Manufacturing and performance test of a 800 mm space optic

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ABSTRACT

Next generation space telescopes, which are currently being developed in the US and Europe, require large-scale light-weight reflectors with high specific strength, high specific stiffness, low CTE, and high thermal conductivity. To meet budget constraints, they also require materials that produce surfaces suitable for polishing without expensive over-coatings.

HB-Cesic® – a European and Japanese trademark of ECM – is a Hybrid Carbon-Fiber Reinforced SiC composite developed jointly by ECM and MELCO to meet these challenges. The material's mechanical performance, such as stiffness, bending strength, and fracture toughness are significantly improved compared to the classic ECM Cesic® material (type MF). 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.

This paper will present the whole manufacturing process of such a space mirror starting from the raw material preparation until the polishing of the optic including cryo testing .

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, short carbon-fibers.

Keywords: Ceramic material, Composite material, Mirror, low CTE, SiC, Cesic, C/SiC

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 CTE, 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, 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 blocks up to 2 m in size or even larger will become available as circular or square blocks.

ECM’s large CNC controlled milling machine of 2.5 x 1.75 m allows us to manufacture large, light-weighted, 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 light-weighting holes or of T-shape for increased stiffness.

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 fibers to form carbon-fiber reinforced SiC -- HB-Cesic®. The density of the infiltrated HB-Cesic® composite is around 2.98 g/cm³.

After controlled cool-down, the HB-Cesic® structure is carefully examined visually and by other NDT methods, such as dye penetrant or ultrasonic tests. The structure is then 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 good electrical conductivity. This machining method is fast compared to grinding, it is relatively inexpensive, and it yields a surface and location accuracy (e. g., for screw holes and mounts) 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 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.

Summarizing this section we would like to show the following mechanical properties of HB-Cesic®, which are now established :

Property	Unit	Value
Density	g/cm3	2.97
Bending strength	MPa	320
Young's modulus	GPa	350
Poisson's ratio		0.18
CTE @ RT	ppm/K	2.3
Thermal conductivity	W/m*k	125
Fracture toughness value KIC	MPa·m1/2	3.6

Table 1. HB-Cesic® material properties

2. DESIGN OF THE 800 MM SPACE MIRROR

ECM developed a light-weighted design for an 800 mm space mirror based on the following external requirements:

- Diameter 800 mm with a height of 80 mm
- Radius of curvature R=1592 mm
- Mass below 15 Kg
- 3 interfaces for mounting the mirror
- Limited gravity deformation due to horizontal mounting during cryo test
- Stable mounting concept for cryo testing

Based on the already existing experience at ECM with such light-weighted mirrors ECM developed the following design concept, which is shown in the next figure:

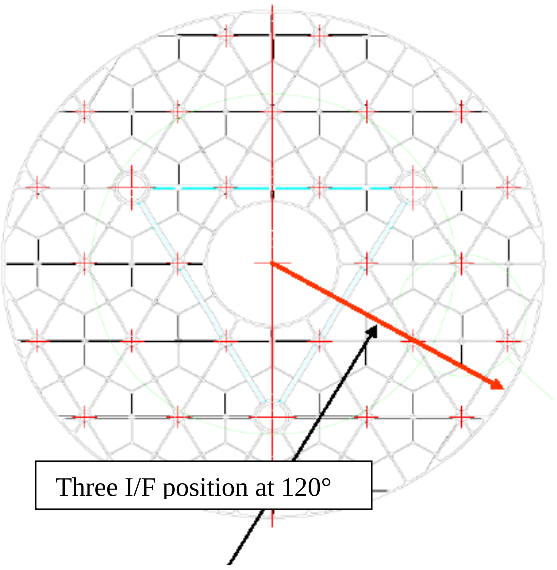


Fig.1: Initial mirror design

Based on this initial design MELCO and ECM started to optimize the design mainly in order to minimize the gravity deformation of the mirror during cryo test in horizontal position. Therefore the following parameters were changed :

- Rib thickness of main ribs (2.5 mm or 5 mm)
- Face sheet thickness (3 mm or 5 mm)
- Reinforcement of main ribs with hammerhead shaped (T-shaped) ribs
- Increasing height of the mirror by 20 mm (to 100 mm)
- Position of I/F
- Amount of interfaces (3 or 6 interfaces)

These parameters had very different influence to the gravity deformation of the mirror. The gravity deformation of the different mirror designs changed from 968 nm to 63.5 nm. The following two pictures shows the two extreme designs:

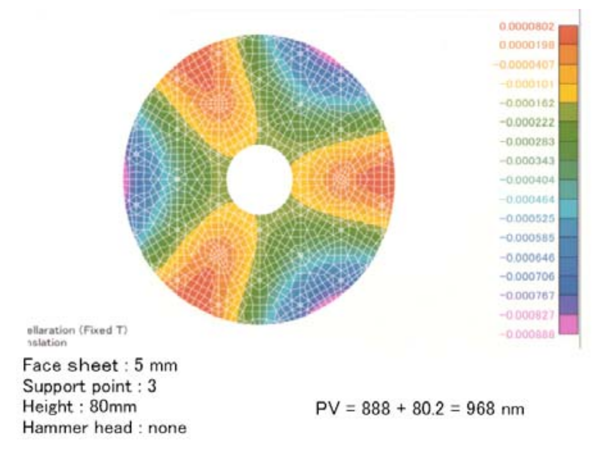


Fig.2 : Design with maximum gravity deformation

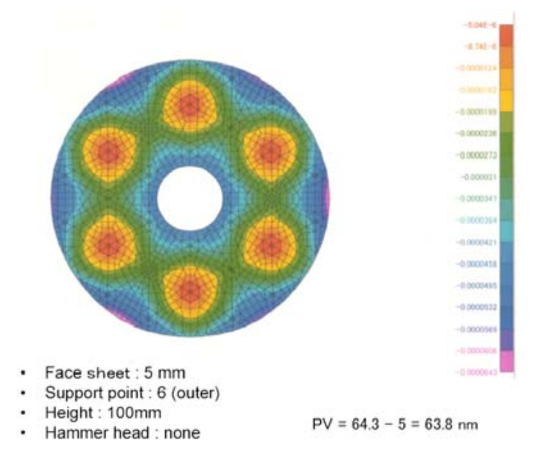


Fig.3 : Design with minimum gravity deformation

Finally Melco and ECM used the following compromise between minimized gravity deformation and test set-up in the cryo facility:

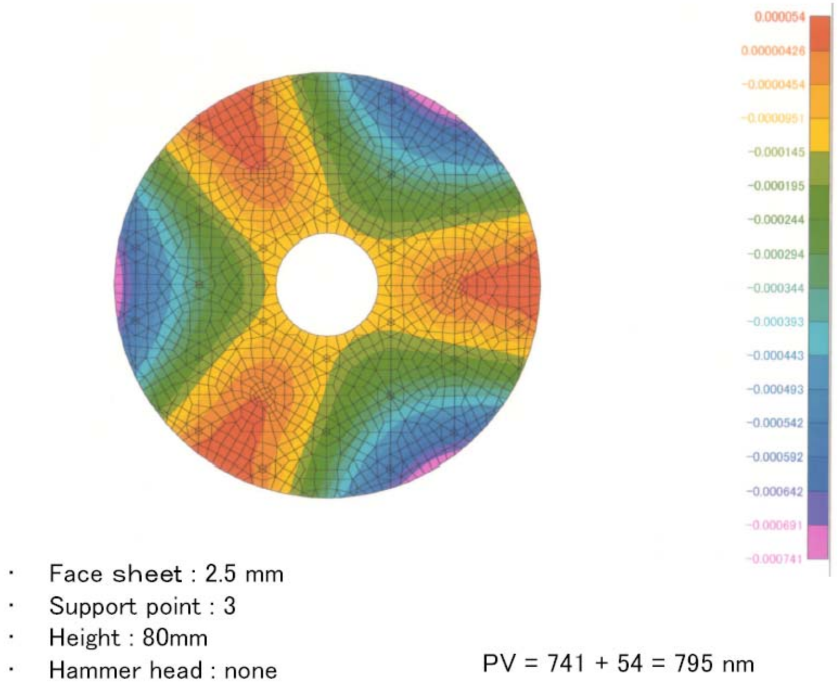


Fig.4 : Finally used mirror design

After the mirror design was fixed MELCO and ECM designed in addition to the mirror an optical bench to mount this mirror during the cryo test without any influences due to force introduction to the mirror during fixation of the mirror in the cryo test facility. In order to be completely separated from the metal component of the facility ECM proposed the following optical bench design to support the mirror.

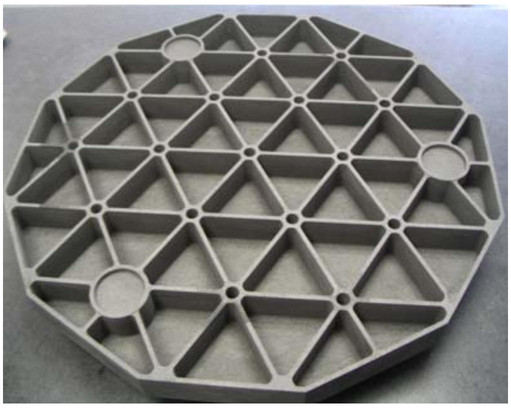


Fig.5a : Backside-Design of optical bench

Fig.5b : Frontside-Design with center reference for cryo testing

In order to have also an stress free mounting Melco design Isostatic mounts out of INVAR 36. These mounts were screwed between the optical bench and the mirror interfaces.

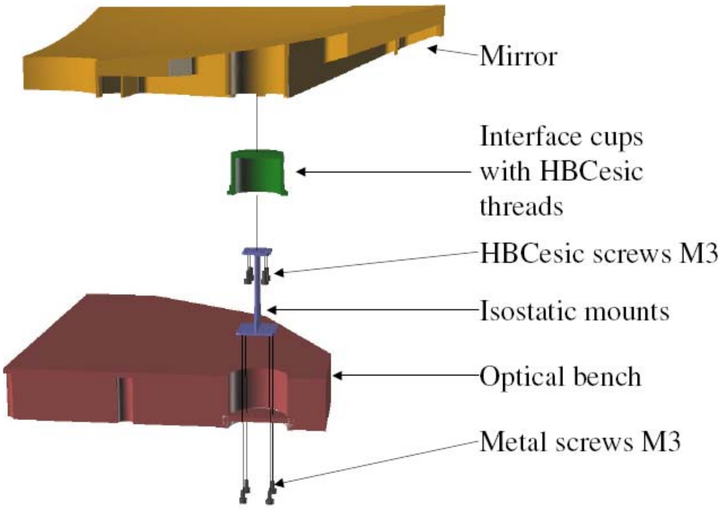


Fig.6 : Assembly of the mirror system

After completion of the design work ECM manufactured a 1:1 scale plastic model of all the parts in order to have a final check of the machining programs and also to check

3. C/C MATERIAL FOR HB-CESIC®

The C/C raw material for HB-Cesic® was developed by MELCO 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 classic Cesic® material (type MF). The following figure shows the manufacturing process of the new C/C raw material:

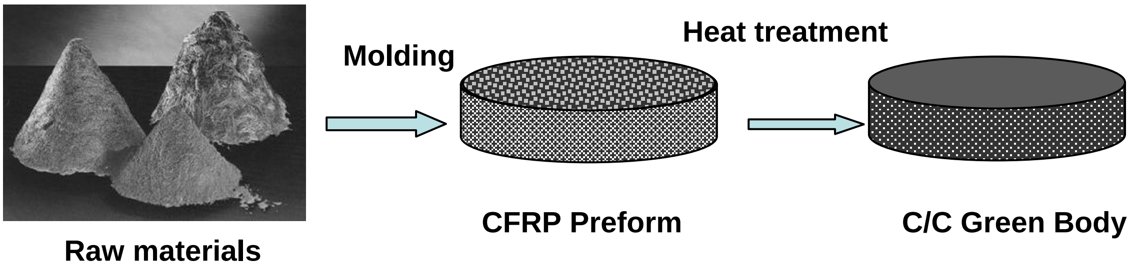


Fig. 7. Manufacturing process of the new C/C raw material

4. MANUFACTURING PROCESS OF AN 800 MM HB-CESIC® SPACE MIRROR

ECM manufactured the mirror out of a solid block with a diameter of 820 mm and a thickness of 75 mm. Prior to light-weighting the C/C material, which was provided by MELCO was checked during income inspection at ECM according to the ECM space standard procedures in order to qualify the C/C material for the production.

The use of C/C greenbody manufacturing is one of the key technologies of the Cesic® process. During this manufacturing step ECM has a lot of positive features to create very light-weighted mirror and also structures.

The C/C material being not fragile, the light-weighting on the CNC machine is easy, fast and with virtually no risk of greenbody failure. Large ribs with less than 1,5 mm thickness are easily shaped, and the machining time for full machined mirrors up to 1m class is only a few days.

In the following pictures some steps of the light-weighting of the 800 mm space mirror are shown.

Fig.8a : Start greenbody manufacturing

Fig.8b : Greenbody manufacturing backside completed

The time period for the greenbody manufacturing of the backside was only 5 days and without any defects or cracks of the C/C material even with the 2.5 mm ribs only. After completion of the backside ECM checked directly on the CNC machine the correct structure with a special 3D coordinate measurement device. Having the possibility of measuring the structure directly on the CNC machine is a very big advantage, because in case of any non conformance the structure could be re-machined without new alignment on the machine which is especially very critical with complex structures of thin ribs. After confirmation that the complete structure was manufacture in full accordance to the specification ECM turned the mirror structure on the machine and started to machine the spherical mirror surface with a radius of 1592 mm. The machining of the mirror surface with an rather deep curvature was machined in 2 days.

After completion of the greenbody manufacturing the mirror was successfully infiltrated in ECM’s large furnace. After the infiltration the mirror surface was completely sandblasted in order to remove the excess silicon and measured. The final diameter of the 800 mm mirror was 800.05 mm which is well inside the specification of +/- 0,2 mm. The following pictures shows the sandblasted backside of the mirror structure.

Fig.9 : Mirror sandblasted

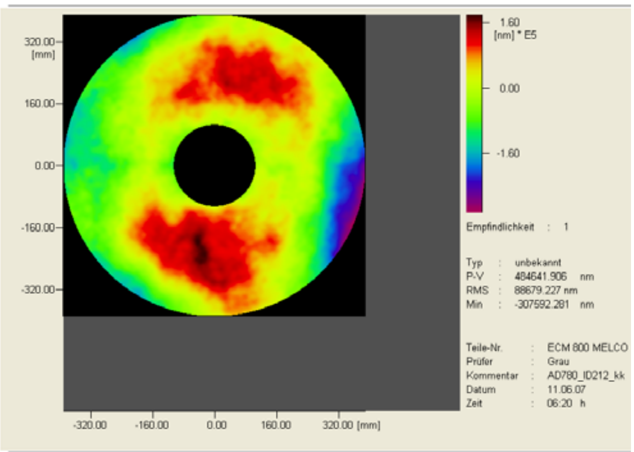
After the infiltration the mirror interfaces were machined to the specified tolerances and afterwards the mirror was send to Zeiss for grinding/pre-polishing of the mirror surface.

5. MIRROR SURFACE PREPERATION

In this program ECM used the first time for an rather large optic a pure silicon layer in order to get the final specification of the mirror with an WFE of 60 nm RMS.

For this pure silicon layer the mirror surface has to be pre-shaped to 10 – 15 µm P-V and the micro-roughness should be better than 20 nm to have no print through of the micro structure inside the silicon layer. The pre-polishing was done at Zeiss, Germany.

The first measurement after the infiltration and a first step of lapping to smooth the surface for the measurement shows that the mirror was deformed by only 484 µm P-V, which was absolutely in the expected range, especially due to the very thin and light-weighted structure.



Empfindlichkeit : 1

Typ : unbekannt
P-V : 484641.906 nm
RMS : 88679.227 nm
Min : -307592.281 nm

Teile-Nr. : ECM 800 MELCO
Prüfer : Grau
Kommentar : AD780_ID212_kk
Datum : 11.06.07
Zeit : 06:20 h

Fig.10 : Mirror surface deformation directly after infiltration

In the following weeks Zeiss improved the mirror surface down to 12.8 µm P-V. The following table shows the progress of the lapping and pre-polishing phase prior to the silicon coating.

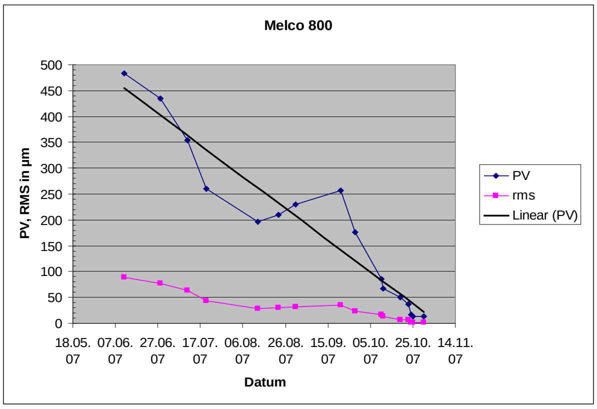
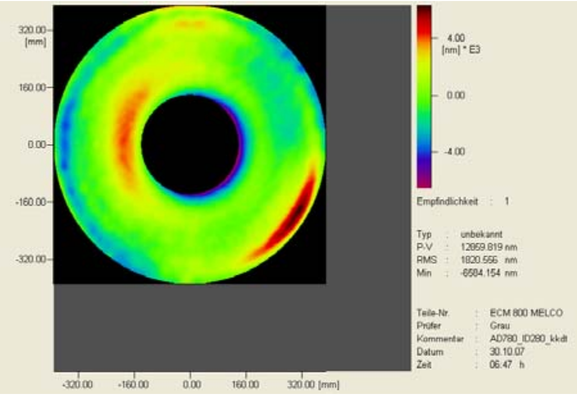


Fig.11 : Progress curve of lapping/pre-polishing

Fig.12 : pre-polished mirror during wipe test

After this pre-polishing phase ECM cleaned the mirror in a vacuum process and shipped the mirror to the coating facility.

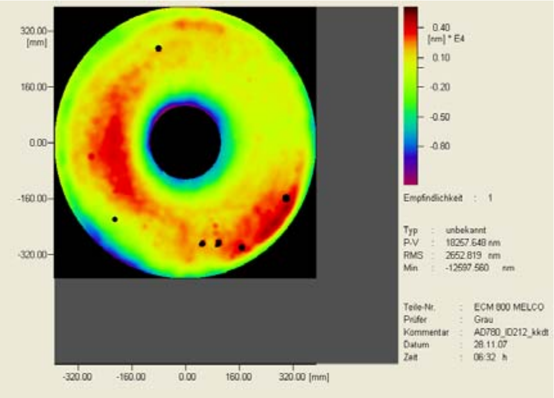
The used silicon coating is an amorphous silicon with a thickness of >50 mm. In order to have a good knowledge about also the layer deviation Zeiss performed a final measurement before the coating and directly after the coating without any polishing. The results of these measurements shows a very good and uniform layer thickness over the complete 800 mm surface.



Empfindlichkeit : 1

Typ : unbekannt
P-V : 12859.819 nm
RMS : 1820.556 nm
Min : -6584.154 nm

Teile-Nr. : ECM 800 MELCO
Prüfer : Grau
Kommentar : AD780_ID280_kkdt
Datum : 30.10.07
Zeit : 06:47 h



Empfindlichkeit : 1

Typ : unbekannt
P-V : 18257.648 nm
RMS : 2652.819 nm
Min : -12597.560 nm

Teile-Nr. : ECM 800 MELCO
Prüfer : Grau
Kommentar : AD780_ID212_kkdt
Datum : 28.11.07
Zeit : 06:32 h

Fig.11 : Mirror surface before coating – 12.8 µm

Fig.12 : Mirror surface after coating – 18.2 µm

After the coating was successfully performed Zeiss continued to correct the mirror surface down to the specification of 60 nm RMS WFE. The first correction steps were done with a 3D coordinate measurement device until the surface was prepared for optical measurements. During the first phase of polishing the interfaces and the isostatic mounts were not bonded to the mirror structure. The fine lapping phase was finished after 2 month, from this time the polishing was controlled by optical measurements.

At the end of the 1 polishing phase Zeiss also measured the radius of curvature of the mirror and the result was well inside the specification of 1592 mm +/- 2 mm.

In the following phase the mirror was polished down to 60 nm RMS on the silicon layer. During this phase the mirror was already mounted on the optical bench during the measurements in order to have the possibility to correct any influences of the mounting. Therefore after each polishing step the mirror was reassembled on the optical bench prior to the optical measurement. For this assembly a dedicated procedure was developed to guarantee a high rate of repeatability.

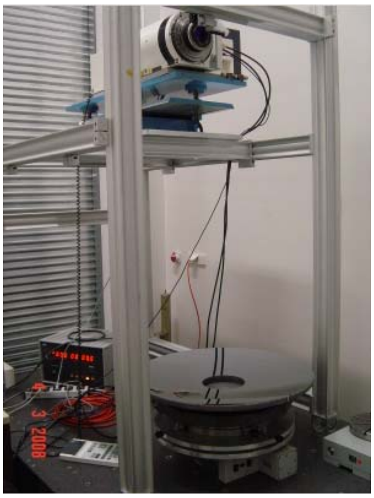
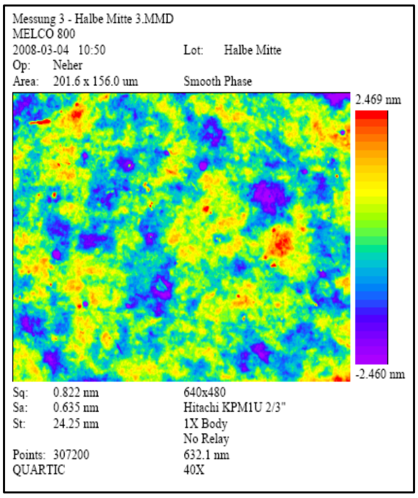


Fig.13 : Mirror during assembly to optical bench for optical measurement

Fig.14 : Optical measurement set-up

The complete polishing to the final specification was performed in 4 month. In this program the micro roughness was only specified better than 20 nm RMS, therefore no final polishing to achieve best possible micro roughness was performed on this mirror. However the final reached micro-roughness on this mirror was around 0.6 nm RMS which could according to Zeiss strongly improved with a dedicated polishing process, if required.

At the end of the program Zeiss performed on the polished mirror surface some micro roughness measurements which is shown in the following figure. The measurements were done with PROMAP.


Messung 3 - Halbe Mitte 3.MMD
MELCO 800
2008-03-04 10:50 Lot: Halbe Mitte
Op: Neher
Area: 201.6 x 156.0 um Smooth Phase

Sq: 0.822 nm 640x480
Sa: 0.635 nm Hitachi KPM1U 2/3"
St: 24.25 nm 1X Body
No Relay
Points: 307200 632.1 nm
QUARTIC 40X

Fig.15 : Micro roughness of mirror surface

Fig.16 : Micro roughness measurement set-up