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Full-SiC EUCLID's very large telescope

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ABSTRACT

Euclid is a part of the European Space Agency Cosmic Vision Medium Class program. This mission's goal is to investigate the nature of dark energy, dark matter and gravity by observing the geometry of the Universe and the formation of structures over cosmological timescales.

Euclid Payload Module (PLM) includes a large three mirrors anastigmatic Korsch telescope feeding a visible imager (VIS) and a near-infrared spectrometer and photometer (NISP). The hardware of all of them will be mainly made of Boostec® SiC material.

The SiC telescope has been designed by Airbus Defence and Space team in Toulouse (France).

The PLM is divided in two cavities which are separated and hold by a very large SiC baseplate; the front one includes the primary and secondary mirrors and the associated support structure while the back one consists of the telescope folding mirrors, the tertiary mirror, the two instruments (VIS and NISP) and other optical devices. The focal length is 24.5 m and the useful pupil diameter is 1.2 m. A passive thermal concept has been developed, thus requiring minimum heating power and providing best thermal stability. The telescope will operate at ≈130 K.

In addition to its high thermal conductivity, the Boostec® SiC has been chosen for its mechanical properties and its ability to greatly reduce mass. The full SiC telescope architecture gives high optical stability.

The present paper describes the very large full-SiC telescope and the manufacturing process of its SiC parts, in particular the mirrors, the lightweight baseplate and the spider.

Keywords: space telescope, silicon carbide, Euclid, SiC mirror, SiC structure, thermomechanical stability, lightweight

1. INTRODUCTION

Euclid is Medium Class mission of the ESA Cosmic Vision 2015-2025 program. This survey mission will investigate the nature of dark energy, dark matter and gravity by observing their signatures on the geometry of the Universe.

Thanks to its high specific stiffness and its high thermal stability, the Boostec® SiC material has been selected for manufacturing full-SiC space telescopes for the last 20 years. 18 of them are (or have been) operational in space since 2004.

Euclid payload module (PLM) is a three-mirrors-anastigmatic Korsch telescope which feeds NISP (infrared) and VIS (visible) instruments. The telescope has a Ø 1.2 m entrance pupil; it is based on a thermal passive concept. It is called "full-SiC" because both mirrors and structure are made of SiC material.

The present paper begins by reviewing the Boostec® SiC material properties and explaining why it is so promising for space optics. Then, after having described the design of Euclid PLM, it presents the manufacturing technology of all its SiC parts, in particular the most challenging of them: the Ø 1.25m SiC CVD coated primary mirror, the 2.50 m x 2.15 m lightweight baseplate and the Ø 1.50 m spider. The last two are brazed assemblies of several monolithic SiC parts.

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2. BOOSTEC SiC® MATERIAL FOR SPACE OPTICS

Mersen Boostec manufactures a **sintered silicon carbide** which is named **Boostec® SiC**. Its key properties are a high specific stiffness (420 GPa / 3.15 g.cm^{-3}) combined with a high thermal stability (180 W.m^{-1}.K^{-1}/ 2.2 . 10^{-6} K^{-1}).

Its high mechanical strength allows making mirror but also structural parts, such as the structure of Euclid telescope and its two attached instruments.

Thanks to its isotropic microstructure, the physical properties of this alpha type SiC are perfectly isotropic and reproducible inside a same large part or from batch to batch. In particular, no CTE mismatch has been measurable, with accuracy in the range of 10^{-9} K^{-1} [1].The CTE of Boostec® SiC is decreasing from 2.2 . 10^{-6} K^{-1}@ room temperature down to 0.2 . 10^{-6} K^{-1}@ 100K and close to zero between 0 and 35K. Its thermal conductivity remains over 150 W/m.K in the 70 K-360 K temperature range.

This material shows no mechanical fatigue, no outgassing and no moisture absorption nor release. It has been fully qualified for space application at cryogenic temperature such as NIRSpec instrument which will be operated in space at only 30 K [2].

Although perfectly tight, Boostec® SiC material exhibits a < 2.5 vol.% residual porosity which leads to unacceptable level of stray light, particularly for visible and UV range application. This is the reason why the mirrors optical face is generally coated with a pore-free SiC CVD layer, as it is the case for all Euclid optics.

Since 2004, 18 full-SiC telescopes made of this technical ceramic are (or have been) successfully operating in space, including Rosetta Osiris NAC, Herschel and Gaia [3] [4] for science purpose together with Sentinel-2 Multi Spectral Instruments and a lot of Korsch ones dedicated to earth observation [5].

Table 1. Basic Properties of Boostec® SiC

Properties	**Typical Values @ 293 K**
Density	3.15 g.cm^{-3}
Young's modulus	420 GPa
Bending strength / Weibull modulus (coaxial double ring bending test)	400 MPa / 11
Poisson's ratio	0.17
Toughness (K_{1C})	4.0 MPa.m$^{1/2}$
Coefficient of Thermal Expansion (CTE)	2.2 . 10^{-6} K^{-1}
Thermal Conductivity	180 W.m^{-1}.K^{-1}
Electrical Conductivity	10^{5} Ω.m

3. EUCLID

3.1 Euclid mission

Euclid is an ESA medium class astronomy and astrophysics space mission, to be launched in 2021.

The Euclid mission aims at understanding why the expansion of the Universe is accelerating and what is the nature of the source responsible for this acceleration which physicists refer to as dark energy. Dark energy represents around 75% of the energy content of the Universe today, and together with dark matter it dominates the Universes matter-energy content. Both are mysterious and of unknown nature but control the past, present and future evolution of Universe.

THALES Alenia Space is charged of the construction of the satellite and its Service Module while Airbus Defence and Space provides the Payload Module. The mirrors and the structures of all the PLM instruments will be mainly made of Boostec® SiC material, giving required lightweight, stiffness, strength and dimensional stability.

Euclid will embark a 1.2 m Korsch telescope feeding 2 instruments, VIS and NISP: a high quality panoramic visible imager (VIS), a near infrared 3-filter photometer (NISP-P) and a spectrograph (NISP-S). With these instruments physicists will probe the expansion history of the Universe and the evolution of cosmic structures by measuring the modification of shapes of galaxies induced by gravitational lensing effects of dark matter and the 3-dimension distribution of structures from spectroscopic red-shifts of galaxies and clusters of galaxies, with a look-back time of 10 billion years.

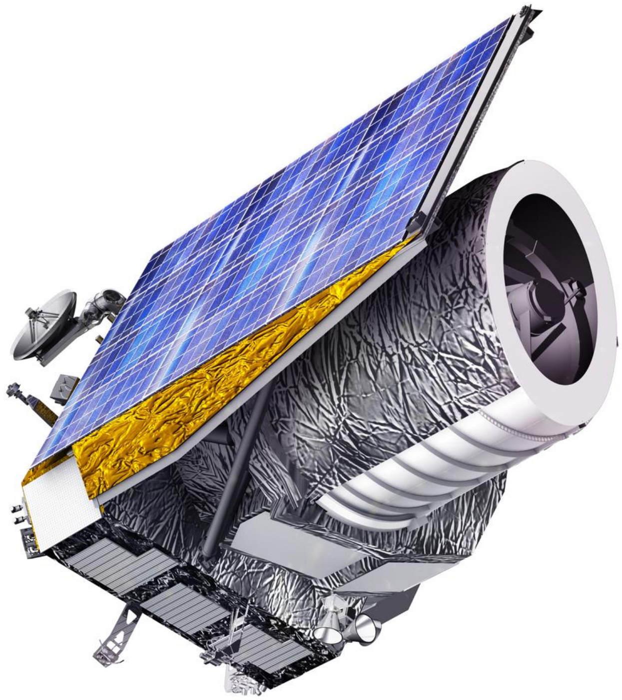

Figure 1. Artist's impression of Euclid satellite (credit ESA)

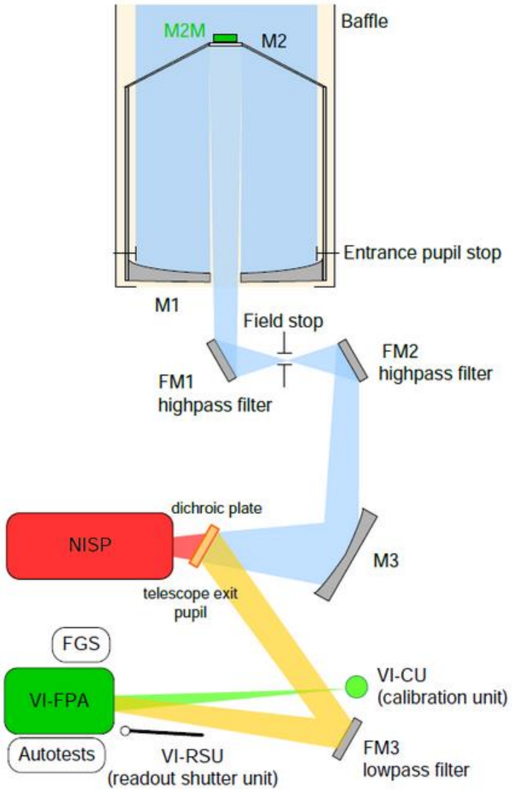

Figure 2. Payload Module scheme (credit Airbus)

The 2200 kg satellite (Fig. 1) will orbit at L2 Sun-Earth Lagrangian Point for a 6 years mission; it will cover 15000 deg² of sky area (30000 fields of 0.5 deg² each).

3.2 Payload Module (PLM)

The Euclid PLM is designed around a three-mirrors-anastigmatic Korsch telescope which feeds NISP and VIS instruments [6] (Fig. 2). The light is separated between the two instruments with help of a dichroic splitter located at exit pupil of the telescope. The PLM provides mechanical and thermal interfaces to the instruments (radiating areas and heating lines). The secondary mirror (M2) is mounted on a mechanism (M2M) allowing refocusing and tilt adjustment to compensate for launch and cool-down effects.

A large central SiC baseplate acts as the PLM backbone; it divides it in two cavities:

- The front cavity (Fig. 3) including the primary mirror (M1), the secondary mirror (M2), the M2 refocusing mechanism and all relevant support structures; it is thermally insulated by a baffle.
- The rear cavity (Fig. 4) including the telescope folding mirrors (FoM1, FoM2 and FoM3), the tertiary mirror (M3), the dichroic plate, the Fine Guidance Sensor (FGS), the NISP & VIS instruments, the shutter and calibration source of the VIS channel. The hardware of both NISP and VIS is also made of Boostec® SiC material, thus providing the required thermomechanical stability [7] [8].

The optical combination is a Korsch telescope design with a FoV offset of 0.47°. The useful pupil diameter is 1.2 m and the focal length is 24.5 m. The central obscuration has been minimized by designing a thin spider and careful design of M1 and M2 baffles. The resulting collecting area is larger than 1 m².

As for GAIA, a passive thermal concept has been adapted, requiring minimum heating power and providing best thermal stability. The telescope is cooled-down to its equilibrium temperature around 130K. In nominal operations, only local heating capacity at constant power is needed to adjust instruments interface temperatures to the prescribed value. This cold telescope offers high thermo-elastic stability (0.4 µm/m/K SiC CTE) and cold environment (135 K) to the instruments.

Table 2. Euclid telescope fact sheet [6]

Telecope type	Korsch[3]
Focal length	24.5 m
Entrance pupil	Ø 1200 mm
Paraxial F-number	F/20.42
M1	Ø 1250 mm
M2	Ø 350 mm
M3	535 x 406 mm²
FoM1	358 x 215 mm²
FoM2	283 x 229 mm²
FoM3	358 x 215 mm² (same as FoM1)
Dichroic plate	Ø 117 mm
M1-M2 distance	1756 mm
Useful collecting area	1.006 m²
Offset along Y axis	0.47°

Figure 3. Front view of the PLM without baffles (credit Airbus)

Figure 4. Rear view of the PLM (credit Airbus)

3.3 Euclid PLM mirrors

The telescope includes 3 aspherical mirrors (M1, M2 & M3) and 3 flat ones (FoM1, FoM2 and FoM3), the main sizes of which are presented here above in Table 2.

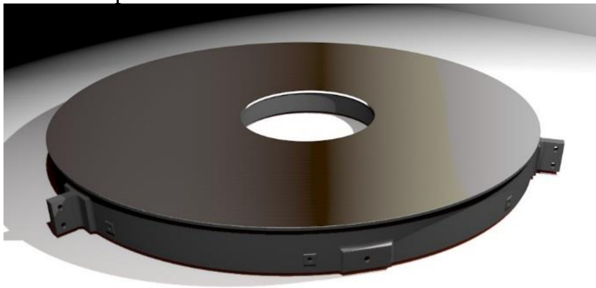

Figure 5. Euclid M1 design, optical face

Figure 6. Euclid M1 design, rear face

The M1 is the most challenging of them. It has been designed by Toulouse Airbus Defence & Space team, compliant with the following requirements i) weight < 40 kg, ii) WFE < 9 nm rms under 120 K cool-down and iii) telescope global WFE < 25 nm rms, all effects being taken into account. It has been highly optimized for purpose of both mass and cooldown WFE reduction. It features i) a Ø 1.25 m circular outer contour, ii) a Ø 0.37 m decentered circular inner hole, iii) on-axis concave optical face, iv) three outer pads to be bolted on the isostatic mounts, v) a mass of only 38 kg and vi) a first eigen frequency of 140 Hz.
The M2 is convex, off-axis and mounted with help of a rear central fixture to be bolted.
The M3 is concave, off-axis and interfaced through 3 outer pads to be bolted to bipods.
The FoM1 and FoM3 flat mirrors share the same design, including a rear central fixture to be bolted.
The FoM2 flat mirror will be mounted through 3 outer pads to be glued to bipods.

The optical face of all these mirrors is coated with pore-free SiC CVD layer a few hundred micrometers thick, thus masking the residual porosities of the sintered SiC which should be a source of straylight.

3.4 Euclid PLM structure

The Euclid structure has been designed around a large baseplate (2.50 m x 2.15 m), the backbone of the instrument.
On front cavity (Fig. 3), the M2 and its mechanism are hold by a Ø 1.5 m spider which is connected to the baseplate via six glued lightweight struts, 1.65m long. The spider has been designed to hold the secondary mirror with minimized obscuration.

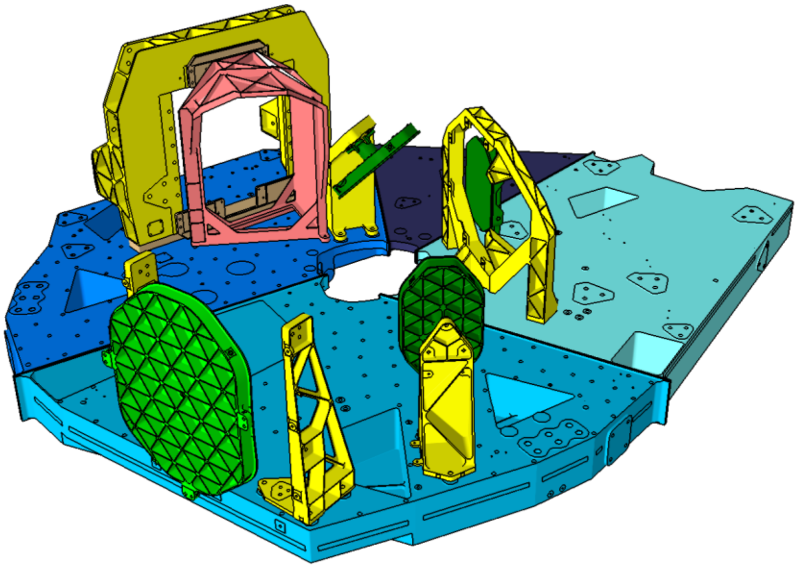

Figure 7. SiC parts of the rear cavity of Euclid telescope structure

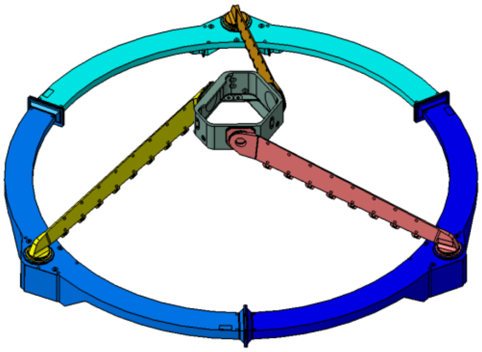

Figure 8. Ø 1.5 m SiC spider

On rear cavity (Fig. 7), a VIS Focal Plane hood and several SiC brackets are bolted on the baseplate; these brackets hold the M3 and all FoM mirrors, the dichroic plate, the VIS instrument, etc. NISP is a stand-alone instrument [6]; it is directly interfaced on the central baseplate through 3 bipods.

The baseplate and the spider have been designed very lightweight: respectively 187 kg and 25 kg; they are the most challenging parts. Being too large for monolithic manufacturing, they are obtained by brazing several sintered and ground SiC parts: 4 for the baseplate (Fig. 7) and 7 for the spider (Fig.8). Furthermore, the baseplate includes around 650 interfaces which must be lapped to required flatness.

4. MANUFACTURING TECHNOLOGY FOR EUCLID SIC PARTS

4.1 Manufacturing technology for monolithic structure elements

Commonly, Mersen Boostec manufactures and tests monolithic SiC parts of up to 1.7 m x 1.2 m x 0.6 m or Φ1.25 m according to the sequence of steps of Figure 9. The parts are machined very close to the final shape at the green stage i.e. when the material is still very soft (similar to chalk). The collected chips are reused for producing new raw material. These shaped parts are then sintered by heating-up to around 2100°C under a protective atmosphere, thus transforming the compacted powder blank into a hard and stiff ceramic material. The “as-sintered” surfaces look highly smooth (typically Ra 0.4 µm); they can be used as is, without any sand blasting or any other rework. After sintering, the interfaces are generally ground and then lapped in order to obtain scratch-free surfaces and also accurate shape and location.

Heavily loaded areas are mechanically proof-tested, thus reducing the risk of hidden defects in the material; even if unlikely, this is above all an easy way to really prove that the SiC blank is able to withstand with the predicted most critical loads. The SiC parts are checked crack-free with help of UV fluorescent dye penetrant, before and after such a proof-test. They are measured with a large size accurate CMM or a laser tracker.

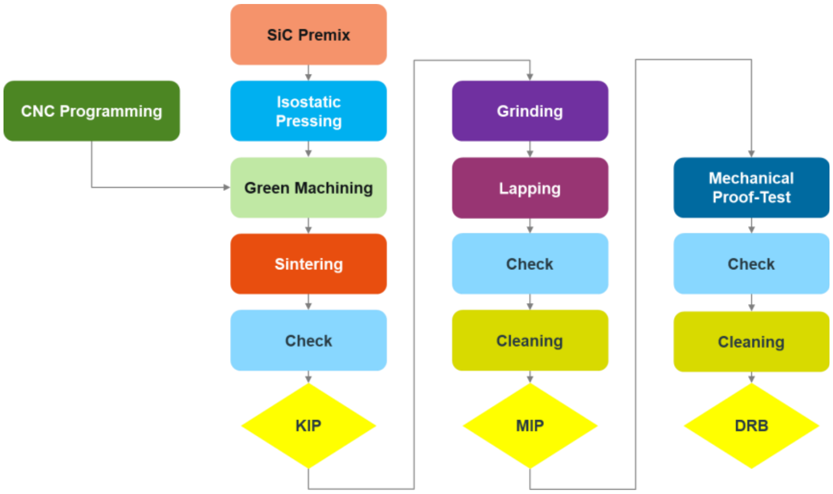

Figure 9. Sequence of steps for manufacturing monolithic structure elements

4.2 Manufacturing technology for mirrors

All ready-to-polish Euclid mirrors have been manufactured according to the sequence of steps of Figure 10 which differs from the previous Figure 9 only by the added right column, which concerns the SiC CVD coating.

The SiC CVD coating of Euclid mirrors has been feasible thanks to the large size of Mersen Gennevilliers reactor.
An important requirement was the saving of un-coated zones (ribs and pockets of backside, interface pads or central fixtures). Mersen Boostec has designed and mounted additional tooling in order to prevent from SiC deposition on such desired areas. After coating, the CVD layer thickness and also the optical face shape have been measured directly on the mirror blank with help of a CMM. Some witness samples have also been checked for purpose of i) coating thickness measurement, ii) cut-out microstructure investigation and iii) crystal structure analysis.
According to right column of Fig. 10, the SiC CVD layer has been then slightly ground in order to obtain a smoother surface, a more homogeneous CVD layer thickness and a shape closer to the final target.

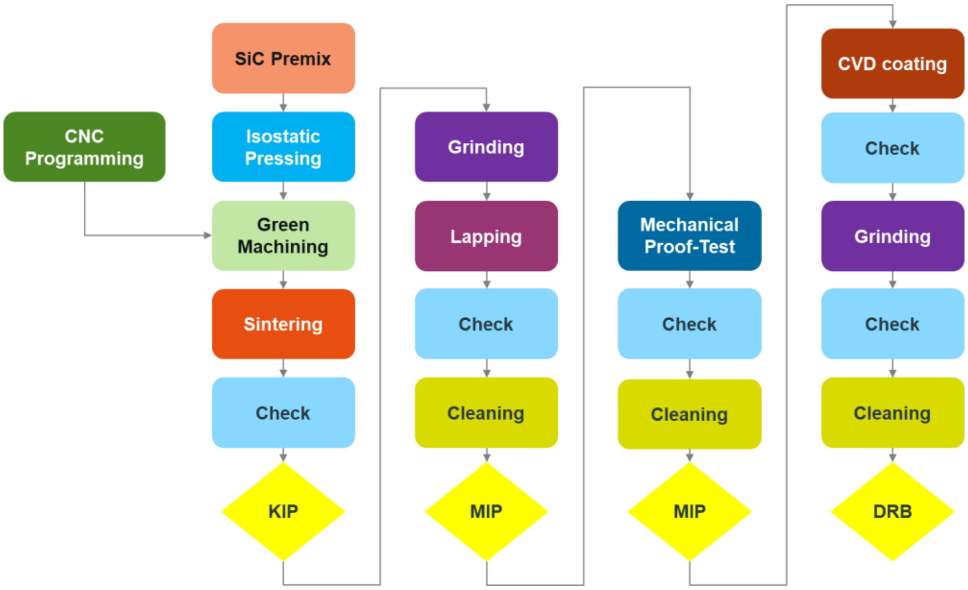

Figure 10. Sequence of steps for manufacturing ready-to-polish mirrors

4.3 Manufacturing technology for large structure elements: brazed assemblies

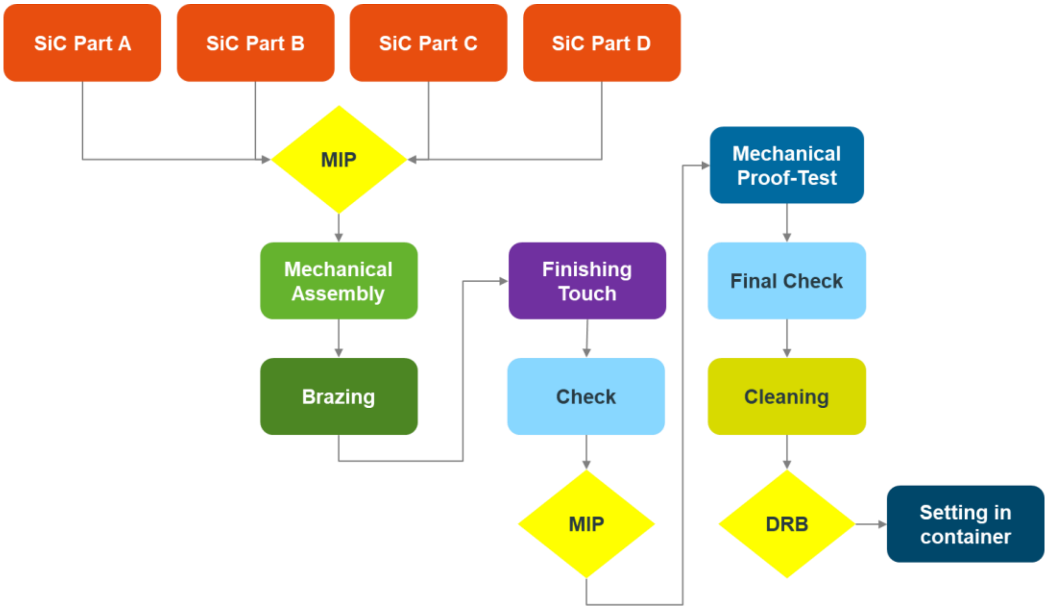

Figure 11. Sequence of steps for manufacturing Euclid brazed baseplate from 4 SiC parts

The SiC parts the size of which exceeds 1.5m x 1.0m are obtained by **brazing** the assembly of previously sintered and ground pieces. The joint is made of a silicon alloy and it is typically less than 0.05 mm thick. This technique had been previously used for producing very large space parts such as the Φ 3.5 m Herschel primary mirror and the main structure of the GAIA instrument (the torus) [3] [4].

On Euclid project, this is the case for the baseplate and the spider. The SiC elements to be brazed are manufactured according to the here above steps of Figure 9. The sequence of steps for manufacturing the brazed baseplate is described in Figure 11. The spider manufacturing steps are very similar, starting from a central barrel, three thin beams and three 120° sectors of the outer ring (Fig.8).

An ultrasound-based technique has been developed specifically with the CEA (the French Nuclear Agency) for checking the brazed joints. It allows the detection and the cartography of possible voids down to a few mm². The baseplate and spider designs took into account the requirements of this specific inspection (NDI). The most loaded brazed joints have furthermore been validated with specific mechanical proof-tests.

5. MANUFACTURING RESULTS

5.1 Mirrors

Mersen Boostec has manufactured two sets of mirrors. The first set, to be used on the Structural and Thermal Model (STM) has been delivered to Airbus Defence and Space without CVD coating. The second one includes the Flight Models (FM), the optical face of which has been SiC CVD coated; they have been manufactured conform to specifications and delivered to SAFRAN-REOSC (France) or to AMOS (Belgium) companies which are in charge of polishing and coating them.

The main characteristics of the ready-to-polish M1 FM are exhibited in Table 3.

Table 3. main characteristics of the ready-to-polish Euclid M1, Flight Model

Properties	**Measured Values**
Weight	39.0 kg
Outer diameter	1250.05 mm
Decentered inner hole diameter	367.29 mm
Average SiC CVD layer thickness	365 µm
Flatness of ISM pads	1 µm PV
Optical face shape defect	80 µm PV

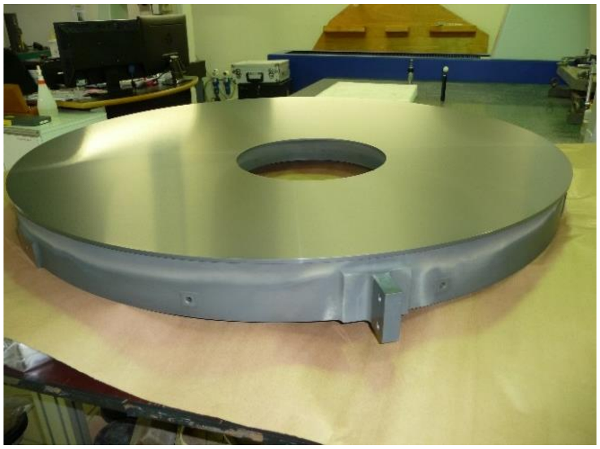

Figure 12. Ready-to-polish M1 FM blank, front face

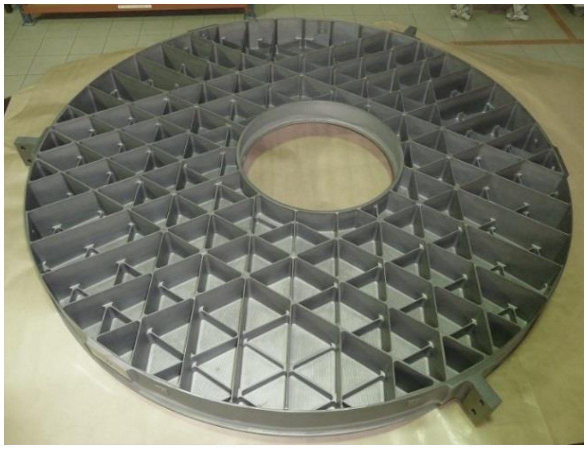

Figure 13. Ready-to-polish M1 FM blank, rear face

Figure 14. Ready-to-polish M2 FM mirror

Figure 15. Ready-to-polish FoM1 FM mirror

5.2 Structures

As for mirrors, Mersen Boostec is manufacturing two sets of structure SiC elements: a STM and a FM. Nearly all STM parts have been manufactured conform to specifications and delivered to Airbus Defence and Space.

The STM baseplate and spider which are the most challenging have been successfully achieved. The targeted masses have been reached. No significant defects were found in their brazed joints, from ultrasonic Non-Destructive-Inspection. They furthermore successfully passed their proof-test.

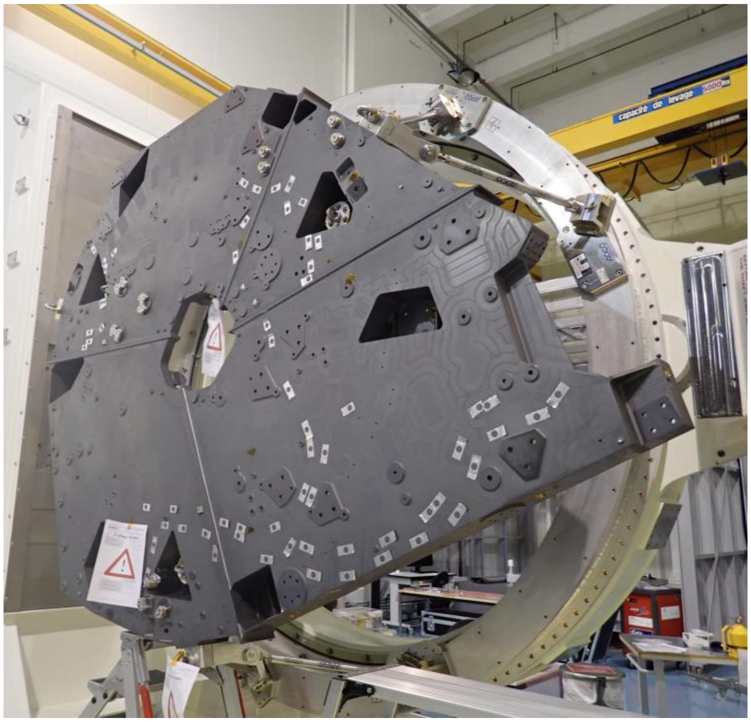

Figure 16. Brazed Baseplate starting integration (credit Airbus)

Figure 17. CMM measurement of the spider

Figure 18. FoM1 support

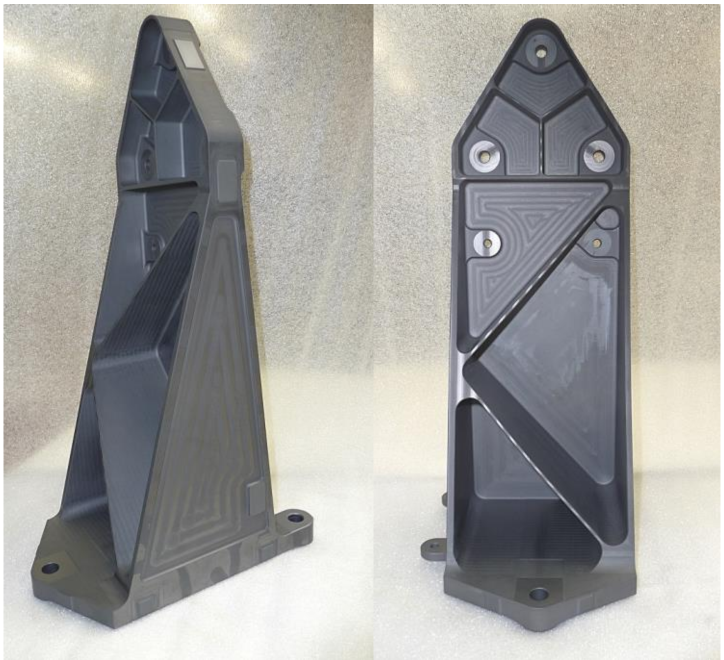

Figure 19. FoM3 support

6. CONCLUSION

Following Herschel and GAIA, Euclid is a cornerstone mission of ESA which fully takes profit of the BOOSTEC SiC® technology. Among a lot of SiC parts, it includes a Ø 1.25 m CVD coated primary mirror and two very large and lightweight brazed structure elements: a 2.50 m x 2.15 m baseplate and a Ø 1.50 m spider which have been successfully manufactured and tested. The Euclid telescope is the largest full-SiC Korsch instrument ever made in the world. This project confirms BOOSTEC SiC® technology as the only one available for manufacturing full-SiC space telescopes with entrance pupil larger than Ø 1 m.

REFERENCES

[1] Bougoin, M., Castel, D., Levallois, F., "CTE homogeneity, isotropy and reproducibility in large parts made of sintered SiC", Proceedings Volume 10564, International Conference on Space Optics — ICSO 2012; 10562410 (2017)

[2] Honnen, K., Kommer, A, Messerschmidt, B., Wiehe, T., "NIRSpec OA development process of SiC components", Advanced Optical and Mechanical Technologies in Telescopes and Instrumentation. Edited by Atad-Ettedgui, Eli; Lemke, Dietrich. *Proceedings of the SPIE,* Volume 7018, 2008.

[3] Bougoin, M., Lavenac, J., « From Herschel to GAIA, 3m-class SiC space optics », Optical Manufacturing and Testing IX, *Proceedings of the SPIE*, Volume 8126, 8160V-1, 2016

[4] Bougoin, M., "SiC challenging parts for GAIA", Proceedings Volume 10565, International Conference on Space Optics — ICSO 2010; 105652C (2017)

[5] Breysse, J., Castel, D., Bougoin, M., "All-SiC telescope technology at EADS-Astrium – Big step forward for space optical payloads ", *Proceedings of ICSO 2012 (International Conference on Space Optics)*, Ajaccio, France, Oct. 9-12, 2012

[6] Racca, G.D., Laureijs, R., Stagnaro, L., Salvignol, J.-C., Alvarez, Criado, G. S., *et al.*, "The Euclid mission design", Proc. SPIE 9904, Space Telescopes and Instrumentation 2016: Optical, Infrared, and Millimeter Wave, 99040O (19 July 2016)

[7] Bougoin, M., Lavenac, J., Pamplona, T., Martin, L., Gimenez, J.-L., Castel, D., Maciaszek, T., « The SiC structure of the Euclid NISP instrument », Proceedings Volume 10562, International Conference on Space Optics — ICSO 2016; 105624J (2017)

[8] Pamplona, T., Gimenez, J.-L., Febvre, A., Ceria, W., Martin, L., Prieto, E., Maciaszek, T., Foulon, B. Ducret, F., Bougoin, M., Castel, D., « Silicon carbide main structure for Euclid NISP instrument in final development », *Proceedings of the SPIE*, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation II, Volume 9912, 2016