HB-CESIC COMPOSITE FOR SPACE OPTICS AND STRUCTURES

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Keywords: *Ceramic material, Composite material, Mirror, low CTE, SiC, Cesic®*

Abstract

One of the key technologies for next generation space telescopes requiring large-scale reflectors are light-weight materials having high specific strength, high specific stiffness, low coefficient of thermal expansion and high coefficient of thermal conductivity. Several candidates, such as fused silica, beryllium, silicon carbide and carbon fiber reinforced composites, have been evaluated.

An example of the latter material is a Hybrid Carbon-Fiber Reinforced SiC composite or HB-Cesic® – a trademark of ECM – which has been developed by ECM and MELCO to meet the stringent space telescope requirements. Mechanical performance, such as stiffness, bending strength and fracture toughness, were significantly improved using HB-Cesic® compared to our classic Cesic® material. Thermal expansion and thermal conductivity of HB-Cesic® at cryogenic temperatures are now partly established and excellent performance for large future space mirrors and structures are expected.

In this paper we will report on the current status of development of HB-Cesic® and describe the first successful applications made with this new improved material.

1. Introduction to HB-Cesic®

HB-Cesic® is a ceramic matrix composite that is manufactured by ECM. It is characterized by high stiffness and mechanical strength, high thermal conductivity, low thermal expansion, and quick, relatively inexpensive manufacturing times. These characteristics make HB-Cesic® an ideal material at reasonable cost for large high-precision space optical and structural applications.

The starting material in the manufacturing of HB-Cesic® is a short, chopped, randomly oriented carbon fiber material. A typical microstructure is shown in the following figure.

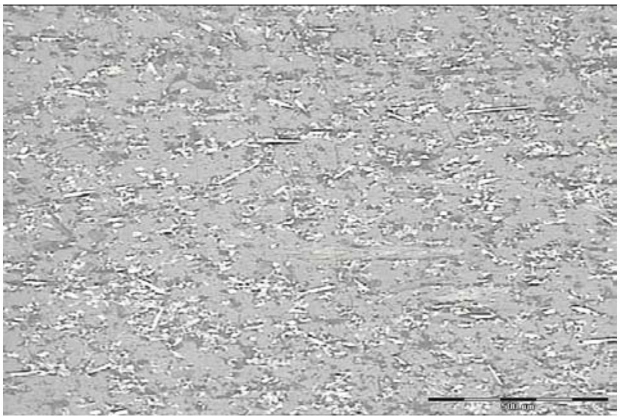

Fig. 1. REM microphotograph of the greenbody

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 (Fig. 1). At the present time circular blanks are available in sizes up to 1 m, with a thickness up to 200 mm. In the future greenbody blocks up to 2 m in size or larger will become available as circular or square blocks.

Through the use of ECM's large CNC controlled milling machine of 2.5 x 1.75 m, we are able to manufacture large lightweighted monolithic structures, such as mirrors and components for optical benches. For example, in the manufacture of optical mirrors, curved face sheets (including off-axis designs) can be machined with reinforcing ribs as thin as 1 mm and of any geometry, including ribs with holes or with T-shape.

Upon machining the greenbody is infiltrated under vacuum conditions with liquid silicon at temperatures above 1600°C. Capillary forces wick the silicon throughout the porous greenbody, where it reacts with the carbon matrix and the surfaces of the carbon fibres to form carbon-fiber reinforced SiC -- HB-Cesic®. The density of the infiltrated HB-Cesic® composite is typically 2.98g/cm³.

After controlled cool-down, the HB-Cesic® structure is carefully examined visually and/or by other NDT methods such dye penetrant or ultrasonic tests. The HB-Cesic® structure can then be micro-machined with suitable diamond tools or by EDM machining to achieve the required surface figure and interface geometry (e.g., mirror adaptation and mounting). EDM machining is possible because of HB-Cesic®'s electrical conductivity. This machining method is fast compared to grinding, it is relatively inexpensive, and it yields a surface and location (e. g., screw holes and mounts) accuracy of about 10 µm tolerance over a large area.

Manufacturing times of HB-Cesic® mirrors and other structures are typically only a few weeks, upon procurement of the C/C raw material, which is much shorter than the manufacturing times of other ceramic or glass structures. Highly complex and large projects take somewhat longer, e.g., mirrors with closed backs, meter-plus-class mirrors that require precision joining of the greenbody or infiltrated segments, and large multi-segmented optical benches.

The maximum size of HB-Cesic® components is only limited by the size of the Si-infiltration furnaces. ECM's current largest furnace has a useable diameter of 2.4 m with up to three levels, each of height 1.2 m. In the following figures the large ECM facility for infiltration is shown.

Fig. 2. ECM – XL facility for infiltration

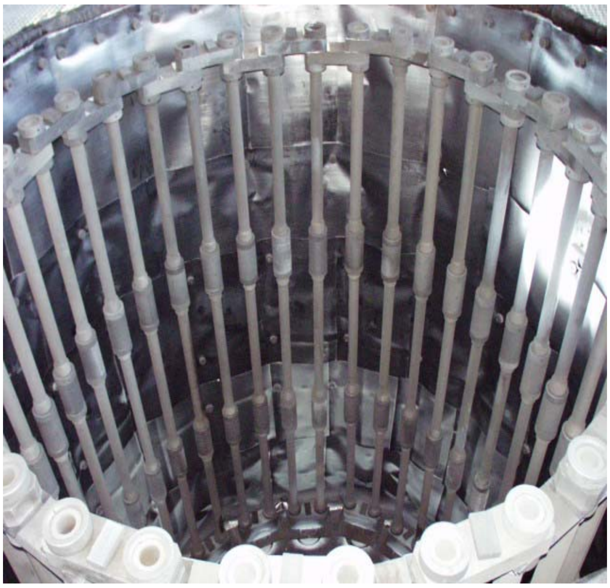

Fig. 3. Heater unit designed for best thermal homogeneity

2. C/C material for HB-Cesic®

In the past three years ECM and MELCO developed a new improved C/C raw material compared to the ECM classic C/C material for Cesic® in order to improve the homogeneity and thermo-mechanical characteristics of the final, Si-infiltrated product, especially for cryogenic mirror applications. The following figure shows the manufacturing process of the new C/C raw material:

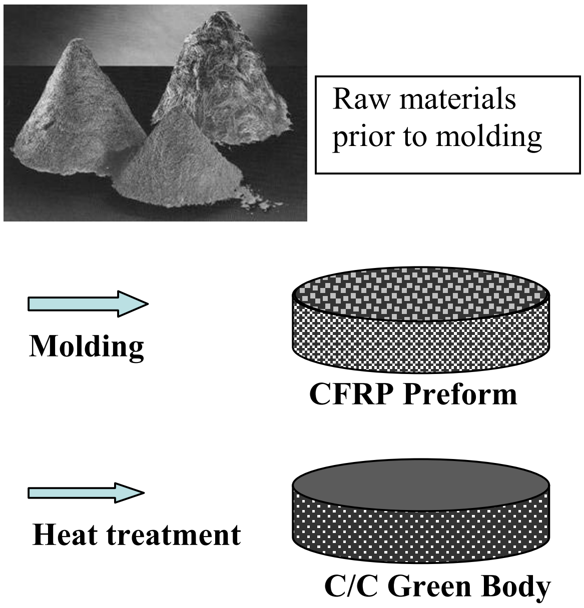

Fig. 4. Manufacturing process of the new C/C raw material

We call the new composite material "HB-Cesic®" to distinguish it from our classic Cesic® material (type "MF Cesic®"). As we will describe in Section 4, we have conducted several tests of the new HB-Cesic® material and demonstrated that it possesses superior mechanical and thermal performance characteristics compared to classic Cesic®. Thus, ECM can propose with confidence HB-Cesic® for future cryogenic ultra-lightweighted mirrors and structures.

This C/C raw material is composed out of a mixture of different chopped short carbon fibers and this is the reason why it is called hybrid (HB).

3. Manufacturing process of HB-Cesic®

The machining of greenbodies uses standard tooling and technologies, such as ECM's 3-D CAD/CAM controlled machine, to mill, turn and drill holes. All light-weighting operations are also done in the greenbody stage and, therefore, are fast compared to the volume of carbon to be removed. The C/C greenbody is not fragile, so very thin walls can be machined as, for example, ribs down to 1 mm thickness with a height of up to 120 mm. The possibility of manufacturing very thin plates and complex shaped elements and of joining at the greenbody stage before or after machining allows the rapid manufacture of complex, ultra-lightweighted HB-Cesic® mirrors and structures, to meet the challenges of future space requirements.

Greenbody blocks can be joined by gluing after machining, but before Si-infiltration, which allows the manufacture of large, monolithic HB-Cesic® components. Si-infiltration transforms the glued section into HB-Cesic® without any discontinuities. In the near future, we plan to carry out bending tests of samples manufactured from continuous and joined C/C greenbodies to confirm, as in the case of our classic Cesic® material, that joining does not introduce any mechanical or thermal discontinuities.

After greenbody machining the C/C greenbody is infiltrated at high temperature with liquid silicon. This is a cost effective and fast process with a rapid heat cycle, the cold to cold cycle duration being less than 72 hours.

One of the main advantages of the HB-Cesic® manufacturing process is the very low shrinkage during infiltration of only 0.6% ±0.05% compared to other silicon carbide materials, some of which have a shrinkage up to 20 % with a deviation of ±1%. I.e., our process is "near-net-shape." The low shrinkage of HB-Cesic® during infiltration allows a highly accurate prediction of the machining at the greenbody stage, limiting the final over-thickness needed for corrective machining after infiltration. This small shrinkage also limits residual stresses during infiltration and cooldown, as all the parts of the structure undergo only very small contractions.

3.1. Final maching of HB-Cesic® to prepare high precision interfaces

After infiltration, HB-Cesic® components can be machined with high accuracy and without any risks using Electro-Discharge Machining (EDM). The ability to EDM-machine HB-Cesic® components is due to the material's good electrical conductivity, which is rather high for a ceramic and a major advantage compared to other silicon carbide materials.

EDM-machining allows no risk, high-precision finishing of surfaces in local areas inside and outside the structure in preparation for adding screw inserts or bolting fixation devices. It can also be used to reduce section or thickness at the final machining stage and to make, for example, integrated filtering blades (mounting devices) on mirrors, as we successfully demonstrated with our classic Cesic® in past programs. Of course, HB-Cesic® can be also ground by traditional techniques over large surface areas.

3.2. HB-Cesic® mirrors – polishing of surfaces

In the past year ECM and MELCO investigated the polishing performance of HB-Cesic® mirrors.

For mirrors of sizes up to 160 mm we demonstrated that bare HB-Cesic® surfaces – i.e., surfaces without any cladding or overcoatings – can be polished to a surface roughness of 3-5 nm rms.

The following picture shows an optical measurement of the micro-roughness of a bare HB-Cesic® surface.

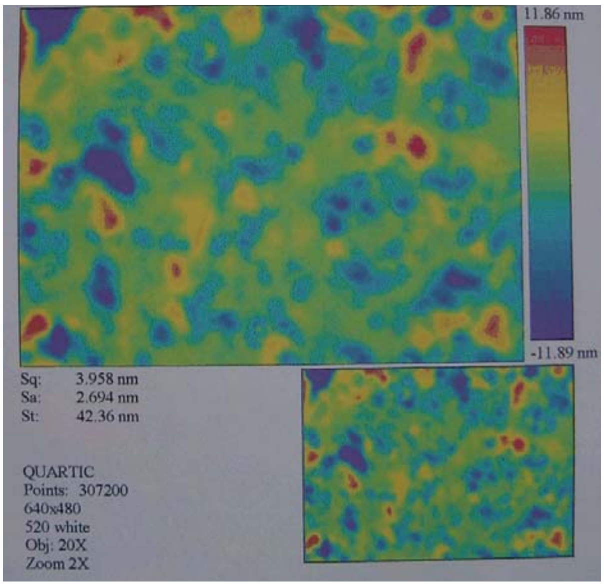

Fig. 5. HB-Cesic® Microroughness

4. Material characterization and thermo-mechanical properties

ECM and MELCO have recently measured several mechanical and thermal properties of HB-Cesic®:

- CTE near RT
- CTE from RT down to 100K – initial tests
- 4-point bending
- Young's modulus

4.1. CTE measurement facility

The CTE measurements were done in a cryo chamber, which is shown in the following picture. The test facility is located at Mitsubishi Electric Corporation, Japan.

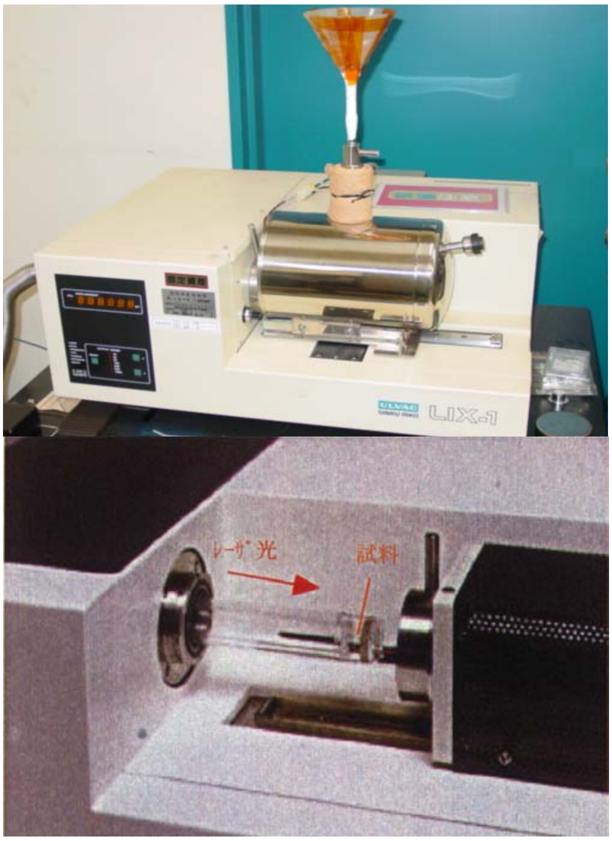

Fig. 6. Laser thermal expansion indicator , LIX-1(ULVAC)

The total number of HB-Cesic® samples measured was six: 3 samples in the X-direction and 3 samples in Y-direction. The samples' shape is illustrated in Fig. 7, with sizes 3t x 5w × 15L according to Melco internal standards, corresponding to 3 x 5 x 15 mm.

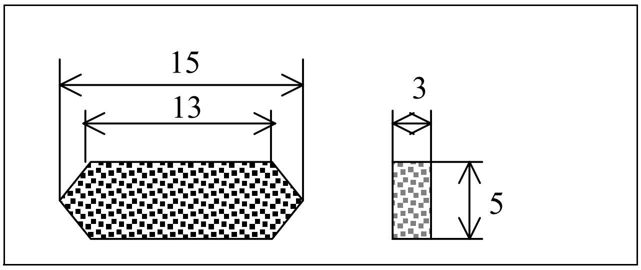

Fig. 7. Shape of the CTE samples

The measurement principle of the facility is shown in the next picture.

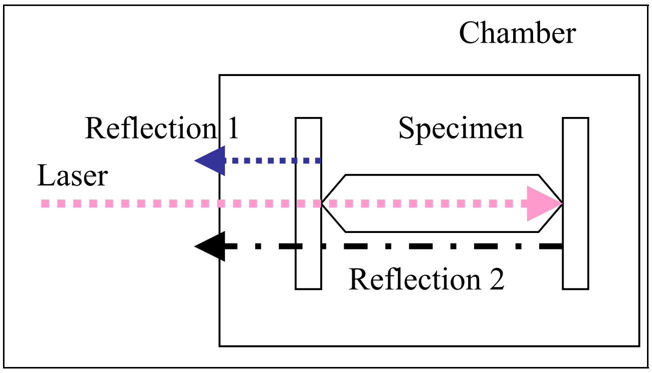

Fig. 8. Measurement principle

To avoid any impact of the environment on the measurements such as vibration, the whole measurement system was isolated using rubber pads and placed on a stiff optical bench table. From the data, CTE is calculated as:

$$CTE = \frac{\textit{(Displacement change)}}{\textit{(Distance between targets)} \times \textit{(Temperature change)}}$$

4.2 Results of CTE-testing

Before the start of the measurements, the system was calibrated with a specified aluminum sample, for which the exact cryo data were available. After this calibration, the HB-Cesic® samples were installed in the cryo chamber. For all the CTE-measurements, just one silicon diode was used for the measurements of the HB-Cesic® samples and one for the copper plate temperature. Both diodes were calibrated before measurements. Before cooling to cryogenic temperatures, the samples were maintained at a temperature of 310 K for two hours to achieve complete initial temperature uniformity. With these test conditions we were able to successfully obtain an overall thermal deformation between 300 K and 110 K with an accuracy of about 0.1 micron,

The results of the CTE measurements are shown in the next two figures.

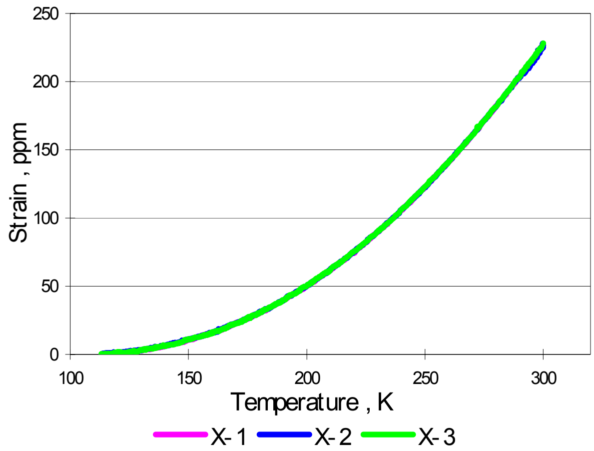

Fig. 9. CTE in X-direction

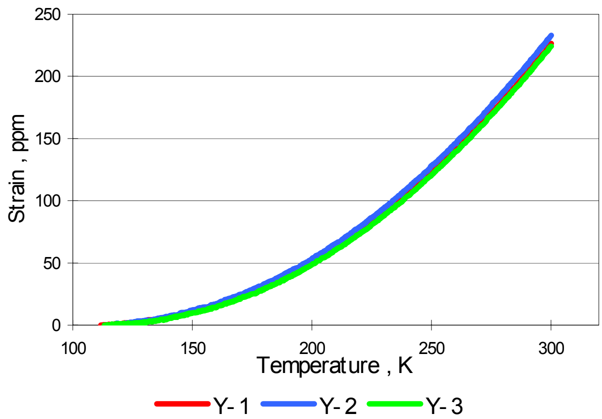

Fig. 10. CTE in Y-direction

4.3 Four-point bending test of HB-Cesic®

4.3.1 Test Set-up Description

The bending tests for HB-Cesic® were performed at Thales Alenia Space (TAS), Cannes, France:

- Compression/strain machine: Zwick Z250
- Strength sensor: 100 kg
- Acquisition system: MGC Catman, Solartron captor conditioner

- Loading speed: 0.5 mm/min
- NIRSpec bending tool, two superior points articulated
- Span length: 40mm/ 80mm
- Log radius: 20 mm
- LVDT sensor placed under the sample in order to measure precisely the displacement in the load axis.

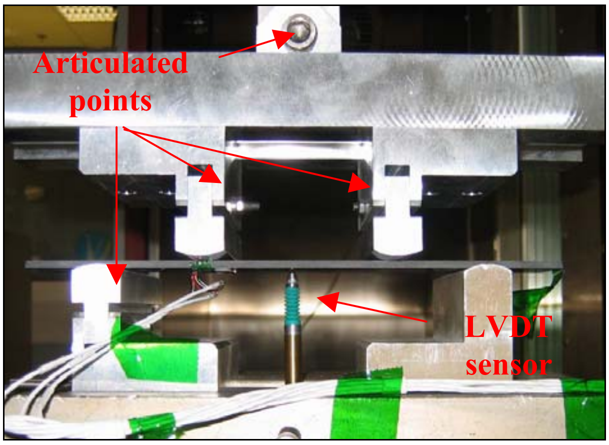

Fig. 11. Sample in 4-point bending test configuration at TAS. Test-setup shown is for a sample of length 240 mm. The HB-Cesic® tests were made with samples of length 120 mm

4.3.2 Sample Description

The tests were performed on HB-Cesic samples with the dimensions 120 x 20 x 3 mm.

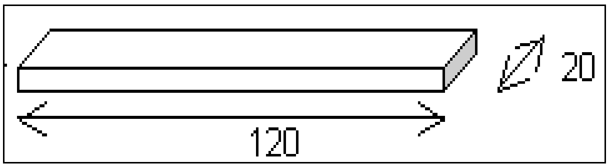

Fig. 12. Size of HB-Cesic® 4-point bending samples

Number of samples:
55 XY samples
5 Z samples

XY-direction (length axis of sample perpendicular to pressing direction). Z-direction (length axis of sample in parallel to pressing direction).

The surface of load implementation (120 x 20 mm) and the length side (120 x 3 mm) were ground.

4.3.3 Test Results

Direction	Strength (MPa)	Modulus(GPa)
XY	266	351
Z	244	337

Table 1. Mechanical results of 4-point bending test

4.3.4 Comparison to Classic Cesic® (type MF)

The following table compares Young's modulus and 4-point bending strength of classic Cesic® (type MF) and HB-Cesic® .

	Cesic® MF	HB-Cesic®	Increase to Cesic® MF
E XY	258	351	36%
E Z	218	337	55%
σ XY	126	266	110%
σ Z	115	224	95%

Table 2. Young's modulus and strength of classic Cesic compared to different HB-Cesic® batches

The test results demonstrate the superior mechanical properties of HB-Cesic® compared to classic Cesic®.

4.3.5 Weibull modulus

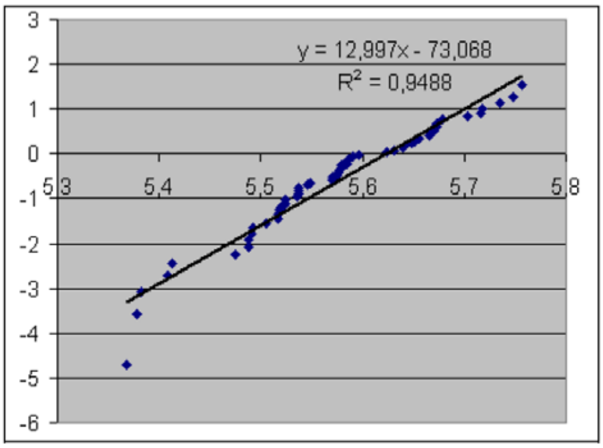

Fig. 13. Experimental curve for Weibull modulus

We calculated the Weibull modulus for HB-Cesic® by the least square fitting method and obtained the following value:

m = 12.2

5. Recent applications out of HB-Cesic®

ECM has used HB-Cesic® in the manufacture of a number of components:

Beside some demonstration parts, ECM has manufactured a 320-mm mirror out of HB-Cesic®. The following pictures show this mirror during optical polishing and optical measuring.

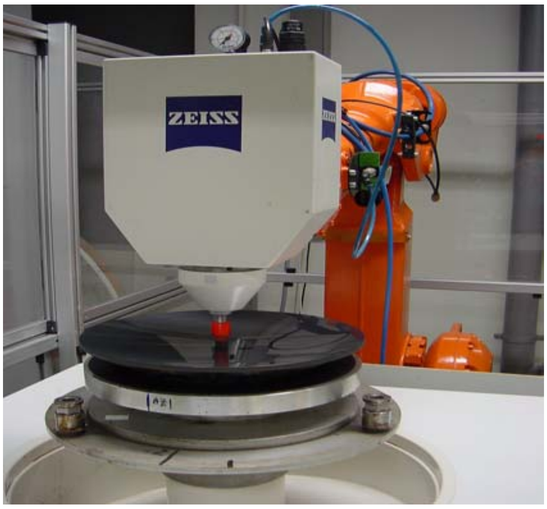

Fig. 14. Mirror during polishing

Fig. 15. Mirror during optical measurements

Also, ECM manufactured structural parts, such as a focal plane structure with dimensions of 410 mm x 210 mm and designed for 24 CCD's, in order to demonstrate the high stiffness and thermo-mechanical performance of the HB-Cesic® material compared to traditional focal plane materials. Due to the fact that this project is classified we cannot show any pictures.

As part of this project we demonstrated the extraordinary machining possibilities with HB-Cesic®. For instance, we machined HB-Cesic® screws, nuts and threads. The threads were machined directly into the focal plane structure. See figures 16 and 17.

Fig. 16. HB-Cesic® srew and nut

Fig. 17. HB-Cesic® thread inside structure