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CESIC® - OPTOMECHANICAL TECHNOLOGY LAST DEVELOPMENT RESULTS AND NEW HBCESICã HIGHLY LIGHTWEIGHTED SPACE MIRROR DEVELOPMENT INCLUDING CORRECTIVE FUNCTION

7TH INTERNATIONAL CONFERENCE ON SPACE OPTICS', OCTOBER 2008

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ABSTRACT

Thales-Alenia-Space and ECM has developed a new SiC ceramic composite to produce very lightweight space mirrors and structure. Cesic© made by ECM has been selected for its own intrinsic properties (high specific Young modulus, high conductivity , low CTE, high strength for a ceramics) and its large manufacturing capabilities. Recently a full monolithic space instrument for earth observation, with a monolithic Cesic© structure and with Cesic© mirrors has been designed, manufactured and space qualified and is now ready for launch. The Cesic© telescope assembly has been tested under shock environment, vibration loads, and full qualification thermal environment. All these qualification tests were done directly on the flight model.

Extensive development has been also performed to design, size, manufacture and test a very light weight reflector shell made as a single part. This 1 meter reflective shell has an areal density of less than 10 Kg/m^2 has been manufactured with its surface grounded to the bi parabolic shape. Such challenging areal density has requested a very thin skin associated with a ribs thickness of less than 2mm. In order to demonstrate the high stability and strength of Cesic© the reflector has been tested successfully under very aggressive environment up to 350°C and also an acoustic test with flight representative levels was successfully performed. To produce future very lightweight space mirrors ECM develop with the support of Thales-Alenia-Space since some years an improved version of Cesic© ceramic, called HB-Cesic© . HB-Cesic© made by ECM is developed for its higher intrinsic properties, Young modulus, strength and especially its direct polishing capabilities down to 3 nm micro-roughness. One of the major targets for this development was also to overcome size limitations of the C/C raw material of currently around 1x1 m to produce mirror up to 3,5 m diameter out of a single C/C raw material block. .
Under ESA study a 600 mm mirror with a surface density of only 18 Kg/m^2 has been designed, sized and manufactured and is currently under polishing at SESO. The polishing to a micro-roughness of far less than 20 nm RMS without expensive overcoatings has been already validated on mirrors up to 800 mm. This 600 mm mirror will be polished to a WFE of less than 20 nm, and afterwards the mirror will be tested under cryogenic environment to measure the WFE evolution between ambient and cryo. The mirror is equipped with a system for focus and astigmatism modification. During the cryo test this system will be activated at cryo temperature to also demonstrate the function of this system. This correction system is developed for future large mirrors for interferometric nulling or aperture synthesis missions like the Darwin mission .
For such missions very large and very lightweight mirrors up to 3,5 m diameter with an areal density of less than 25 Kg/m^2 are required and thank to the HB-Cesic© technology such performance is now feasible.

1. CesicÒ interesting Key properties

Cesic® is a ceramic composite material composed out of SiC, Si and C. This material is obtained from the transformation of Carbon/Carbon raw material into a SiC composite, using a liquid phase infiltration at high temperature of the C/C greenbody with silicon (Figure 1) .

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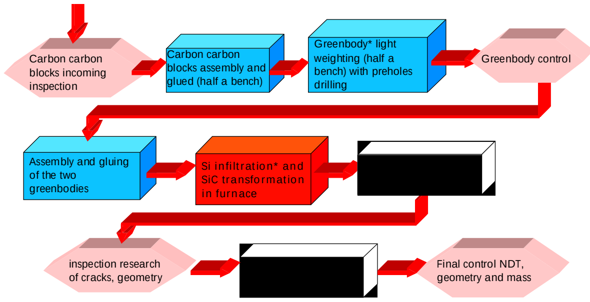

Figure 1 Cesic manufacturing flow chart

Cesic® is now a mature technology offering high structural capacity thank to its high mechanical performances associated to very high manufacturing capabilities :

- Reliable Isotropic material: all properties are independent of surface status, raw initial C/C blocks & infiltration runs, independent of direction,
- Very high ratio E x Inertia/M well above other advanced materials, E=255 GPa, d=2,65 g/cm^3 giving an high specific bending stiffness : E/ρ^3 >13,7 ,
- High mechanical strength, σ > 130 MPa: insensitivity to fatigue, no impact of internal C/C junction, insensitivity to surface status, Strength in bi-axial bending : 160 MPa : No impact of biaxial stress, compatible of screwed link under large loads,
- High fracture toughness for ceramic : K_1c>4,6,
- High thermal conductivity : 160 W/mK at 300K & 35 W/mK at 40 K ,
- Isotropic & Quasi null CTE on a large cryo temperature range from 20 K to 100 K, CTE<0,003 10-6 m/m°.

2. CesicÒ High manufacturing capabilities

The use of C/C greenbody manufacturing is one of the key technologies of the Cesic® process. Due to this manufacturing step ECM has a lot of positive features to create very complex stiff and lightweight structures. Through the use of a large CNC controlled milling machines directly linked to CAD systems, ECM is able after the joining of C/C blocks, to manufacture large lightweighted panels for flight structures up to 2.5 x 1.8 m.

The C/C material is not fragile, panel lightweighting using CNC controlled machines is easy and fast with no risk of greenbody failure. Large ribs even with less than 1,5 mm thickness are easily shaped, and the machining time for a full reinforced panel is less than 10 days for 1 m^2 (Figure 2).

Figure 2 view of a 1 meter milled panel

Due to the specific joining technology, it is possible to manufacture very easily and fast C/C parts with conventional tools and join them prior to the silicon infiltration process. Such process allows to obtain in one part a very stiff monolithic structure with great geometrical inertia like structure in "I" shape. Through the infiltration process this joined structure will become afterwards a monolithic piece without discontinuities and differences of thermal and mechanical properties.

The current existing ECM XL furnace allows the infiltration of part up to a diameter of 2,4 m.
According to the properties of Cesic® it is possible to use different methods for final machining for the I/F preparation or other functional areas:

Ø Grinding with diamond tools
Ø Electron Discharge Machining (EDM) and wire erosion machining.

Due to the possibility using EDM machining and wire erosion we have a final machining method with no risk even for very thin structures of 1 mm to realize precise surface qualities and location tolerances.

We can therefore summarize the manufacturing properties of Cesic® process as :

Ø Capacity to built large structure in one piece with semi closed back design offering a high bending stiffness, as greenbody junction offers same strength and others properties guarantying the homogeneity of the structure
Ø Machining by EDM (electro discharge machining) offering precise I/F at no risk,
Ø Schedule and cost attractive with an easy near net shape greenbody manufacturing.

A large number of part has been already designed and built by the TAS/ECM team in the frame of internal or ESA funded development activities. In the following we will show some examples (Figure 3):

- Ø 1 meter cryogenic optical bench tested down to 30 K and under 80 g QSL,
- Ø Large focal plane(700mm)
- Ø 1 meter mirror of only 16Kg
- Ø 3D ultra stable structure (800mmx400mm)

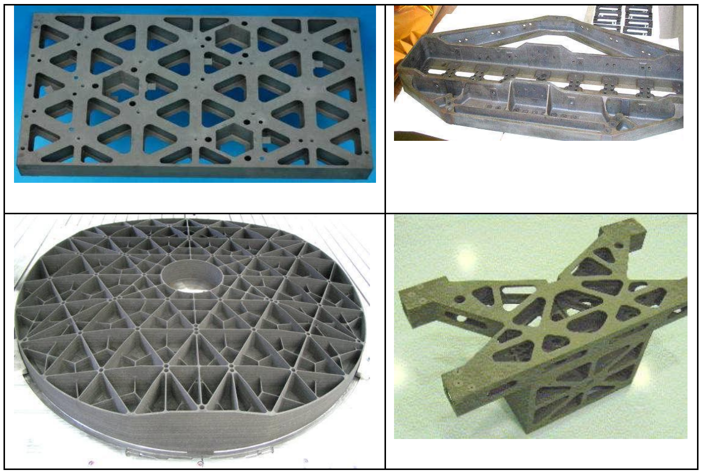

Figure 3 Examples of Cesic® realisations

3. Cesicâ first flight applications

All the development activities have now concluded to the high maturity status of Cesic® technology for the application of space instruments for structure parts as for mirrors or focal planes.
Therefore the Cesic® technology has been selected for the realisation of a small full integrated space flight instrument, structure and mirrors being made out of this material .
Thank to the high integration capabilities of Cesic®, the structure is made in one single piece and the M1 & M2 mirrors also, therefore a full telescope has been manufactured and assembled only out of 3 main parts (Figure 4).

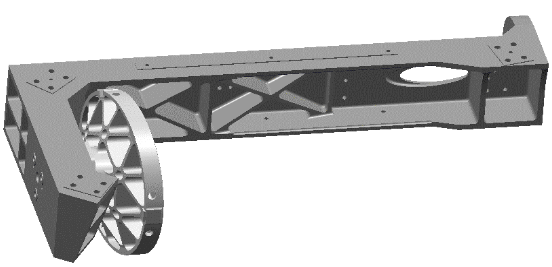

Figure 4 monolithic Cesic® telescope

The monolithic structure hold all the elements (mirrors, detection units and dioptres) and have therefore numerous I/F, which are fine machined thanks to EDM (Figure 5). In order to be stiff enough and notably in torsion , the central part of the structure has a closed box design . This has been made possible only thank to the greenbody assembly capabilities before infiltration.
The flight mirrors are manufactured as off axis aspherical mirrors using EDM machining the mirror surface shape in reference to the mounting I/F. This process saved a lot of cost due to the much easier machining in comparison to traditional grinding of the mirror surface with a high level of metrology for off-axis aspherical mirrors. Directly after machining all mirrors have been coated by CVD-SiC and were afterwards polished (Figure 6).
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Figure 5 view of the 2 flight structures

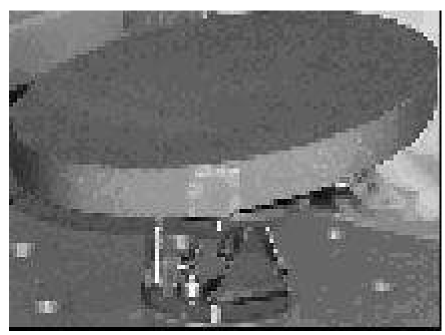

Figure 6 flight mirror before polishing

The flight mirrors and structures have been manufactured and qualified with success : (2 flight structures were performed by ECM directly in one shot without development model and non conformities).
The mirrors has been polished down to less than 20 nm WFE RMS by Sagem and has been space qualified afterwards by TAS under vibration & choc.
The mirrors has been tested up to 40G QSL on a shaker for a satellite qualification level of 30G QSL.
The structures has been qualified with mirror dummies mass under vibration and under shock tests:

The qualification in vibrations sinus & random lead to in sinus a QSL at structure of 21G at I/F with locally a G_{max} of 23G on the structure. In random, the structure has seen a QSL of 20g RMS (3σ) at I/F with locally a G_{max} of 34G RMS (3σ) (Figure 7).

The measured 1st mode of the structure was 200 Hz in comparison to 202 Hz which was predicted by the FEM calculations.

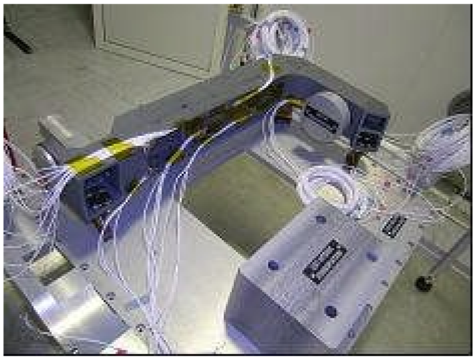

Figure 7 FM Cesic structure equipped for vibration tests with mass dummies

The assembled instrument has been also qualified under high shock level by a representative test done at STM satellite level using a “pyrotechnic Dassault kit” (Figure 8).

The following shock level were reached:

- Ø SRS max at I/F structure: 700g
- Ø SRS max at I/F mirror: 400g.

Figure 8 FM flight telescope under shock tests

After integration and fine optical alignment at first all Cesic© parts has been space qualified and afterwards an intensive qualification test sequence at payload and SL level was performed and all was accepted by the customers (AST/CNES/DGA).

The two first Cesic© payloads are now integrated on the SL and are now ready to be launched.

4. Cesicâ applications for high temperature antenna

Thanks to its high stiffness, low mean CTE and high manufacturing capabilities, the Cesic© technology has been also proposed for the realisation of a very lightweight accurate and a very stable High Gain Antenna made in Cesic® (Figure 9) working under very challenging environment (-180°+350°C) .

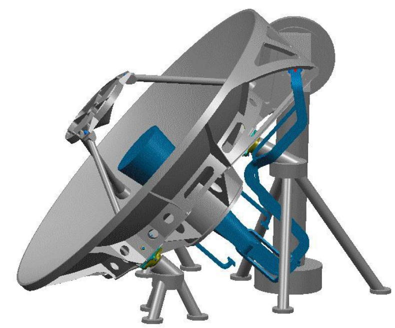

Figure 9 Bepi Colombo - Cesic® HTHGAntenna

The main part is a Cesic® monolithic main reflector with 1 m diameter and a skin and ribs of less than 2 mm in thickness. Such antenna is able to sustain a temperature change from –180°C up to 350°C with thermal gradient up to 250°C on the surface, while maintaining a very accurate shape of less than 100 µm RMS SFE. In order to demonstrate these performances, TAS/ECM, under ESA/KDA TDA contract, have designed and manufactured a fully flight representative 1 m main reflector integrating numerous support I/F functions (Figure 10).

Figure 10 1 meter main reflector

The mass of the reflector was less than 10 Kg. After manufacturing the antenna main reflector has been submitted successfully to qualification acoustic loads and to thermoelastical test sequences up to 350°C where its shape stability has been demonstrated.

The front face has been also ground to meet the RF shape requirement. The antenna had a high aspheric conicity however the grinding convergence tests have demonstrated the feasibility to reach the SFE requirement (Figure 11).

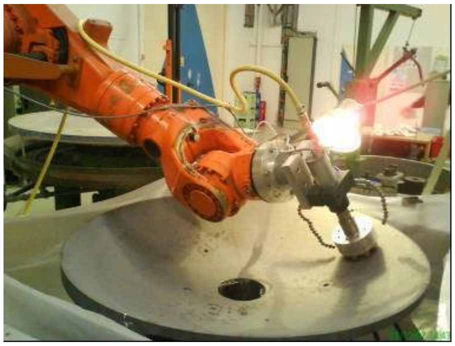

Figure 11 Antenna reflector during grinding operation

5. Development of HB-Cesicâ and HB-Cesicâ properties

HB-Cesic® is an improved version of standard Cesic®, Type MF as it is made using a new generation of C/C greenbody specially developed having a higher Young Modulus and strength with a more homogenous microstructure.

We call the new, Si-infiltrated composite “HB-Cesic® to distinguish it from the classic Cesic® material type MF.

The letters "HB" in HB-Cesic® stand for "hybrid" to indicate that the C/C raw material is composed of a mixture of different types of chopped carbon-fibers.

The C/C raw material for HB-Cesic® was developed by ECM and MELCO,Jp during the past three years in order to improve the homogeneity and thermo-mechanical characteristics of the final, Si-infiltrated product, especially for cryogenic mirror applications, compared to ECM's Cesic® material (type MF). The following figure shows the manufacturing process of the new C/C raw material (Figure 12) :

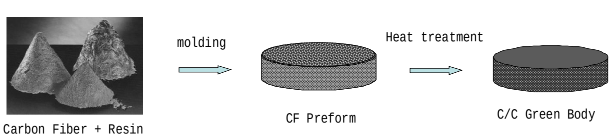

Figure 12 greenbody manufacturing sequence

The starting material in the manufacturing of HB-Cesic® is a short, chopped, randomly oriented carbon fiber material, consisting of both pitch-based and other fibers. The fibers are mixed with a phenolic resin and molded into a blank, which then is heat-treated under vacuum. The result is a light-weight, porous, relatively brittle C/C greenbody. At the present time circular blanks are available in sizes up to 1.6 m, with a thickness up to 200 mm. In the near future greenbody blanks up to 2 m in size or even larger will become available as circular or square blocks.

The manufacturing of blocks up to 4 meter diameter will be not an issue, because the already by MELCO manufactured blocks with 1,6 meter diameter have shown a perfect homogeneous and isotropic carbon distribution.

The microscopic isotropicity has been demonstrated thank to microscope pictures showing no difference between Z direction to X & Y direction.

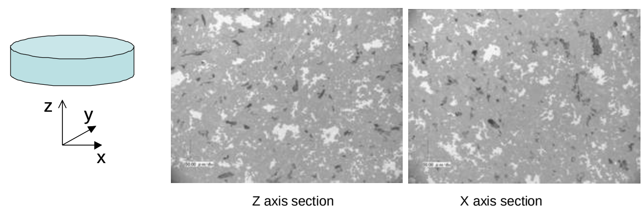

Figure 13 homogeneous and isotropic microstructure

Such C/C blocks will be lightweighted and infiltrated according to the same and already qualified processes for standard Cesic®.

Its high specific stiffness allows to manufacture very thin shell, having very low shape deflection under gravity, and those without counter back structure. Such a property leads to a great advantage for high lightweighting manufacturing capabilities of large mirror shell and to simplify strongly manufacturing tools for the infiltration process .

MELCO plans to manufacture in near future blocks up to 2 m diameter and afterwards for more demanding missions (Darwin, SPICA) it is possible to manufacture blocks with a diameter larger than 3,6 m.

For the most important step, the carbonisation step, 4 meters useful diameter carbonisation furnace are already existing in Europe and carbonisation could be done in Europe, like today ECM carbonise small greenbody blocks for MELCO .

One other solution is to use at ECM a future new dual 4 m furnace able to carbonise the block and then after lightweighting to perform the infiltration.

HB-Cesic® mechanical properties has been fully characterised and tests results demonstrate that it possesses superior mechanical and thermal performance characteristics compared to classic Cesic® and shows very high mechanical properties:

- Ø Young modulus: 350GPa
- Ø Strength: > 200 MPa
- Ø Density: <3 g/cm^3.

One of the additional advantages of HB-Cesic® is also the quasi zero CTE between 100K and 4K.

6. HB-Cesicâ cryo mirrors development for future projects

One of the big advantages of HB-Cesic® is it capability to be directly polished without expensive overcoatings to a microroughness of < 5 nm , which is suitable at least for NIR applications. After optimisation of the polishing process, representative HB-Cesic® samples with a diameter of 100 mm has been polished by SESO down to less than 3-4 nm (Figure 14).

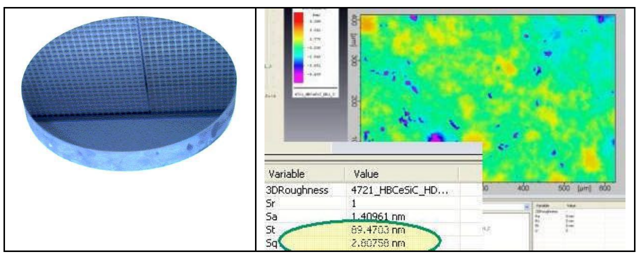

Figure 14 high polishing capability Ra<4 nm

An others advantage of HB-Cesic® is the cabability to manufacture already in greenbody very thin ribs of just 1 to 1,2 mm leading the possibility to obtain very lightweight mirror designs without very expensive grinding operations in the ceramic status.

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Using HB-Cesic®technology a mirror with a diameter of 3,5 m has been already designed and optimised by deep FEM analyses.

This mirror design has been optimised to meet high WFE performances, to be fully compatible with launch and cryogenic operational environment and its nominal mass is only 200 kg, which corresponds to an areal density of only 20,7 Kg/m^2 with an 1st mode higher than 95 Hz.

The design has been also optimized to limit the gravity deformation to allow unambiguous and precise optical measurement on ground (140 nm SFE with horizontal axis without gravity compensation and 140 nm SFE with vertical axis using limited number of gravity compensators.

The skin thickness and secondary ribs has been also sized to allow a polishing without quilting effects, so such a mirror could be polished down to 20 nm RMS.

Such mirror could be produced using a monolithic HB-Cesic® blank in order to guarantee the full CTE homogeneity and therefore its low deformation during cool down to 4 K.

Thanks to Thales experience in high performance cryogenic mirror, a mirror I/F fixation has designed and optimized to minimize strongly the impact of CTE difference between HB-Cesic®, Invar and glue on mirror WFE during cooling down.

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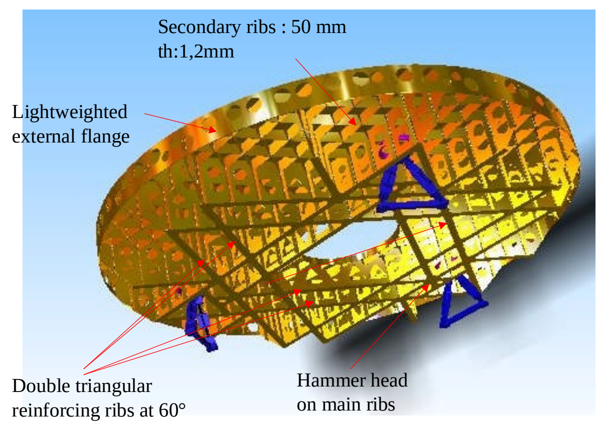

Figure 15 3,5 m mirror design for less than 200 kg

In the frame of Darwin TDA, Thales get an ESA contract to study a 3,5 m mirror integrated with a focus and astigmatism compensation device and to validate it on a 600 mm mirror breadboard to be tested under cryogenic condition.

Emma configuration is constituted of three 3,5 m receiver mirrors which focus the star light on a central hub (Figure 16). Receivers are located on a virtual parabola and when the base diameter is changed the mirrors shall have their shape (focus and astigmatism) adapted .

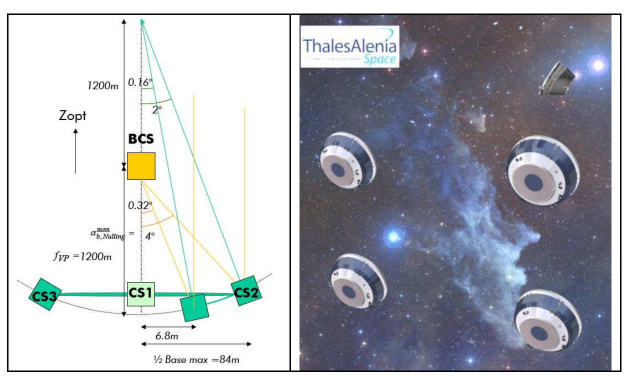

Figure 16 Darwin : Emma mirrors configuration

Therefore especially for the imagery mode an astigmatism PtV term up to 10 µm and independently a defocus PtV term up to 5 µm have to be introduced in the receiver mirrors.

The already designed HB-Cesic® mirror with a diameter of 3,5 m has a reactive truss structure (mounted on the backside) allowing by changing the beam length through a temperature change to create independently a pure astigmatism or focus (Figure 17) .

Designs of both mirror and Astigmatism Control Device have been optimised through coupled NASTRAN / optical ASAP iterations (Figure 18).

The 3,5 m mirror has a 200 mm thickness, with homogenous quasi isotropic semi close back design , skin thickness is 2,5 to 3 mm and ribs thickness 1,5 mm with lightweight internal holes. An independent mirror curvature correction is done along X and Y by two beams, the affine addition allowing to control astigmatism and focus. Pure tangential torque on mirror induce pure radius curvature variation in one direction.

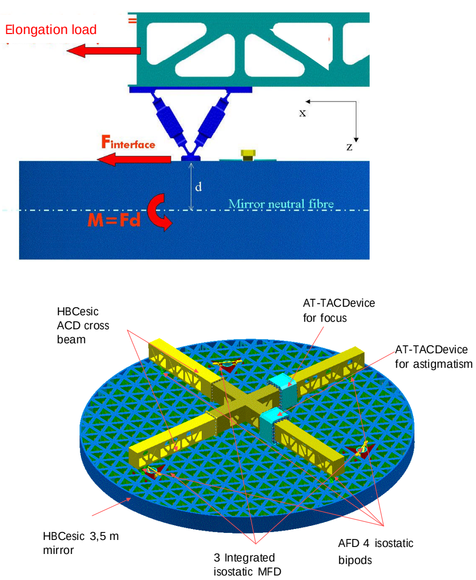

Figure 17 mirror with active control of focus and astigmatism

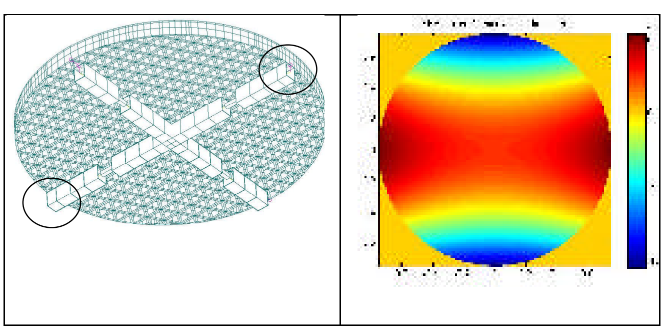

Figure 18 optical performance validation by FEM

In order to validate in one hand the high optical quality performance of a very lightweight HB-Cesic® mirror and the other hand the possibility to modify the astigmatism by simple reaction beam a 600 mm mirror breadboard has been designed and sized by TAS and already successfully manufactured by ECM (Figure 19).

The facesheet thickness is only 3 mm with ribs of 1,2 mm. The interfaces have been specially designed to avoid cryogenic distortion on the front face due to difference of CTE between HB-Cesic®, glue and Invar.

Figure 19 600 mm HB-Cesic® mirror of 5 kg

The mass of this 600 mm mirror is only 5 kg leading to an areal density of less than 17,5 Kg/m^2. The mirror is currently under polishing at SESO and will be tested at TAS under cryogenic condition with WFE measurement before the end of this year. During the last cryo test the mirror will be equipped with the back reactive beam also made out of HB-Cesic® and its astigmatism shape will be modified (Figure 20).

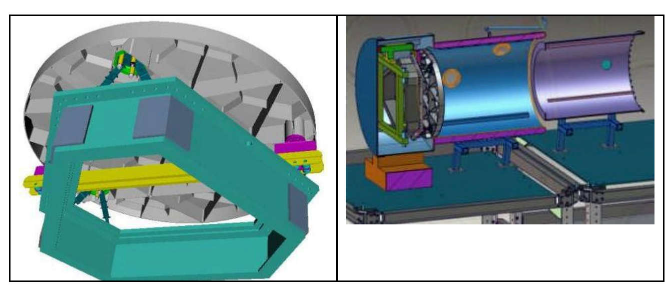

Figure 20 HB-Cesic® mirror on test jig for cryo test

Conclusion

Thank to large development effort performed conjointly by Thales-Alenia-Space and ECM and supported by ESA, Cesic® and now also HB-Cesic® are mature technology offering :

- Ø Large structural capacity thanks to its high mechanical properties associated to its large manufacturing capacity : very high EI/M ratio,
- Ø High mechanical strength : insensitive to fatigue, junction, and surface status, compatible of bolted link under high loads ,
- Ø Machining by EDM offering high precise I/F,
- Ø Unequalled mirror manufacturing capabilities : large lightweight and stiff mirror, directly polishable for IR use without overcoatings,
- Ø Ultra high stability performance for cryo applications ,
- Ø Cost and manufacturing time competitive,
- Ø Potential of evolution (manufacturing of more complex structure, enhanced properties..) .

Cesic® and HB-Cesic® are space qualified and available for future space applications.