Ultra-lightweight C/SiC Mirrors and Structures

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Silicon-carbide (SiC) ceramic mirrors and structures are becoming increasingly important for lightweight opto-mechanical systems that must work in adverse environments. At DSS and IABG, a special form of SiC ceramic (C/SiC) has been developed under ESA contract which offers exceptional design freedom, due to its reduced brittleness and negligible volume shrinkage during processing. This new material has already been used to produce ultra-lightweight mirrors and monolithic reference structures for eventual space application.

Introduction

Several different SiC-type ceramic manufacturing processes have been developed around world in recent years, usually in seeking to develop structures and components that provide: high stiffness at low mass, high thermo-mechanical stability, and high isotropy. Due, however, to the inherent brittleness of SiC ceramics and their tendency to shrink during processing, hardware made of SiC is limited to a low structural complexity, relatively large wall thicknesses and open-back structures. In seeking to overcome these deficiencies, ESA initiated the development of a new material called C/SiC. Its unique manufacturing process enables one to realise:

- extremely complex three-dimensional structures
- wall thicknesses of less than 1 mm
- open- and closed-back structures for lightweight mirrors.

The manufacturing process is simple and straightforward and makes use of standard milling, turning and drilling. The size of the structures and mirrors that can be manufactured is limited (to 3 m x 3 m x 4 m) only by the scale of currently available production facilities.

Material properties

The new C/SiC material actually resulted from an extensive study of available materials undertaken within the Phase-A study of the Meteosat Second Generation SEVIRI instrument, and a dedicated development effort within the Ultra-Lightweight Scanning Mirror (ULSM) project. Its main features and advantages are as follows:

- Very broad operating temperature range (4 to 1570 K)
- Low specific density (2.70 g/cm^3)
- High stiffness (238 GPa) and strength (210 MPa)
- Low coefficient of thermal expansion (CTE: 2.0x10^{-6}K^{-1} at room temperature, and near zero below 150 K)
- High thermal conductivity (~ 125 W/mK)
- Electrically conductive (2 x 10^{-4} Ohm.m)
- Isotropic characteristics of CTE, thermal conductivity, mechanical properties, etc.
- Very high chemical and corrosion resistance
- No ageing 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 classical optical materials (Table 1). This advantage is even stronger at cryogenic temperatures, where the CTE of C/SiC is low, but its thermal conductivity is still high.

The manufacturing process

The raw material used is a standard porous C/C rigid felt, which is made from short, randomly oriented (isotropic) carbon fibres

Table 1. C/SIC's thermal properties compared with those of other materials

		Units	C/SiC	Zerodur	Be I-70A
CTE @ RT	α	10^{-6} K^{-1}	2.0	0.05	11
Thermal conductivity	k	W/m K	125	1.64	194
Specific heat	c	J/kg K	700	821	1820
Young's Modulus	E	GPa	270	90.6	289
Steady-state thermal distortion	E k/α		16875	1248	1693
Dynamical thermal distortion	E k/(c)		24.1	1.52	2.8

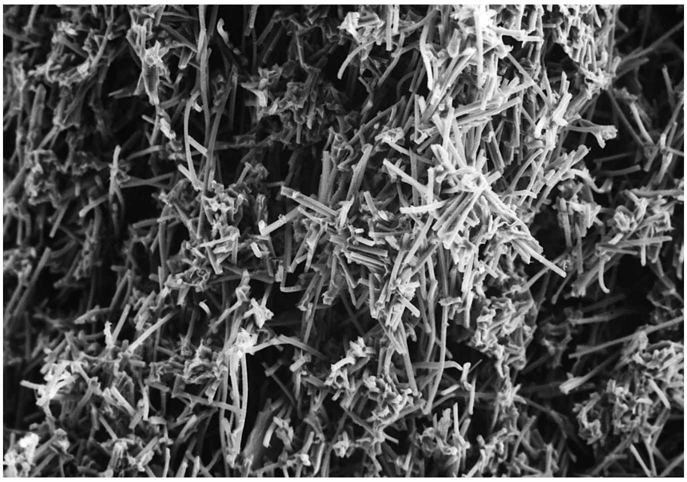


Figure 1. REM microphotograph of the green-body chopped fibre material

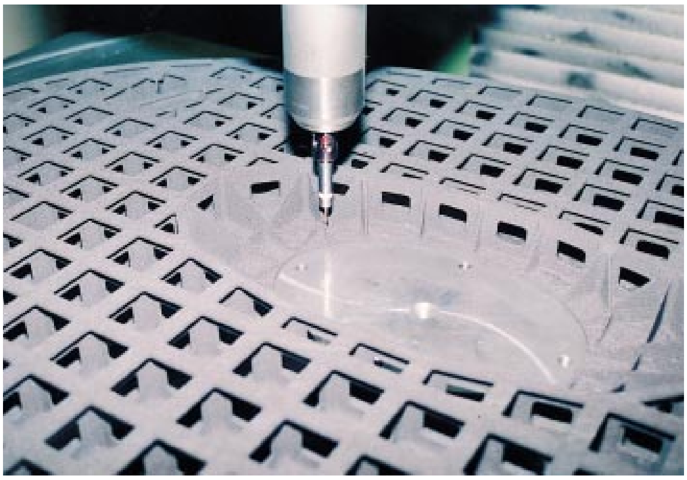


Figure 2. Milling operations on the 80 cm x 50 cm ULSM blank

(Fig.1). The latter are molded with phenolic resins at high pressures to form a type of carbon-fibre-reinforced plastic (CFRP) blank, which can be produced in various sizes. During a pyrolisation/carbonisation heat treatment at up to 1000ºC, the phenolic matrix reacts with the carbon matrix (C/C-felt). The resulting so-called "green body" is then sufficiently rigid for milling to virtually any shape.

Milling

As demonstrated in the ULSM mirror programme, very complex structures can be cut from a single green body by standard computer-controlled milling (Fig. 2). Ribs of 1 mm or even less can be milled with a standard tolerance of ±0.1 mm. This is one of the most significant advantages of this new material, as it drastically reduces the forming costs and enables the manufacture of truly ultra-lightweight mirrors, reflectors and structures. It can also be machined to form struts or tubes without the need to machine support structures in another material.

Infiltration

The milled green-body structure is then mounted in a high-temperature furnace and heated under vacuum to temperatures at which the metallic silicon changes into the liquid phase (about 1400ºC). The liquid silicon reacts with the carbon matrix and the surface of the carbon fibres to form a silicon-carbide matrix in a conversion process. The amounts of carbon and silicon have to be carefully apportioned to prevent a chemical reaction between the silicon and the reinforcing carbon fibres, and so IABG has developed an optimised infiltration process with precise computer control for different-sized chambers. The largest facility can process mirrors of up to 3 m diameter, or large structures up to 3 m in diameter and 4 m long (Fig. 3).

Grinding and polishing

The infiltrated mirror blank is ground to the required surface figure. As the carbon-fibre

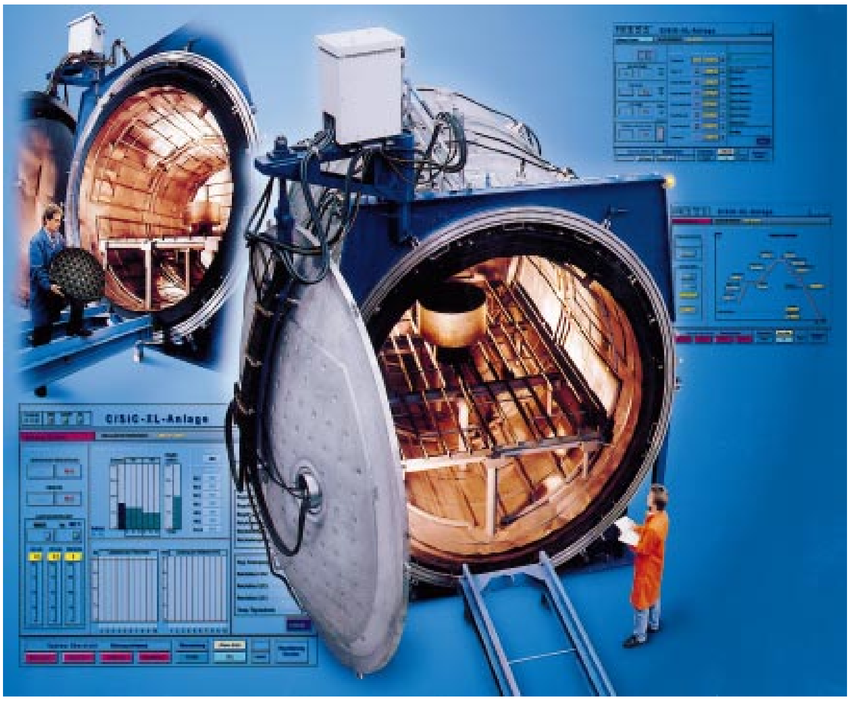


Figure 3. The infiltration facility at IABG in Ottobrunn (D)

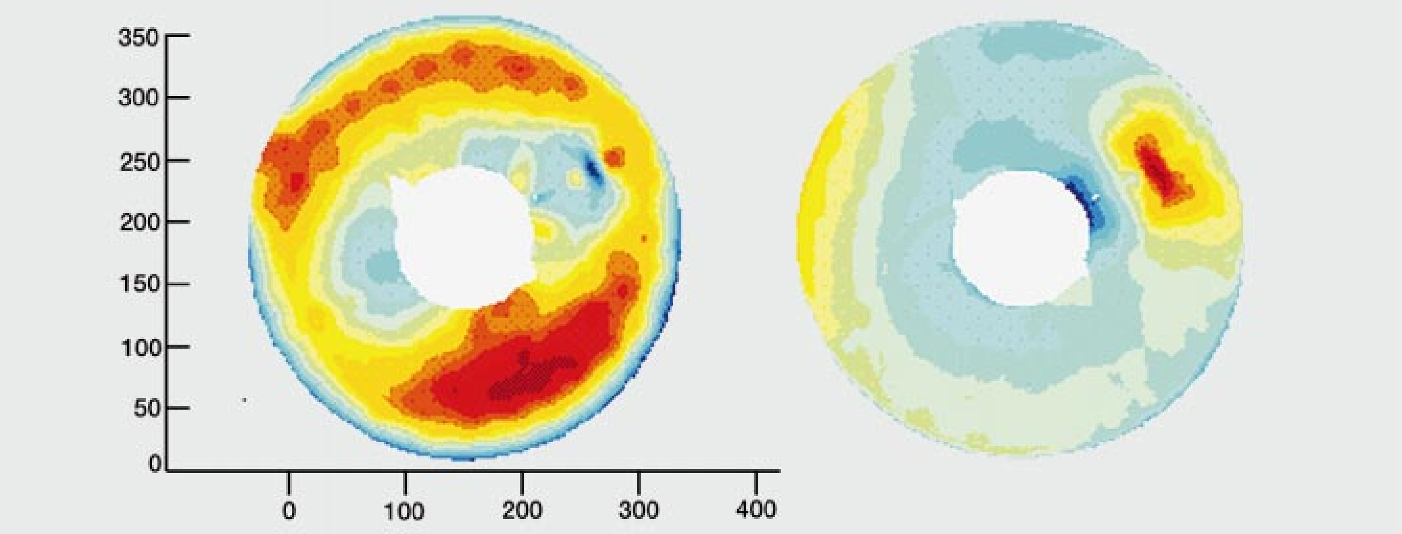


Figure 4. ULSM optical test mirror before and after ion-beam polishing

content contributes to the micro-roughness of the surface, applications at near-infrared, visible and X-ray wavelengths require a polished cladding layer which acts as the optical surface.

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

Although the CVD-SiC coating on the mirror blank is a good candidate in terms of material property matching, it is difficult to achieve a high optical quality due to the material's exceptional hardness. Too high a pressure on the polishing tool causes a "print through" effect, whilst insufficient pressure increases polishing times and the optical performance remains limited. It can, however, be improved by introducing an additional ion-beam polishing step.

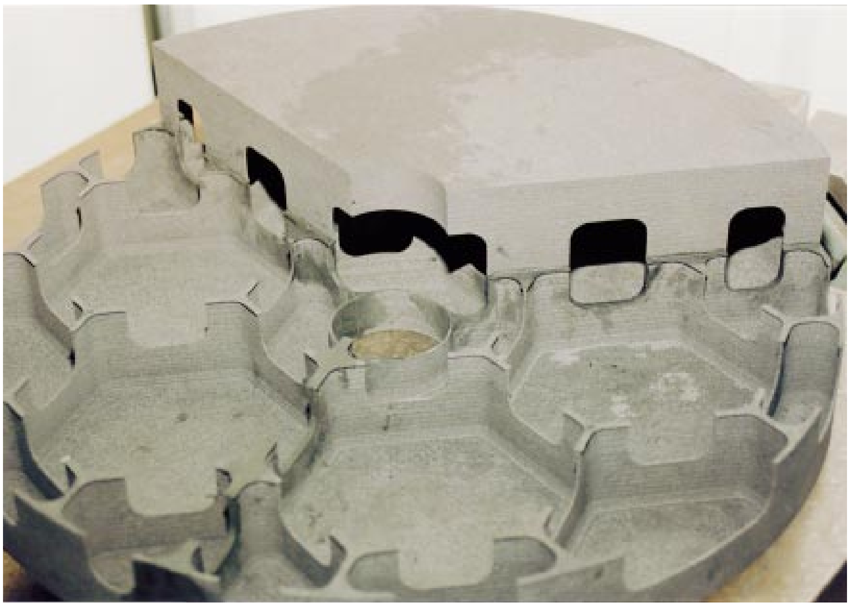


Figure 5. Lightweight closed-back structure with a diameter of 45 cm, made from six pieces joined in the green-body state and infiltrated to a single unit

Ion-beam polishing
After polishing the mirror by classical means, the optical surface is locally treated by plasma etching to reduce the local errors in 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 programme. Figure 4 shows the interferograms before and after the ion-beam treatment. The mirror's rms surface figure error was improved from 123 to 39 nm.

Joining technology
The C/SiC material has another big advantage which is not required in the normal manufacturing process, but which is of considerable benefit for larger mirrors and complex monolithic structures, namely the possibility to join sub-components in the green-body stage to form the final structure. This joining technology allows one to manufacture monolithic mirrors and structures larger than the available green-body C/C felts. It also makes it possible to assemble lightweight mirrors with closed back structures (Fig. 5), and complete instrument structures.

The joining process starts with the gluing of the green-body parts using a special chemical adhesive, developed at IABG, before Si-infiltration. During the subsequent Si-infiltration, the resin reacts to carbon so that a C/C-material is generated which has the same percentage of carbon fibres and carbon matrix, as well as the same porosity, as the rigid carbon felt used. The infiltration process and the reaction with the liquid silicon leads to a monolithic structure which has the same percentage of the three material constituents (carbon fibres, SiC- and Si-matrix), and thereby the same mechanical and thermal properties as the bulk C/SiC ceramic composite itself. This is ideal for, for example, athermal telescopes with mirrors and structures with the same thermo-mechanical properties.

C/SiC applications

ULSM

The C/SiC material was selected as candidate material for the Ultra-Lightweight Scanning Mirror (ULSM) of the SEVIRI instrument on the Meteosat Second Generation (MSG) spacecraft. This mirror has to fulfil very stringent thermo-mechanical-stiffness and optical-quality requirements yet still have an ultra-low mass. Operating in a geostationary orbit on a spacecraft rotating at 100 rpm, it is exposed to both to the heat of the Sun 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 6. 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 CVD-SiC surface coating has been successfully applied and the optical surface polished to a specification of 60 nm rms surface form error 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 (Fig. 7). 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.

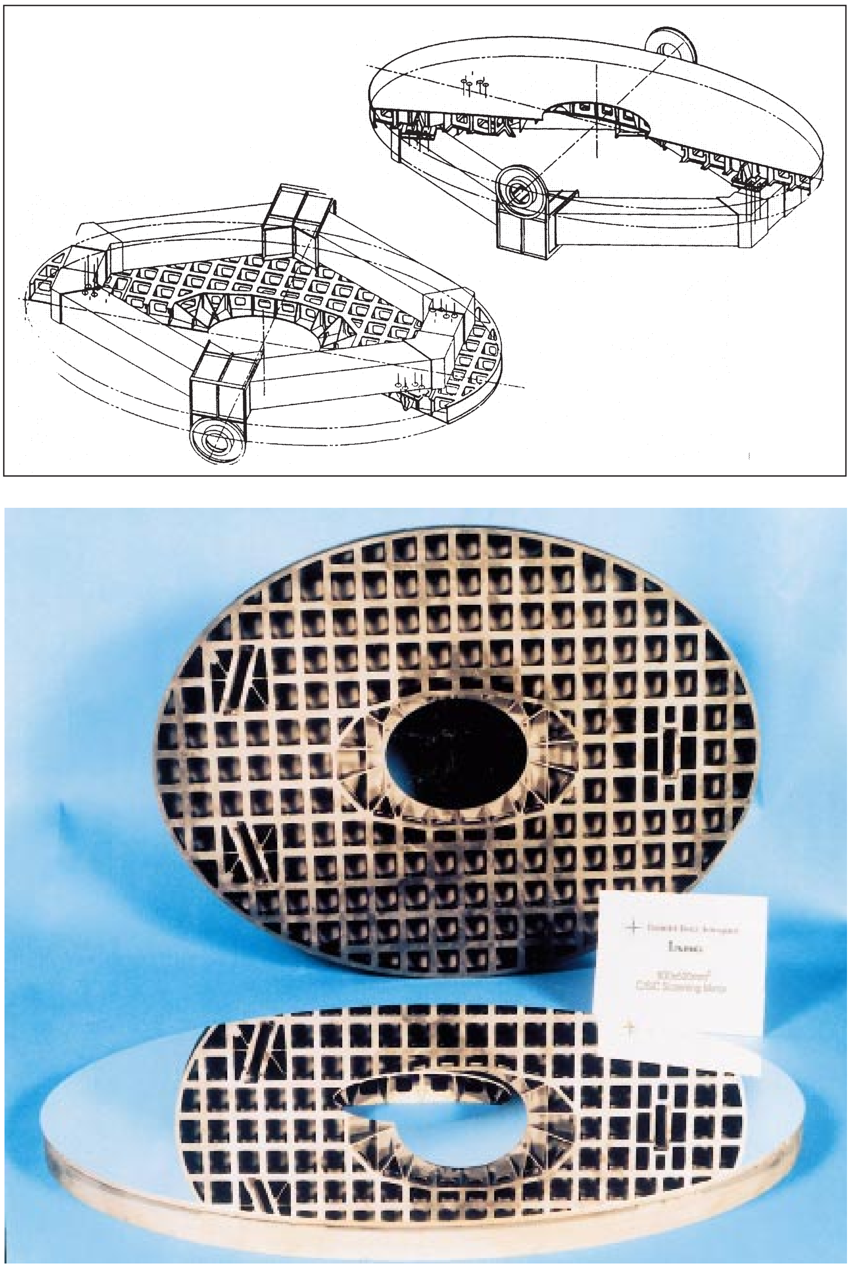
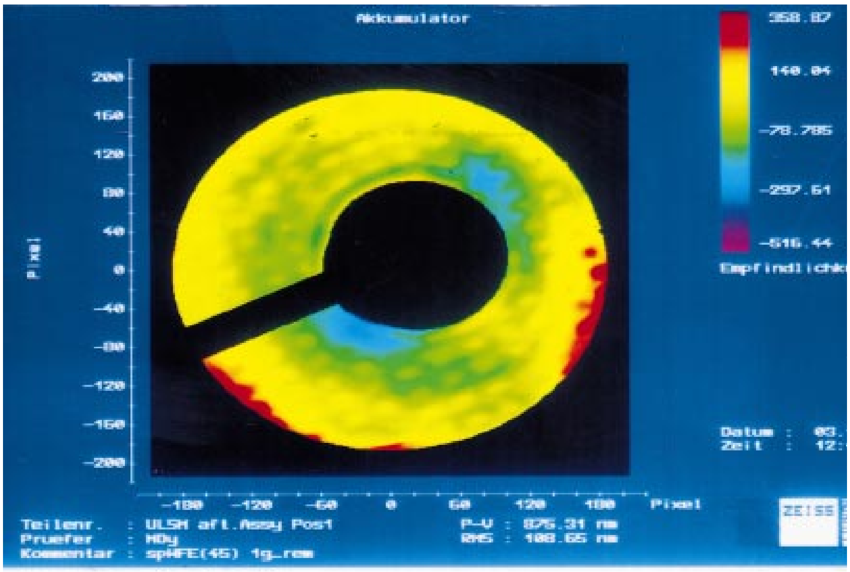


Figure 6. Design and hardware of the 80 cm x 50 cm Ultra Lightweight Scanning Mirror (ULSM), which weighs just 7 kg



Datum : 03.
Zeit : 12:

Teilenr. : ULSM afl.Assy Pos1
Pruefer : HDy
Kommentar : spWFE(45) 1g_rem

P-V : 875.31 nm
RMS : 108.65 nm

Figure 7 . Interferogram of the assembled 80 cm x 50 cm ULSM

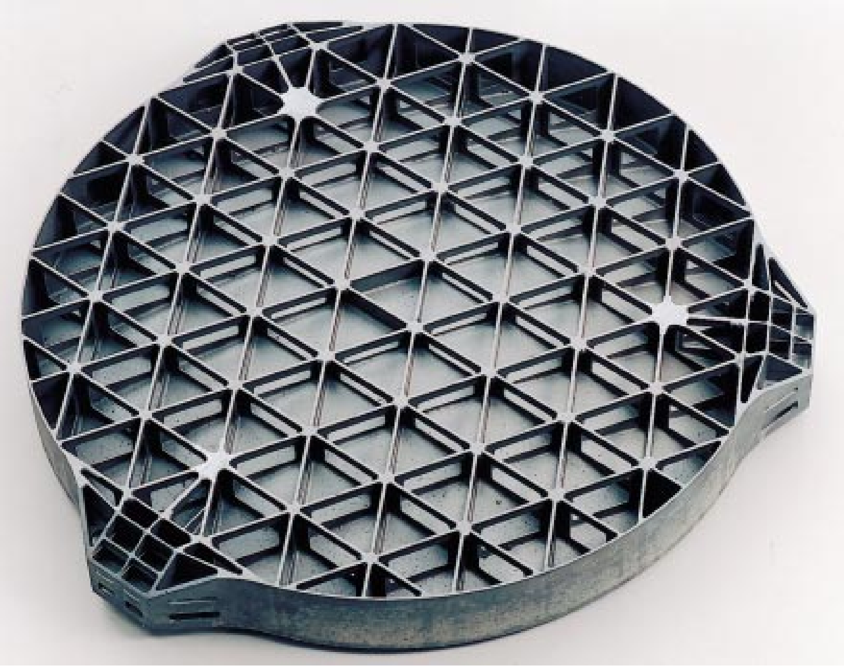


Figure 8. Rear of the 63 cm parabolic mirror for the ATLID application

Figure 9. Large verification structure for the SEVIRI thermal-stability test; the monolithic ceramic structure is 150 cm in diameter and 200 cm high

ATLID

Another example of highly efficient structural design is the ATLID (Atmospheric Lidar Experiment) parabolic mirror (F 0.9, aperture 63 cm). In the stiffening structure (Fig. 8), all unnecessary material has been removed in a trade-off between stiffness and mass, including in the area 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 has been designed to have a first eigenfrequency of over 400Hz and a structural safety margin of 3.9 at 60 g static load.

After fine machining and lapping to 8 micron rms accuracy, the mirror surface was coated with a 150 micron CVD-SiC layer. Sample polishing tests have shown good homogeneity and that a surface micro-roughness of less than 1 nm rms can be achieved. The mirror exhibited no change in radius of curvature after the CVD coating. The “as built” mass of the mirror is just 6.2 kg.

Three-dimensional structures

The excellent “joinability” of the C/SiC material allows individually machined parts and structural elements to be combined to form complex 3D structure. The designer can therefore manufacture a ceramic telescope or instrument structures to final dimensions in the green-body state and then “infiltrate” them to form an integral ceramic component. C/SiC optical components can be used in combination with C/SiC structures to build athermal optical systems.

In addition, monolithic ceramic truss structures with better stiffness and thermo-mechanical properties than conventional all-aluminium or beryllium-type structures can be realised. Figure 9 shows such a large monolithic all-C/SiC reference structure which is currently being manufactured.

Conclusion

A process has been successfully developed that allows C/SiC ceramic materials to be used to manufacture highly complex, lightweight, high-stiffness mirrors and structures with excellent dimensional stability. C/SiC reflectors can be manufactured from a single piece of green-body or, for larger reflectors up to 3 m in diameter, as separate segments which are then joined whilst in the green-body state. This novel approach also allows one to realise closed-back designs, which result in improved structural efficiency. Different polishable surface coatings have also been developed for specific applications, which range from scanning mirrors to large telescope reflectors. Last but not least, this all-ceramic instrument technology delivers consistently high optical performance over a very wide temperature range.