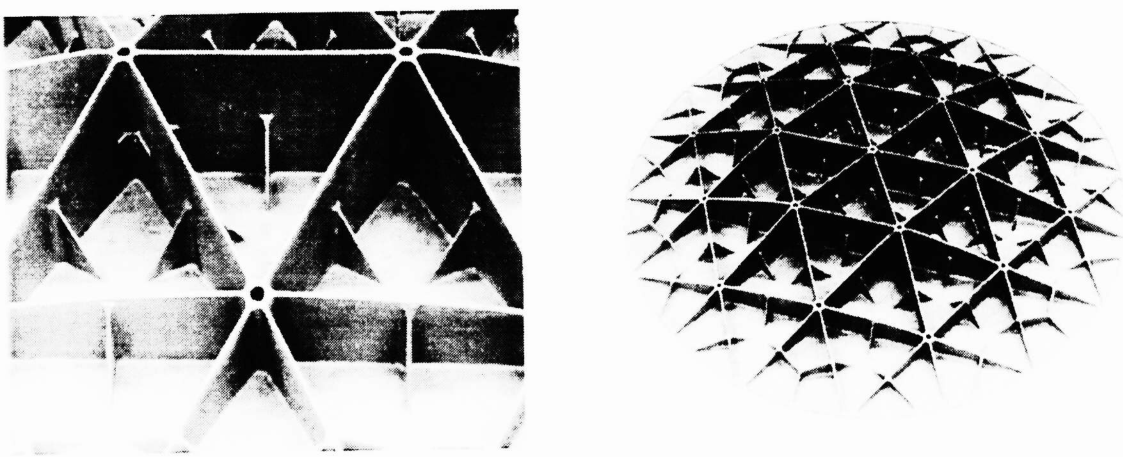
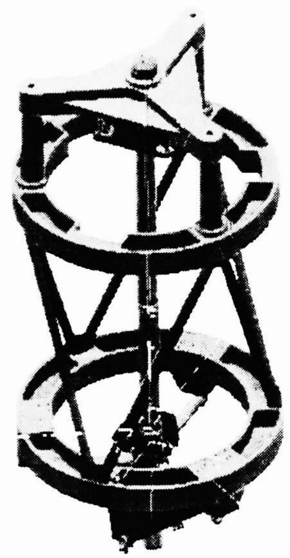


Figure 15: C/SiC® ultra-lightweight NGST demonstration mirror (ULWM) with triangular and cathedral ribs, diameter of 500 mm, height of 58 mm, rib thickness of 1 mm, and areal density of 8 kg/m².

11. Three-dimensional Precision Structures

The unique „joinability" of the C/SiC® material allows individually machined parts and structural elements to be combined to form complex three-dimensional structures. The designer can manufacture a telescope or instrument structure to final dimensions in the greenbody state and then „infiltrate" it to form an integral and monolithic ceramic component. C/SiC® optical components can be used in combination with C/SiC® precision structures to build athermal optical systems (all-ceramic telescopes) [18-22].



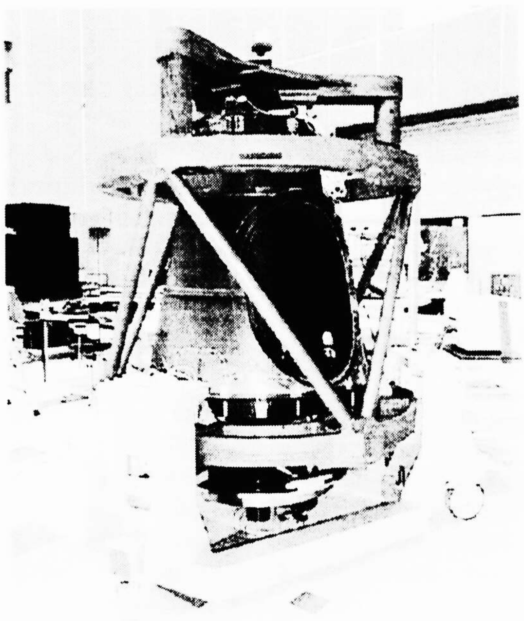
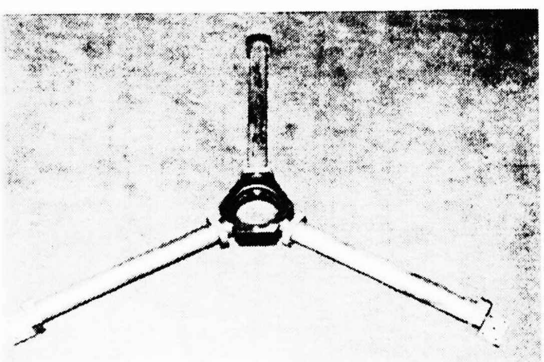


Figure 16: Design principle and realized large C/SiC® verification structure for the SEVIRI thermal-stability and environmental test. The C/SiC® monolithic ceramic structure is 1500 mm in diameter and 2600 mm high.

In addition, monolithic ceramic truss structures, such as optical benches, with better stiffness and thermo-mechanical properties than conventional all-aluminum or beryllium-type structures can be realized. Figure 16 shows the design (1) of a large all-C/SiC®, monolithic reference structure and its completed form (2), which has been designed, manufactured, successful tested, and delivered to DASA and ESA. The lower C/SiC® measurement spider (1) and a measurement device (2) of the verification structure are shown in Figure 17.
This optical bench has a measuring resolution which is principally defined as 1 µm per meter of object size. In the case of the Seviri CFRP telescope it was 1.5 µm in vertical direction and 1 µm in radial direction.



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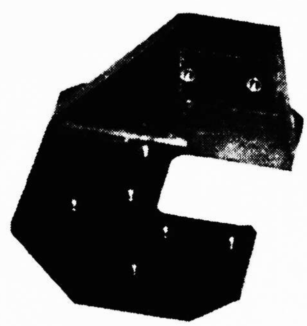

(2)

Figure 17: Lower C/SiC® measurement spider (1) and measurement device (2) of the verification structure

12. C/SiC® Sandwich Structures

Different closed-back C/SiC® sandwich structures with C/SiC® foam or connecting-rods between the front and back plates have been fabricated for different industrial applications. Due to their high thermal conductivity, corrosion resistance, and no porosity, such C/SiC® sandwich structures find application as heat exchangers in high-energy electronic substrates. Future applications will be actively cooled antennas and actively cooled mirrors for laser applications [23-24].

13. Tailoring Capability

We have engineered and tailored a variety of C/SiC® materials with a wide range of mechanical and physical properties. The tailoring relies on tuning the raw materials by varying fiber type, fiber length, fiber pretreatment, fiber content, the geometry of the fiber reinforcement, the molding process, the carbonization and graphitization heat treatment parameters (temperature, pressure, duration), the silicon infiltration process parameters (maximum temperature, pressure, duration, and heat treatment) and the extent of conversion of the carbon fibers to silicon carbide. Thus, the total number of material and process parameter combinations is extremely high. Optical-grade (described in this paper) as well as structural-grade C/SiC® composites are available depending on the requirements of different applications [25-27].

14. Conclusion

Our C/SiC® technology has applications to the manufacture of highly complex, lightweight, high-stiffness optical, optomechanical, and three-dimensional structures with excellent dimensional stability. C/SiC® mirrors, actively cooled antennas, and reflectors can be manufactured from a single piece of greenbody or, for larger reflectors and precision optical structures of up to 3 meter in diameter or 4 meters in length, as separate medium-sized segments that are then joined. This new technology also allows us to construct closed-back designs, which result in improved structural efficiency. Different polishable surface claddings have been applied for specific optical applications, ranging from scanning mirrors to large, ultra-lightweight telescope reflectors. Last but not least, this all-ceramic precision instrument technology delivers consistently high optical performance over a very wide range in temperature.

16. Abbreviations

AIV/AIT	Assembly, Integration and Verification/Testing
C/C	Carbon/Carbon
CFRP	Carbon Fiber Reinforced Plastic
C/SiC	Silicon Carbide with short Carbon Fibre Reinforcement
DSS	Dornier Satellitensysteme GmbH
IABG	Industrieanlagen-Betriebsgesellschaft mbH
ESA	European Space Agency
FE	Finite Element
FEM	FE Model
ISM	Isostatic Mount
MFD	Mirror Fixation Device
MSG	Meteosat Second Generation
MTF	Modulation Transfer Function
NASA	National Aeronautics and Space Administration
OE	Optical Engineering
PA/QA	Product Assurance/Quality Assurance
PM	Primary Mirror
Si	Silicon
SiC	Silicon Carbide
TCM	Tilt Chopping Mechanism
WFE	Wavefront Error

17. Reference Documents

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