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SIC MIRRORS POLISHING

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I. INTRODUCTION

Silicon Carbide is a material of high interest in the design and manufacturing of space telescopes, thanks to its mechanical and thermal properties. Since many years, Reosc has gathered a large experience in the polishing, testing, integration and coating of large size Silicon Carbide mirrors as well as in the integration of full SiC TMAs.

Reosc has manufactured the 3 TMAs of the NIRSpec instrument that will take place on board JWST. Reosc has also polished 2 sets of mirrors for the Japanese HISUI instruments. In addition Reosc has also polished the 1.5m primary mirrors of the GAIA instrument and many mirrors for Airbus Space Instruments [7].

However, the polishing processes require some improvements since the space applications are always more demanding. The next applications will require larger mirrors with lower areal density to allow increasing the collecting surface while limiting the overall mass. The SiC material has can be used in the design of the next instruments and provides some very attractive performances, specifically for cryo applications and light weighted optical mirrors. The goal of the design is a mirror with a diameter in the range 1m to 1.5m with some projects up to 3m, that can withstand the mechanical and thermal environment (mainly the launch environment) and whose weight is as low as possible. The state of the art NIRSpec mirrors had an areal density around 30-40 kg/m². The target for the next projects is 20kg/m² and below.

Yet the manufacturing capabilities need to be improved to achieve these design goals. Two major difficulties are driving the polishing of SiC mirrors:

- The polishing processes must be compatible with the mirror stiffness to minimize the print through
- The mirror must be coated with a polishing layer to allow providing a low micro-roughness

Reosc is currently performing some developments of the polishing process to meet these two requirements.

II. REOSC STATE OF THE ART IN SiC MIRRORS

Since the 1990s, Reosc has worked on the polishing, coating and integration of SiC mirrors for space applications. The polishing process has been improved year after year to be able to provide today's optical instruments with very high performance mirrors.

The size of the mirror produced during the last decade ranges from about 10mm to 1.5m. The optical surface can be flat, spherical or aspherical. The majority of the mirrors are off-axis. The surface figure requirement is about 10 nm RMS or slightly higher for complex aspheres.

The surface microroughness requirement is <1 nm RMS for visible applications in order to limit the stray light. Unfortunately, the SiC material has the drawback of a residual micro porosity. This yields for all known material used for producing SiC mirror blanks.

According to Reosc development, the polishing of the bare SiC material leads to a final surface micro-roughness of about 3nm RMS for the SiC from Boostec/Mersen and to about 10 nm RMS (the literature reports <5 nm [5]) for the HB-Cesic from ECM. The lowest figure of 1.5 nm RMS has been obtained for NTSIC mirror substrates. In all the cases, the structure of the surface is covered by some micro-holes (porosity) that are intrinsic to the manufacturing process of the SiC blank : sintering or infiltration [4], [5], [6].

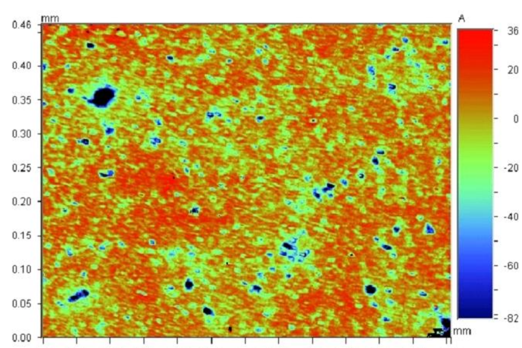

Figure 1 : Example of micro-roughness for NTSIC substrate - 1.5-nm RMS, field 500µm

This is the reason why the standard production of SiC mirrors involves the coating of the mirror with a denser material prior to the polishing. The most common technique is the deposition of a SiC CVD layer. The polishing of this layer allows reaching surface micro-roughness between 0.5-1nm RMS. This process has been used for the achievement of the main projects achieved at Reosc within these last years.

Reosc has polished, coated and aligned the mirrors of the 3 TMAs and the plane mirrors of the NIRSpec instrument working at 20K. It is one of the ESA provided instruments on board JWST. It has been delivered by Astrium last year to NASA for final integration.

The 3 TMAs are made of 3 aspherical off-axis mirrors, concave and convex, in the aperture range of 100mm x 100mm to 300mm x 300mm. The Figure 2 and Figure 3 below show the fully assembled fore optics (FOR), the collimator optics (COL) and the camera optics (CAM). More details about this project have been given in ref [1] and [2].

Figure 2 : NIRSpec FOR TMA

Figure 3 : NIRSpec COL and CAM TMA

Our masterpiece in the domain is the giant pair of off-axis entrance mirror of the European Space Agency (ESA) GAIA astrometric instrument . These world-record off-axis pieces measure 1540 x 490 mm made from Silicon carbide were successfully produced to the huge performance of 9-nm RMS residual surface figure error.

Figure 4 : One of GAIA primary mirror

For the Japanese space project HISUI, most of the mirrors are made from glass ceramic material Zerodur from Schott, widely used for such type of applications. Reosc pioneered the art of lightweighting mirror substrates made from Zerodur by diamond milling and developed high skill in designing optimum rib patterns for such structures.

But the HISUI project has also been the opportunity to qualify the space use of the **N**ew **T**echnology **SI**licon **C**arbide material (NTSIC). This is a high strength reaction sintered SiC material developed by combining key technologies and expertise of several Japanese manufacturers [3], [4]. M1 and M3 mirrors of the MSS TMA are made from NTSIC material. These mirrors are off-axis aspherics up to 500 mm in length.

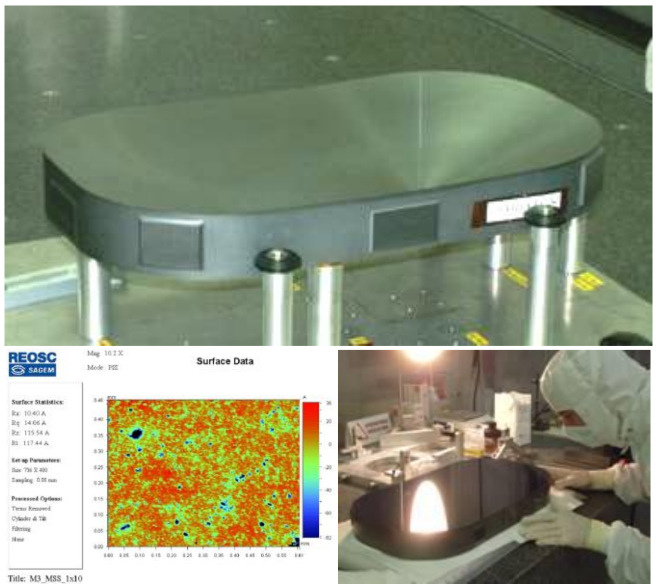

Figure 5 : NTSIC substrate - 1.5-nm microroughness measurement – The polished M3 MSS mirror

Besides these outstanding achievements, Reosc has also produced SiC mirrors for many other space applications.

III. DEVELOPMENT FOR ULTRA-LIGHTWEIGHTED MIRRORS

The design of ultralightweighted mirrors is achieved by reducing the number and thickness of all the ribs of the mirror and also reducing the thickness of the front facesheet (optical surface).

The drawback of this lightweighting for the polishing process is that the stiffness of the mirror is reduced. Therefore, during the polishing 2 problems occur:

- During the polishing, the polishing tool will react differently when above a rib or above a pocket.
- The second issue is that the gravity deformation will cause the mirror to distort during testing.

Those two issues are to be taken into account when elaborating the polishing and testing process.

Reosc is currently polishing a prototype of diameter 560mm diameter of ultralightweighted mirror made of Boostec SiC coated with Boostec/Mersen CVD. This prototype is to be representative of a 2m diameter mirror, with an areal density below 20kg/m². This prototype has to be representative especially in terms of polishing quilting. The design of this prototype is similar to a subcell of the future mirror.

The main goal of this project is to reach the final surface error requirement taking into account that during the polishing the surface above the mirror's pocket will create some "bump" artefacts since the mirror is less stiff at these locations. Some specific tools and process have been designed to reduce this effect or to reduce it to acceptable values, with the goal of applying these procedures for polishing a 2m diameter mirror.

The mirror blank for the prototype has been received by Reosc. The polishing is currently on-going.

IV. DEVELOPMENT FOR NEW POLISHING LAYER

A. Context

As discussed above, a specificity of the SiC material is that it is difficult to reach a low micro-roughness (<1 nm RMS) without coating the mirror with a polishing layer. The state of the art for the polishing layer is a CVD

SiC coating. This material has the advantage to be very dense. It allows achieving a very good surface micro-roughness. Its CTE (coefficient of thermal expansion) is also very close to the CTE of the mirror blank. Therefore, when going to cryogenic temperature, the bending of the mirror caused by the bimetallic effect of the CVD layer wrt the blank material is rather low.

However, the coating of SiC mirrors with CVD layer shows some major technical drawbacks, beside the cost and delay due to this operation.

First, the coating of a mirror blank with a CVD layer is not reversible. In case of failure of the coating or in case of failure during the polishing, the mirror blank is lost because the CVD layer cannot be removed (especially from the backside of the mirror).

The second major drawback is that the process of CVD coating requires facilities that are currently limited to about 1 m diameter and some hardness and thickness inhomogeneity appear for upper dimensions. The process of coating with CVD involves some high temperature and some highly reactive gas. The process is very sensitive and is deemed very difficult to scale to larger size for several reasons: cost, technical difficulties, environmental and operational risks.

In the perspective of the next missions requiring large optical mirrors (up to 3.5m diameter) like for the SPICA mission, Reosc is running together with the European Space Agency (ESA) a development program to investigate some alternative polishing layer.

The goal of this technology research activity is to determine a coating and polishing process allowing the manufacturing of a large size mirror for cryogenic space application that would be scalable to large size mirrors.

The activities planned for this development consist in 3 steps: first a trade-off for the selection of the new polishing layer material, then a development plan on flat samples aiming at developing the coating and polishing processes and finally demonstrate the performance of the process by realizing a prototype mirror of diameter 300mm.

B. Material selection

In a trade-off the candidate polishing layer materials and deposition processes (applicable to mirror diameter up to 3.5m with existing facilities or reasonably possible to develop) had been selected. The CTE of the materials were to be as close as possible to the SiC blank to minimize the bimetallic bending for cryo applications. The material should be removable, allow a smooth polishing (i.e. micro-roughness <1nm RMS) and minimize the technological risks.

Based on its experience of the coating materials and based on the literature, Reosc has investigated exhaustively the candidates for the polishing layer by analyzing the materials known to be possible to polish and possible for the coating of a mirror blank.

The possible metallic materials have been discarded because of the too large discrepancy with the CTE of the mirror blank. Several oxide materials have been discarded because of their too low level of maturity of the coating and polishing.

The 2 interesting remaining candidates that were short listed were Silicon and Fused Silica. Both were deemed suitable for deposition and polishing. The various techniques for the deposition of these material have been taken into account (sputtering, plasma, PECVD, …). However, an additional requirement defined by Reosc was that the thickness of the polishing layer should be sufficient to allow absorbing the flaws of the mirror blank (typically micro-holes).

Therefore, fused silica was preferred to Silicon because the scaling of the coating facility was deemed more reasonable, though Silicon was showing a better compatibility of CTE.

C. Development on flat samples

The principle of the polishing process is rather straightforward. It is made of 3 steps:

- Polishing of the mirror blank (bare SiC)
- Coating
- Polishing of the polishing layer

The difficulty lies in the tuning of the requirements to reach at each step of the process, especially for the polishing of the mirror blank. Two extreme approaches are possible:

- Polish the mirror blank as close as possible to the final specification so that the polishing of the polishing layer is limited to a slight figure error correction and surface micro-roughness smoothing
- Polish the mirror blank with very little effort and achieve all the performance during the polishing of the polishing layer

The difficulty of the first approach is that it is not possible to reach both the surface error and the micro-roughness requirement on the bare substrate. The tools usually used for the figuring trend to degrade the micro-roughness. The risk of the second approach is to remove all the polishing layer during the polishing.

The optimized process is between the two extreme approaches: the polishing of the mirror blank has to be performed with the lowest possible effort while being sure that the requirement will be met when completing the polishing of the polishing layer.

The polishing process has been developed during the manufacturing of about 20 flat samples of diameter 120mm. Two diffrent SiC material were used: Boostec/Mersen SiC and ECM HB-Cesic.

The performance of the polishing process of the raw material is not the same for both substrates. The micro roughness reached for Boostec SiC is about 3nm RMS while it remains above 10 nm RMS for ECM HB-Cesic. The difference in the result is due to the difference in the manufacturing process of the 2 materials. The Boostec/Mersen SiC is obtained by the sintering of a SiC powder mix while the ECM HB-Cesic is obtained by infiltrating Silicon on a carbon matrix. In the ECM HB-Cesic substrate, a bi-morphous structure can be evidenced. The difficulty for the polishing of this material comes from the fact that the 2 main compounds do not show the same hardness (SiC is harder than residual Si). This is why the micro-roughness is more difficult to reduce. Some typical results are presented on the following figure.

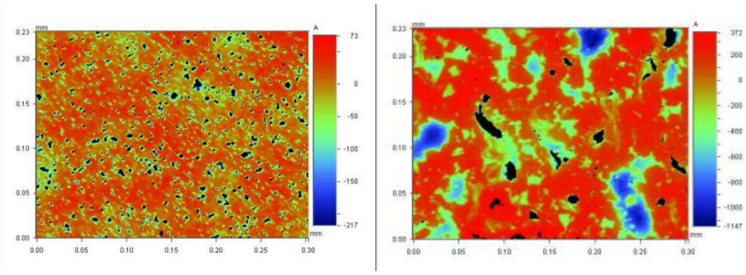

Figure 6 :Boostec SiC polishing (3 nm RMS) / ECM HB-Cesic polishing (30 nm RMS)

Yet, Reosc did not to try to improve the micro-roughness of the polishing of the ECM HB-Cesic bulk mirror because the process of the fused silica polishing layer coating is compatible with this surface micro-roughness. The final surface micro-roughness of < 1nm RMS can be achieved during the polishing of the polishing layer.

The coating process of Fused Silica is rather standard. The difficulty is to reach a sufficient thickness and a dense enough layer. The thickness homogeneity over the mirror diameter needs to be controlled and can be monitored accurately.

The polishing characteristics of the deposited Fused Silica layer are similar to the polishing of raw Fused Silica blanks. The process of polishing this polishing layer is based on Reosc experience of polishing glass material. Robot polishing, smoothing processes, Ion Beam Figuring, Magnetical Rheological Finishing can be used for the polishing of the polishing layer.

D. Results of the polishing of the flat samples

The samples have been submitted to environmental tests (thermal cycling, thermal vacuum and humidity). No evolution of the surface error has been recorded. It shows that the stress in the polishing layer is very stable. There is no ageing or relaxation of the polishing layer to anticipate.

Two removal of the coating procedures have been developed: a mechanical grinding of the coating layer is possible without changing the surface of the mirror blank. This is possible thanks to the difference in hardness between the polishing layer and the SiC mirror blank; a chemical procedure has also been developed. It is compatible of both SiC substrate. The mirror blank can be recovered without any damage in case of failure of the coating process or polishing process.

The micro-roughness obtained after the polishing of the polishing layer is independent of the substrate material (Boostec SiC or ECM HB-Cesic). The micro-roughness obtained is about 0.5nm RMS.

The surface error obtained on the samples is below 15nm RMS (in line with the requirement). The best result obtained on one sample is 3 nm RMS. This very good result is in line with the performance of the ion beam figuring process.

E. Mid-size mirror

In the next step of this project, Reosc has performed the design of a mid-size mirror of diameter 300mm (clear aperture). The design of this mirror has been made to reach an areal density below 20kg/m².

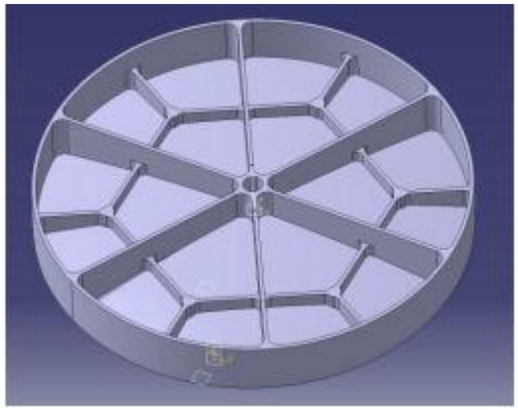

Figure 7 :Design of the mid-size mirror

The design of this mirror has been made to allow a deformation < 7 nm RMS WFE at cryo including the quilting effect of the polishing layer. This design will be used for the manufacturing of a Boostec SiC mirror and for an ECM HB-Cesic mirror in the next phase of this project.

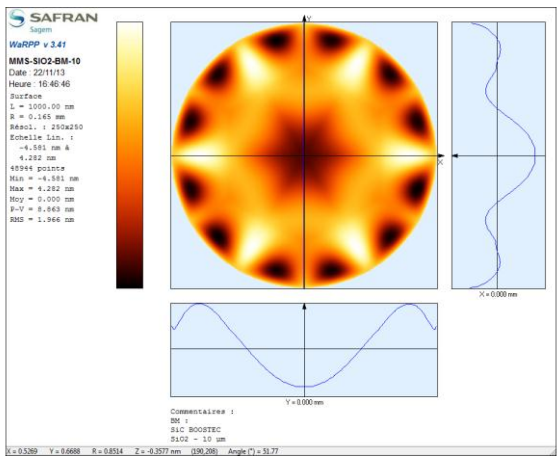

Figure 8 : Distortion at cryo : 2 nm RMS surface error (focus removed) (FE computation)

The manufacturing of the mirrors is on-going.

IV. CONCLUSION

Reosc has built through the years a strong experience and capabilities in the domain of polishing SiC mirrors of all shape and size up to 1.5 m.

Reosc is still improving its capabilities in order to allow the realization of always more demanding projects. Two improvement axis are being developed:

- Polishing of ultra lightweighted mirrors with areal density < 20 kg/m²
- Development of alternate polishing layer

These developments are on-going and showing some promising results.

V. ACKNOWLEDGMENT

We take this opportunity to thank all Reosc technical staff and our customers for the confidence they place in our hands. Especially CNES and ESA for the current development activities.

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