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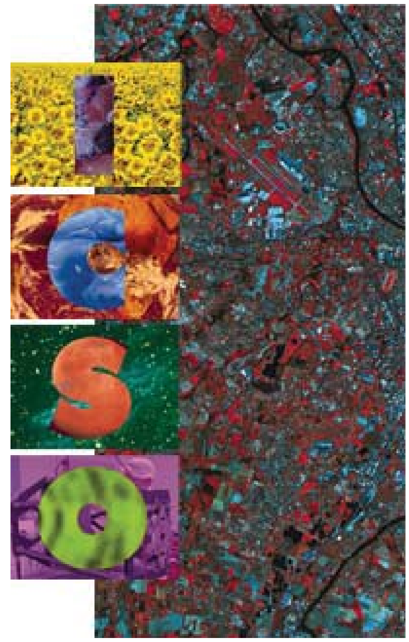

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Michel Bougoin

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SiC MATERIAL AND TECHNOLOGY FOR SPACE OPTICS

Michel BOUGOIN

Boostec Industries
mbougoin@boostec.com

RESUME – Tirant profit de sa grande rigidité spécifique et de sa stabilité thermique inégalée, le matériau de SiCSPACE est maintenant utilisé pour la fabrication des télescopes spatiaux destinés aux applications scientifiques ou commerciales.
Le présent document décrit les caractéristiques de ce carbure de silicium fritté.
Les équipements de Boostec et la technologie décrite ci-dessous permettent de fabriquer des éléments de structure et des miroirs de grandes dimensions (jusqu'à plusieurs mètres), pour un coût compétitif, de l'unité à la moyenne série.
Plusieurs exemples de réalisations destinées aux optiques spatiales sont présentés.

ABSTRACT *- Taking benefit from its very high specific stiffness and its exclusive thermal stability, the SiCSPACE material is now used for the fabrication of scientific and commercial lightweight space telescopes.*
This paper gives a review of the characteristics of this sintered silicon carbide.
The BOOSTEC facilities and the technology described here allow to manufacture large structural components or mirrors (up to several meters) at cost effective condition, from a single part to mass production.
Several examples of SiC space optical components are presented.

1- INTRODUCTION

After 5 years of joint research and development on silicon carbide applications, Matra Marconi Space (now Astrium) and Céramiques & Composites (now Boostec Industries) set up SiCSPACE in 1997. This joint venture aims at combining the knowledge of both companies in order to supply SiC components to the space optics.
The SiCSPACE commercial successes of today confirm the sintered SiC (S-SiC) as the ultimate material for space mirrors and telescopes.

2- CHARACTERISTICS OF SiCSPACE SILICON CARBIDE

2.1- Microstructure and properties

A lot of fully different ceramics are commercialised under the name "silicon carbide": from the coarse grained refractory which is used as porcelain kiln furniture to the high mechanical strength material which is further discussed in this paper.

The SiCSPACE material is a sintered silicon carbide: S-SiC. It shows a polycrystalline structure, with a grain size ranging around 5 µm. These elementary grains are isotropic in shape and oriented at random, thus giving a fully isotropic microstructure, which allows to obtain highly isotropic physical properties.
It is crystallised in the most stable alpha system, taking profit from its high processing temperature.

This S-SiC is a pure material: > 98.5 wt % SiC and < 1 wt % boron as sintering additive. Its lack of secondary phase and its very low residual porosity allow to fully use the inherent properties of the pure SiC phase.

The sintering level is guaranteed over 96.6 %, thus giving a bulk density (ρ) ranging between 3.10 and 3.19 g/cm^3 and a total porosity which is less than 3.4 %. This porosity is fully closed i.e. the pores are not interconnected, thus allowing a good tightness against liquids and gases. The pores are always intergranular and two types can be distinguished:

- a small number of pores not exceeding a few tens of microns : they are caused by some imperfections of the process,
- A large amount of very small pores (< 2µm) because the sintering cannot be fully completed.

The residual porosity is very homogeneously distributed in the whole volume of the material so that the amount of surface porosity is very similar to the volumic one.

For the highly demanding applications where no surface porosity can be accepted, a coating of the optical surface is recommended: for example a CVD or a CVI SiC around 80 µm thick.
The replication of the optical faces is also possible; it should be of great interest in case of mass production.

2.2- Mechanical properties

The mechanical properties of SiCSPACE silicon carbide are remarkably higher than that of glass or glass-ceramics. S-SiC is furthermore insensitive to mechanical fatigue: it is not damaged after 1 million of 300 MPa 4-points bending cycles.
The SiCSPACE material has been demonstrated totally free of internal stresses, thus preventing from deformation due to relaxation.

Bending strength according to DIN 52 292 : *coaxial double ring bending test on flat specimens* Average strength Weibull modulus	 > 375 Mpa > 8
Average tensile strength	200 MPa
Average compressive strength	3 000 MPa
Young Modulus (E)	420 GPa
Shear Modulus	180 GPa
Poisson ratio	0.16
Hardness (HV 500)	22 GPa
K1c Toughness (SENB method)	3.5 MNm$^{-3/2}$
Dry SiC / SiC wear coefficient	0.4

Table 1: Typical mechanical characteristics of SiCSPACE silicon carbide @ R.T.

2.3- Thermal properties

S-SiC can be used from a few K up to 1700 K in air and 2050 K in a protective atmosphere: vacuum or neutral gas.
The coefficient of thermal expansion of SiCSPACE silicon carbide is low and very homogeneous in the whole volume of the material: its dispersion is lower than 0.001 . 10^{-6} K^{-1} . The thermal conductivity of this material is high, similar to that of aluminium.

Coefficient of Thermal Expansion (α)		
	@ 100 K	0.6 . 10^{-6} K^{-1}
	@ 200 K	1.3 . 10^{-6} K^{-1}
	@ 293 K	2.0 . 10^{-6} K^{-1}
	@ 400 K	3.2 . 10^{-6} K^{-1}
Specific Heat	@ 293 K	680 J / kg.K
Thermal Diffusivity (D)	@ 293 K	84 . 10^{-6} m²/s
Thermal Conductivity (λ)		
	@ 100 K	185 W / m.K
	@ 200 K	215 W / m.K
	@ 293 K	180 W / m.K
	@ 400 K	130 W / m.K
Resistance to Thermal Shocks : ΔT_c		325 K

Table 2: Typical thermal characteristics of SiCSPACE silicon carbide

2.4- Figures of merit

The materials of space telescopes are selected from the following figures of merit.

Specific stiffness (E/ρ)	@ 293 K	133 . 10^6 m² / s²
Thermal stability in steady state condition (λ/α)		
	@ 100 K	308 . 10^6 W / m
	@ 200 K	165 . 10^6 W / m
	@ 293 K	90 . 10^6 W / m
	@ 400 K	40 . 10^6 W / m
Thermal stability in transient condition (D/α)	@ 293 K	42 m².K / s²

Table 3: Typical Figures of Merit of SiCSPACE silicon carbide

The graph of Figure 1 gives evidence of SiCSPACE silicon carbide superiority.

The very high specific stiffness of this S-SiC (similar to that of Beryllium) allows to design very lightweight structural parts. Its exclusive thermal stability allows, on the other hand, the design of assemblies that are highly insensitive to temperature fluctuation. It must be also noticed that S-SiC thermal stability is strongly enhanced when the temperature is decreased from R.T. to 100 K.
These outstanding figures of merits make possible a new concept of all SiC telescopes, as developed by SiCSPACE [Anto 99].

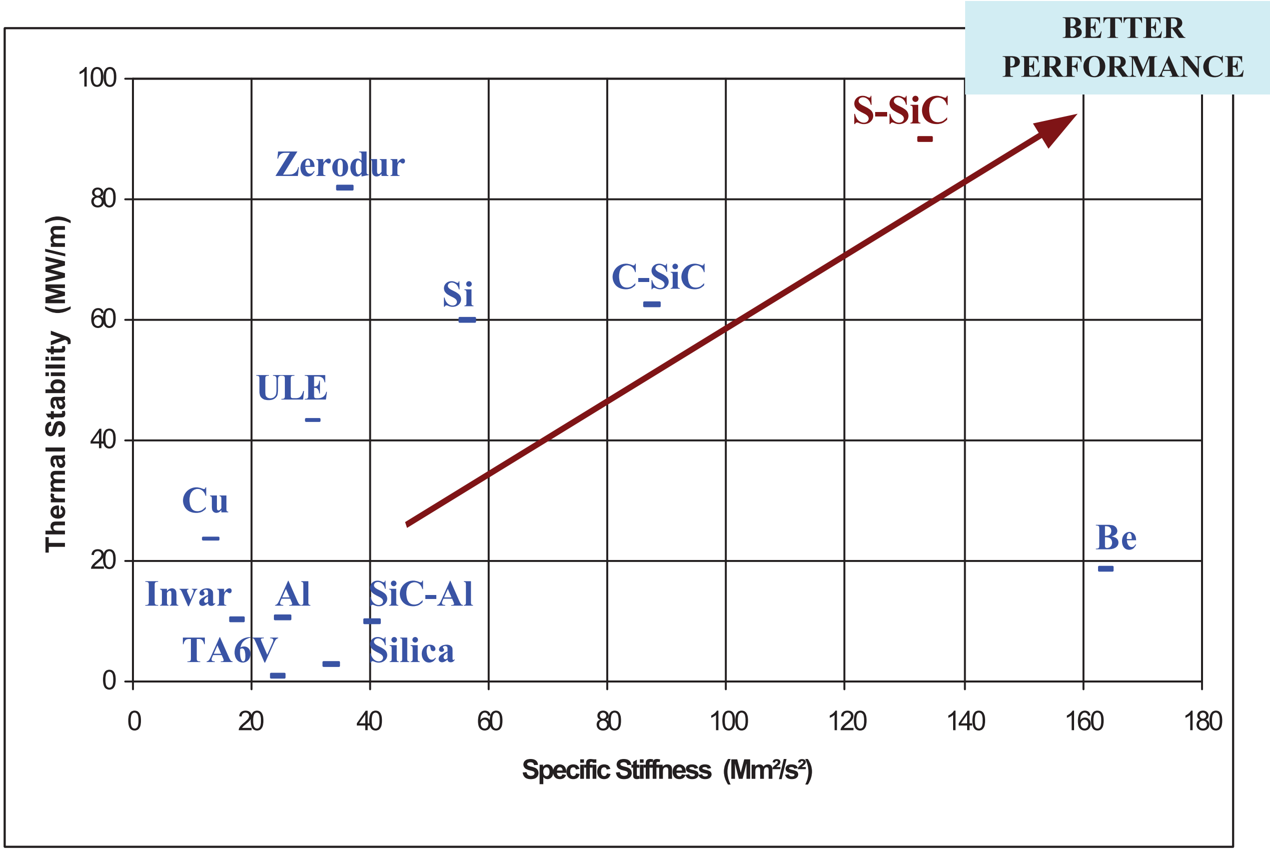

Figure 1: Figures of Merit of SiCSPACE silicon carbide: comparison with other materials

2.5- Other properties

With a resistivity of 10^5 Ohm.m @ 293 K, SiCSPACE silicon carbide is a semiconductor. It is also non-magnetic.

It has been demonstrated that a 200 Mrad irradiation with gamma ray has no effect on the WFE of a S-SiC mirror.

Thanks to its covalent Si-C bonds, the S-SiC is highly stable in time and it shows an outstanding chemical inertia. It is not sensitive to moisture and highly resistant to organic solvents but also to strong acids and alkalis. For instance, it is not attacked by hydrofluoric acid that is well known for etching glass or silica based ceramics.

A very thin layer of silica can occur, due to the oxidation of SiC surface:
- a few molecular layers around 300 K,
- a few nanometers around 900 K,
- a few micrometers above 1800 K.

3- THE SiCSPACE SILICON CARBIDE MANUFACTURING PROCESS

3.1- Process of manufacturing monolithic S-SiC parts

The major steps of manufacturing S-SiC parts are described in figure 2.

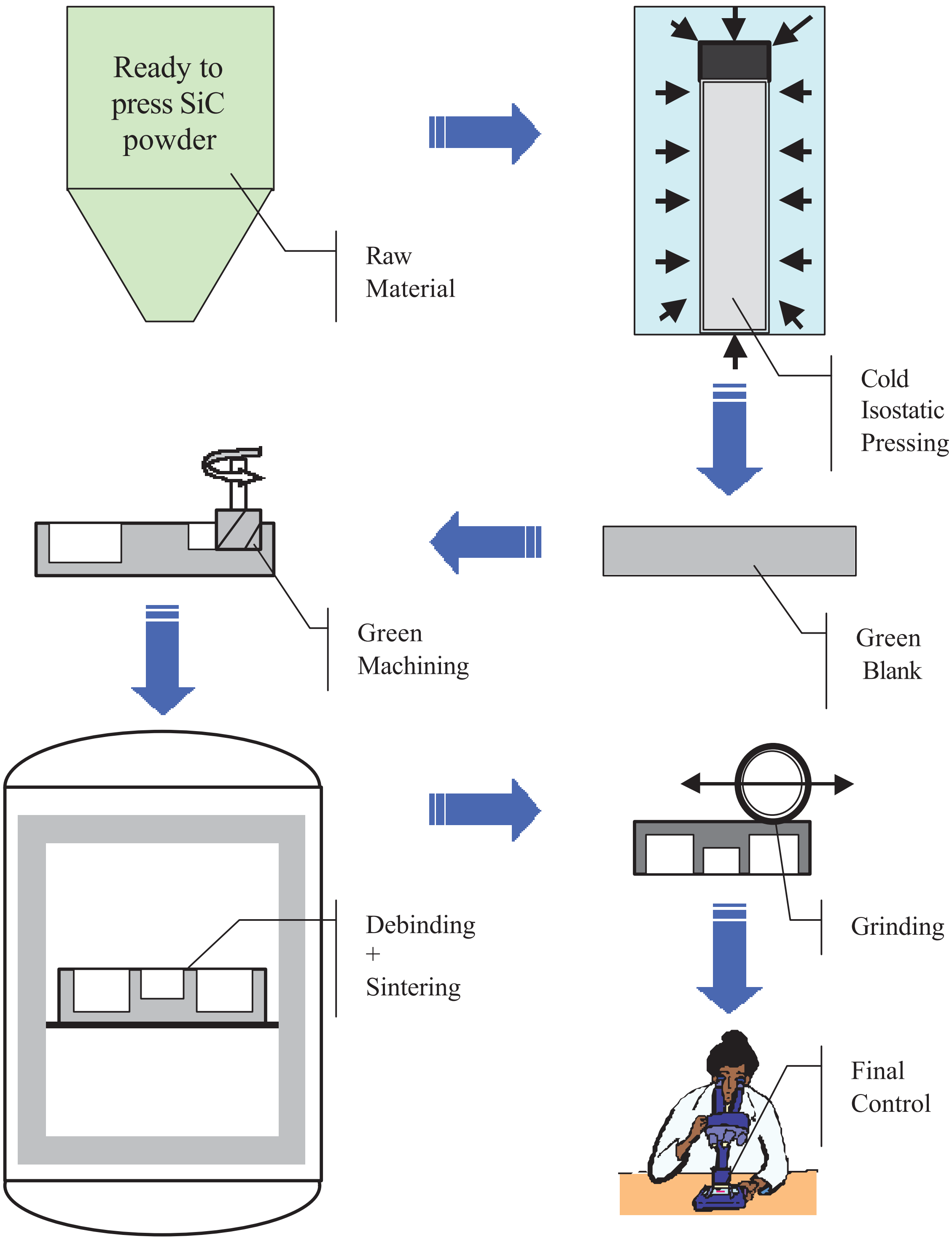

Figure 2: Major manufacturing steps of sintered silicon carbide

The so-called "ready to press SiC powder" is a homogeneous mixture of:

- Fine (sub-micronic) alpha SiC powder: obtained by the Acheson industrial process. A mixture of carbon material (petroleum coke) and silica sand is reacted chemically at high temperature in the range of 1700-2500°C resulting in the formation of SiC. The synthesised SiC powder is then milled in order to reach the required fine grain size.
- Carbon and boron sources: these elements are both necessary as sintering aids
- Organic additives, which further help the shaping process

In the cold isostatic pressing (CIP), the raw material is very homogeneously compacted through a rubber bag, with help of a high-pressure liquid: up to 200 MPa. The iso-pressed part is called the "green blank". It is a block of compacted powder, which can be easily machined, taking profit from its softness.

SiCSPACE uses a near-net-shaping process i.e. that the shape of the part is obtained mainly by machining the "green blank", before sintering. It is particularly the case for all the lightweighing work : ribs down to 1 mm thick can be obtained. This machining of soft blanks makes SiCSPACE process very cost effective and it allows to reduce the manufacturing time. For this purpose, Boostec facilities include several CNC milling machines and a lather.

Figure 3: BOOSTEC has the capability for CNC milling large parts as shown here with a petal of the FIRST Φ 3.50 m reflector

The machined parts are then debound and pressure-less sintered. The sintering operates only with help of the high temperature: typically 2100 °C, under a protective (non-oxidising) atmosphere, in a graphite electrical furnace. During this step, the bulk volume of the SiC part is reduced. This shrinkage is anticipated and well mastered: see §3.2 about the general tolerances.

When accurate geometry or size is required, some areas of the parts can be ground (with help of a diamond wheel) or lapped after the sintering step. Boostec facilities allow flat grinding as well as cylindrical or curved grinding up to 1.4 m in diameter. All curved profiles can be obtained from the CNC grinding machine.

The final control includes typically :

- Size and geometry control, with help of a 3D measuring machine,
- Inspection under U.V. light after an impregnation with a fluorescent dye
- Visual and / or binocular inspection

The S-SiC that is now manufactured by Boostec for space optics has been processed by Céramiques & Composites during 15 years. It is commonly used as a friction material in the pumps of the chemical engineering industry and, for example, in the mechanical seals of the water cooling pumps of the automotive industry. The S-SiC manufacturing process is well suited to the mass production.

3.2- Characteristics of manufactured S-SiC blanks

Thanks to the process described here above, S-SiC physical properties are reproducible and homogeneous in time, from batch to batch and inside a part.

It allows to manufacture a great variety of shapes : prismatic shapes (lightweighed or not), tubes, beams, sheets, etc…

At present time, the main size limitation is due to the isostatic pressing facilities but it allows to obtain monolithic sintered parts of up to 1 m x 1.5 m. Larger parts can be manufactured from different joining techniques: see § 3.4.

Boostec can predict the sintering shrinkage so that the tolerance between as sintered faces is +/- 0.4 %. A further grinding allows to reduce this tolerance in the range of 0.01 mm.

The typical roughness of mechanical parts is :
- 0.3 µm RMS on as-sintered or ground faces
- 0.1 µm RMS on lapped faces

3.3- Polishing and coating

Standard mechanical diamond polishing may be used to polish the S-SiC at $\lambda/30$ RMS.
SiCSPACE has developed the Ion Beam Figuring; a WFE lower than $\lambda/100$ RMS has been successfully obtained on a Φ 200 mm aspherical mirror with help of IBF [Frui 99].

The S-SiC blanks show a lot of key advantages for both polishing techniques:
- a single phase,
- no plasticity and high stiffness,
- high thermal conductivity,
- low weight of the blanks.

The SiC polished surface can be easily coated with thin reflective layers, similarly to glassy materials : Al, Au, dielectrics …

3.4- S-SiC joining techniques

Very large size (> 1 meter) or complex shape S-SiC components are obtained from different joining techniques, which have been qualified by SiCSPACE :

- Bolting on SiC or on another material; the high dry SiC / SiC friction coefficient (0.4) prevents the joined parts from sliding
- Bonding on SiC or on another material: with help of space qualified epoxy glues
- Brazing SiC on SiC, with the Brasic™ process; a non reactive brazing alloy has been designed to perfectly match SiC coefficient of thermal expansion and strength.

4- APPLICATIONS OF SiCSPACE MATERIAL AND TECHNOLOGY

Three examples of applications are very briefly presented hereafter. At present time, BOOSTEC is manufacturing the telescope hardware (both mirrors and structure) of the ROCSAT-2 earth observation satellite, for ASTRIUM.

4.1- SOFIA secondary mirror

SiCSPACE silicon carbide has been selected for the Φ 352 mm secondary mirror of the NASA/DLR SOFIA airborne project. Its mechanical design is optimised for a minimum deformation under gravity and under polishing efforts. It has a first eigen frequency above 1300 Hz, for a mass of 1.7 kg.

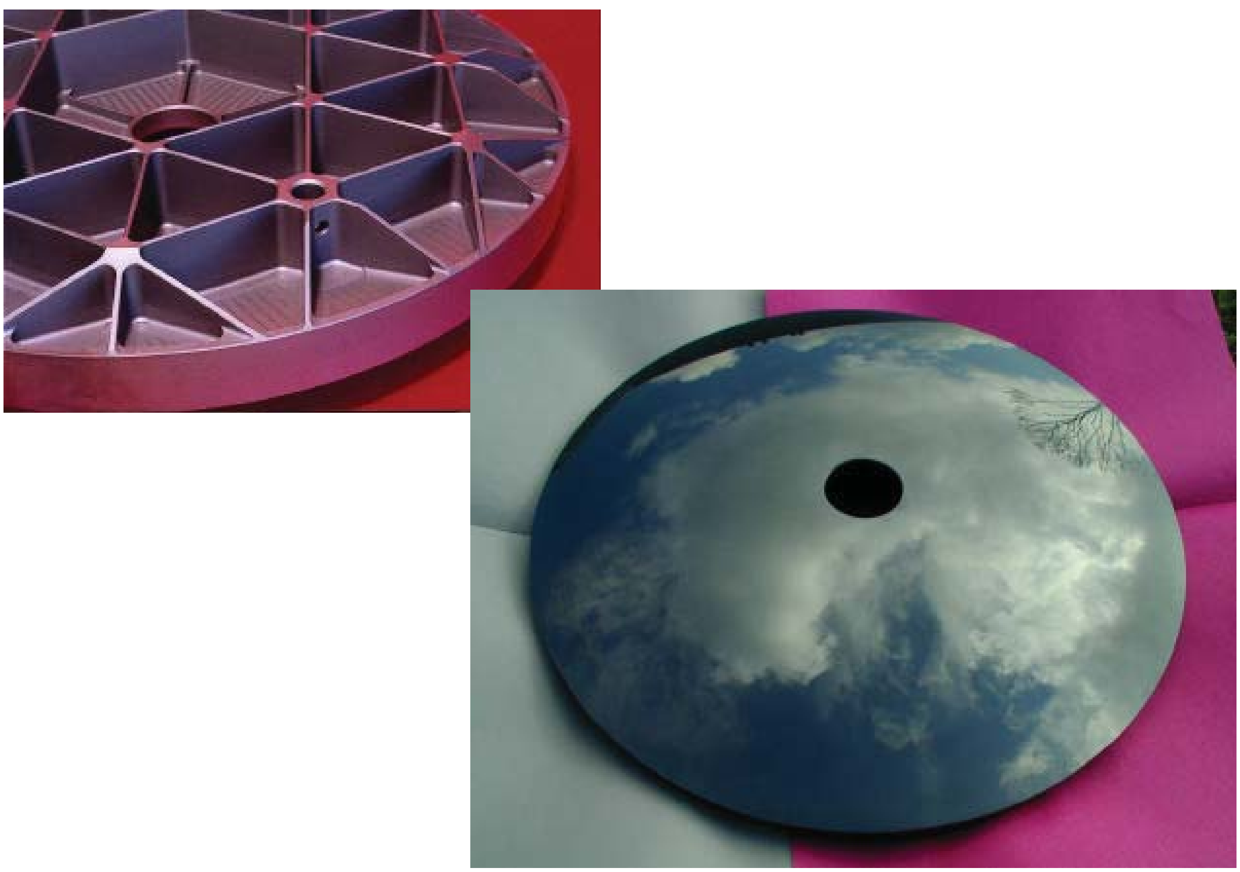

Figure 4: SOFIA S-SiC secondary mirror

4.2- Osiris Narrow Angle Camera (NAC)

Osiris is the remote imaging system of the ROSETTA ESA cometary mission, to be launched in 2003. The NAC is a all-SiC TMA telescope. The structure is a U-shaped one comprising a central tube bonded together with two lightweight walls. The three mirrors are bolted on the structure. The total weight of the NAC is less than 12 kg, including only 5 kg of S-SiC hardware. It suits very well with the requirements of the ARIANE 5 launcher. It will work between –100 and +70°C without any thermal regulation [Cast 99].

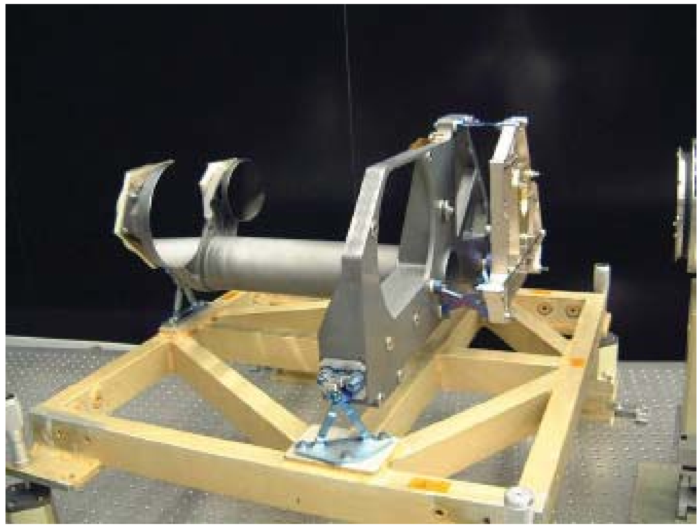

Figure 5: OSIRIS Narrow Angle Camera during assembly at ASTRIUM Toulouse

4.3- FIRST primary mirror

FIRST is an ESA project, which aims at exploring the formation of galaxies and stars. Thanks to ESA funding, SiCSPACE has developed and manufactured a Φ 1.35 m demonstrator involving all the technologies required for manufacturing the Φ 3.50 m primary mirror of the FIRST telescope.

This demonstration model is made of 9 segments brazed together. It has been polished to a mirror error below 2.5 µm and its optical quality measured in thermal vacuum down to 100 K without any measurable effect (< 0.5 µm). It has also been successfully tested for 35 g static loads [Safa 97], [Safa 00].

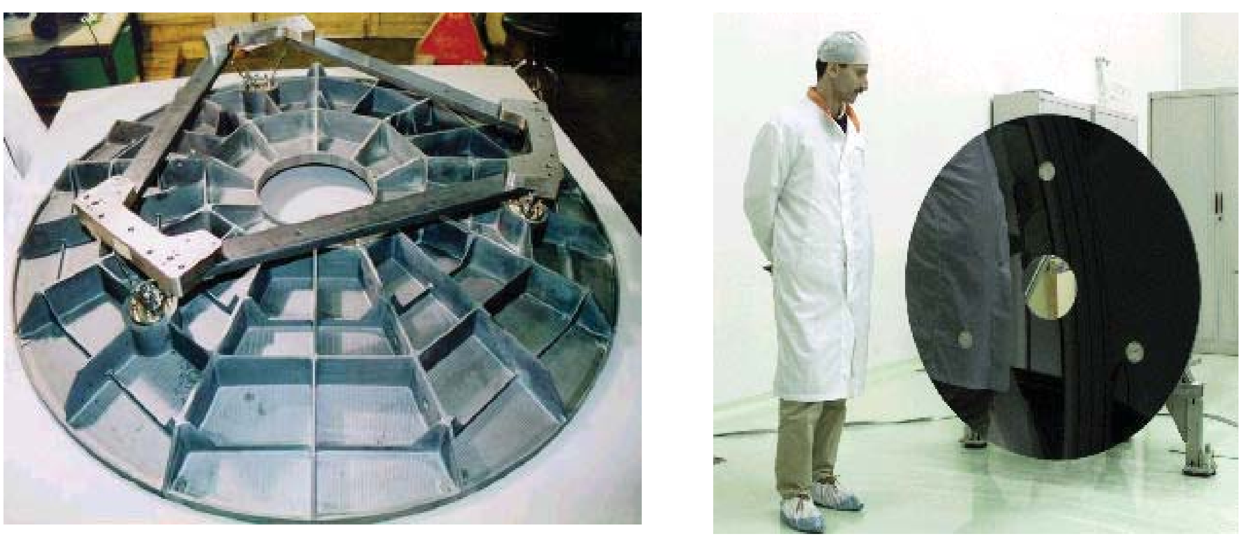

Figure 6: Φ 1.35 m FIRST S-SiC demonstration model

5- CONCLUSION

The SiCSPACE silicon carbide provides a unique combination of key advantages for the fabrication of very lightweight and thermally stable telescopes : both structural elements and reflectors.

As it is very well adapted for the fabrication of large components or for mass production at reasonable cost, this sintered SiC now clearly appears as the ultimate solution for space optics.

After more than five years of pioneering work, the SiCSPACE technology has now started its industrial life.

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