High Precision Optics and Optical Systems

Diffusion Bonded Mirror
Final Presentation

DBM Media Lario Team

04 October 2023

Project Overview

Introduction

- Aluminium alloys obtained by rapid solidification process have been successfully used for manufacturing optical mirrors.
- Rapidly solidified aluminium alloys have a fine and homogeneous grain structure that is more easily polishable than standard aluminium alloys, thus offering the possibility of utilization for optical mirrors.
- The maximum size of this type of aluminium mirrors is limited by the size of the billet, currently about 500 mm, but the need for larger aluminium mirrors is coming from scientific missions that require large collecting areas.
- A possible way of increasing the attainable size of aluminium mirrors is to join together multiple segments and to polish the mirror to the required surface roughness
- An effective joining method is based on the bonding of segments to form larger billets. This process is also known as Diffusion Bonding (DB).

Objective

Development and breadboard demonstration* of the Diffusion Bonding technology for the manufacturing of large Aluminum mirrors by contiguous joint of smaller segments, thus overcoming the size limitations of raw material billets availability.

** Minimum size of 300 mm with at least 3 segments*

Project Team

Media Lario produces optical components and systems, custom-made or in high volumes for Space Telescopes, Satellite Earth Observation Systems, Laser Optical Communications Systems. The design, manufacturing and testing of the mirror breadboard and the cryogenic testing are performed by Media Lario.

RSP Technology was the first to implement the rapid solidification process for commercial production of rapidly solidified Aluminium alloys named RSA. With this motivation, RSP Technology has accepted to partner as sub-contractor with Media Lario for the demonstration of the diffusion bonding process in a more than 300 mm diameter mirror breadboard. The aluminium material and the diffusion bonding process is from RSP Technology BV

ML - Company Overview

Media Lario Overview

- Media Lario S.r.l. founded in 1993
- Located in Bosisio Parini, Italy
- Employing primarily engineers, scientists, high-tech mfg personnel
- Serving global advanced optical markets and leading aerospace companies…

Media Lario production facility, Bosisio Parini, Italy

Located in an area of high-tech manufacturing and optics expertise

Repli-formed Optics™ Capacity is in Place

High-Volume, High-Capacity Baths for Mirror Manufacturing

Space Qualified Production Space – ISO 7

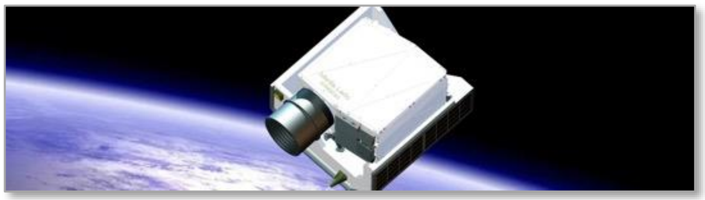
Large ISO 7 Space-Qualified Manufacturing AIT Area in Place

Space Qualified Production Space – ISO 5

ISO 5 Space Qualified Clean-Room Manufacturing Area

Markets

Astronomy



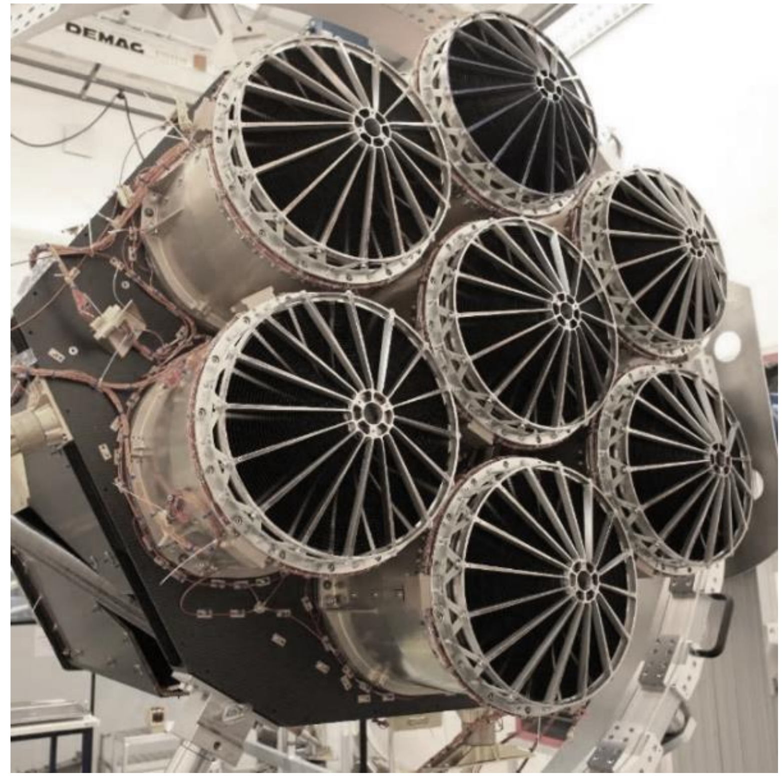
Earth Observation

Free Space Optical Communications

Custom Applications

Repli-formed Optics™ - Enabling Space Telescopes

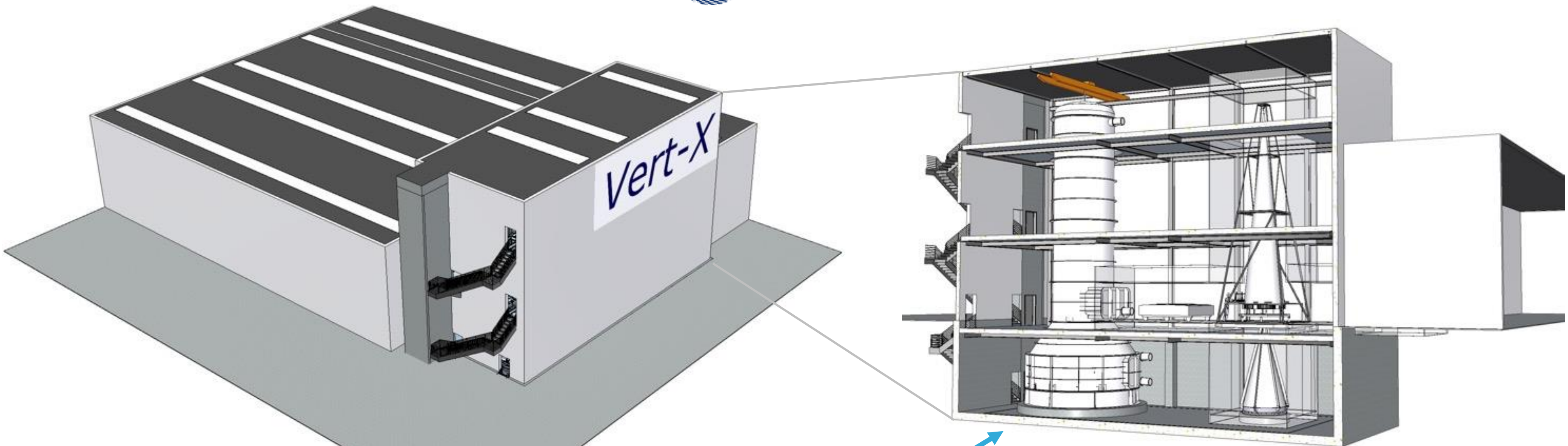
XMM-Newton space telescope (credits ESA)



eROSITA space telescope (credits MPE)

Repli-formed Optics™ *is used on space mission such as*
XMM-Newton, Beppo-SAX, SWIFT, eROSITA, Einstein Probe

ATHENA Assembly and Integration Facility



Exterior View

Telescope alignment
in X-Ray and vacuum

Interior View

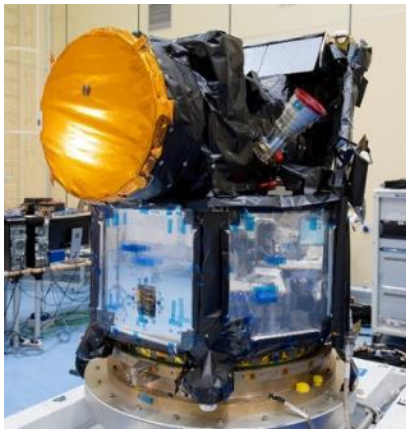
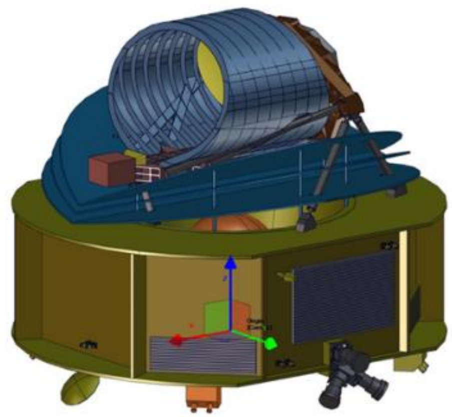
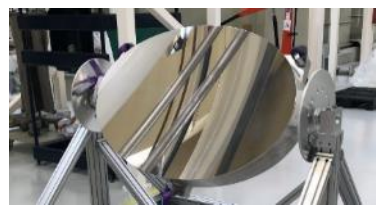
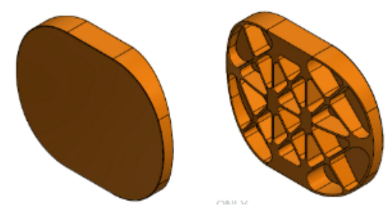
Optics alignment
in UV Light

*Construction has begun on a **World-Class Space Telescope***

***Assembly and Integration facility** at Media Lario*

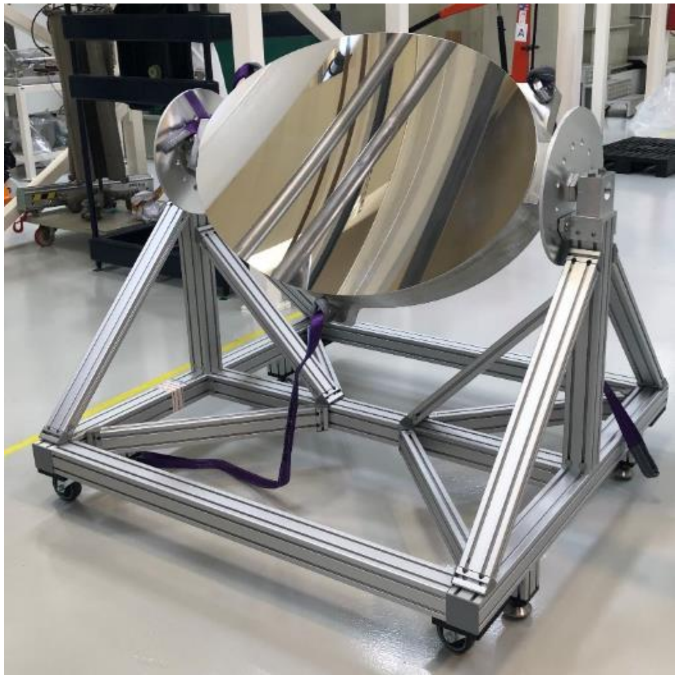
Media Lario in Other Astronomy Missions

Launched and operating now

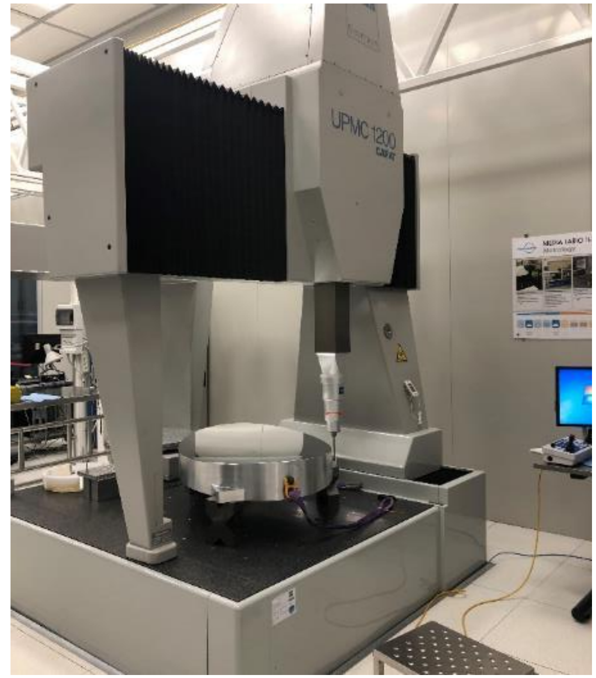
CHEOPS	PLATO	ARIEL	FORUM
			
			
330 mm Zerodur mirror	170 mm aspheric lenses and windows	1100 mm Alum mirror	250 mm Alum mirrors

ARIEL Space Telescope

ARIEL Prototype Mirror M1



M1 in Metrology



IRIDE – High Resolution EO Payload

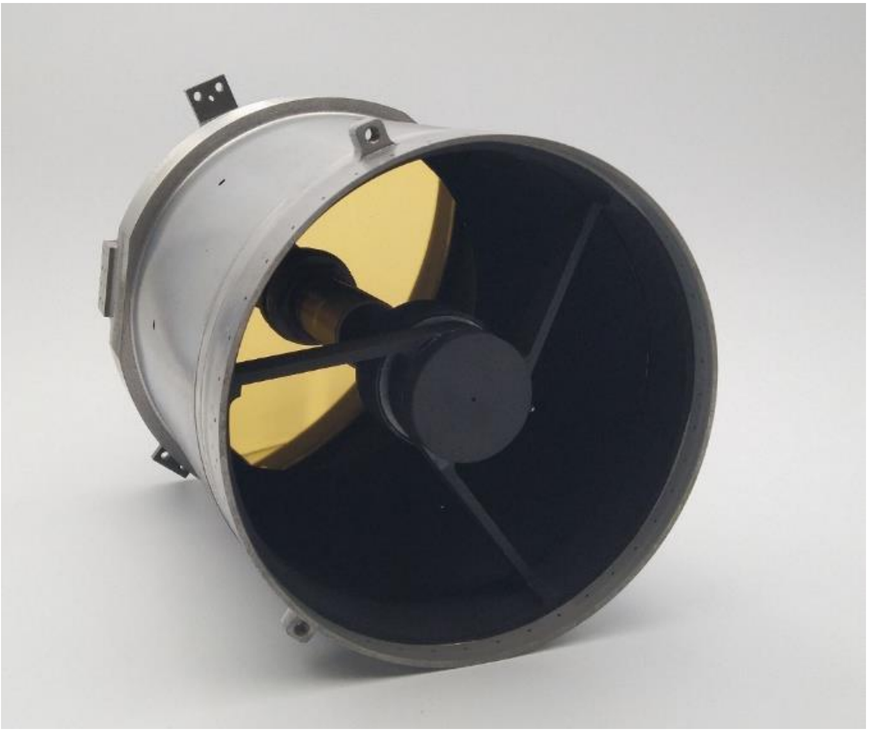
- Very High-Res telescope, 92cm resolution on ground
- Partnering with Thales IT with their NIMBUS platform
- 340 mm low-thermal expansion optics
- Panchromatic channel plus 4 multispectral bands
- 1 sat in 2025 (baseline) + 1 sat option (decision Mar 24)

Contract signed in May 2023 for 1 payload

Option for 2nd payload to be decided in Mar-24

Illustration of the NIMBUS VHR satellite with Media Lario's Optical Payload (credit: Thales Alenia Space)

Repli-formed Optics™ Qualified for Optical Comms



130 mm Opticomm telescope (aperture)

130 mm Opticomm telescope (ocular)

*Telescopes made with **Repli-formed Optics™** can be made in **a few days**!*

‘HERTZ’ Space RF Test Facility Upgrade - ESA

- HERTZ is an RF satellite test facility at ESA
- 2 large RF reflectors to test satellites
- Current facility is performance limited
- New facility will have 20x better accuracy…
- …and 3x larger surface
- ML selected for ALMA & ASTHROS heritage

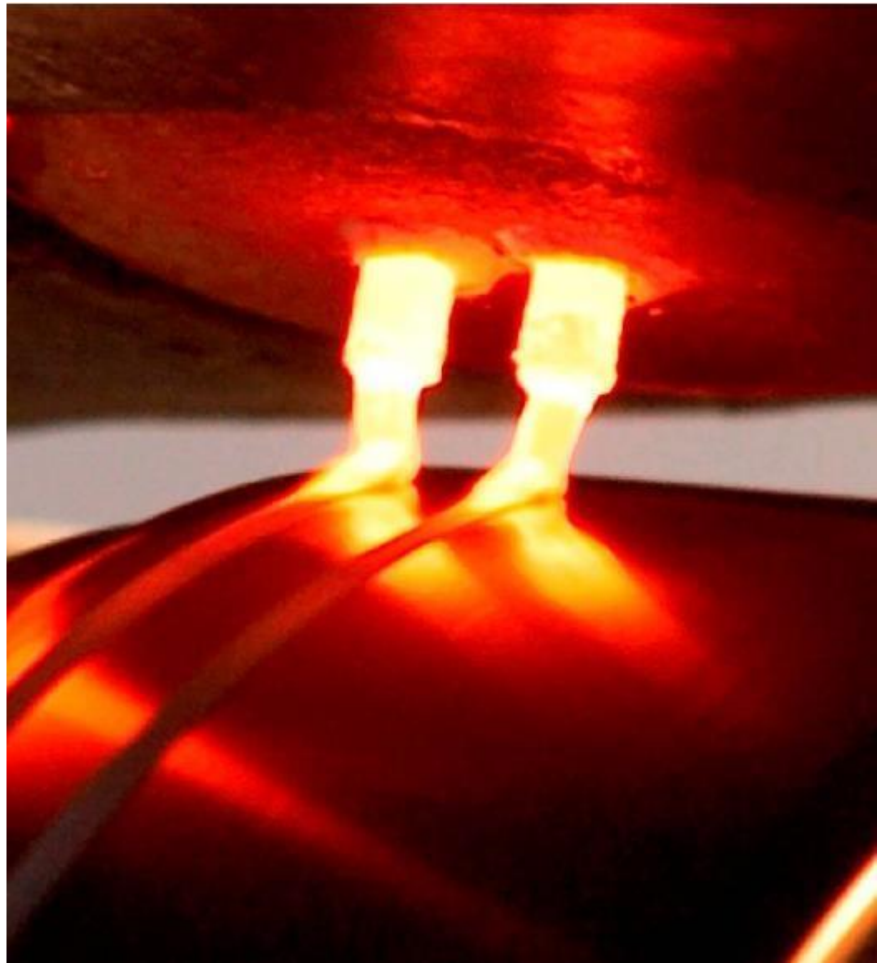
Contract signed in April 2023

See Press Release here

Current HERTZ Facility at ESA ESTEC - Noordwiik, NE

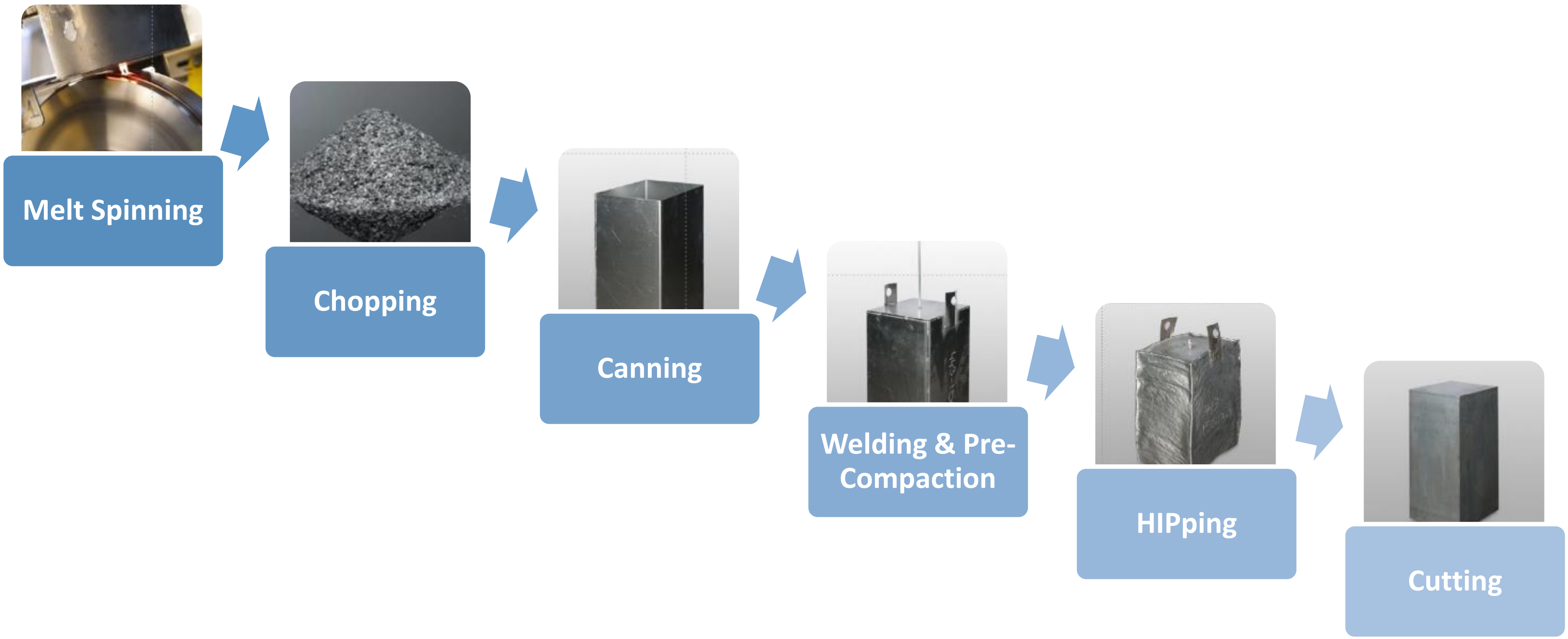
RSP - Company Overview

RSP Technology BV Overview



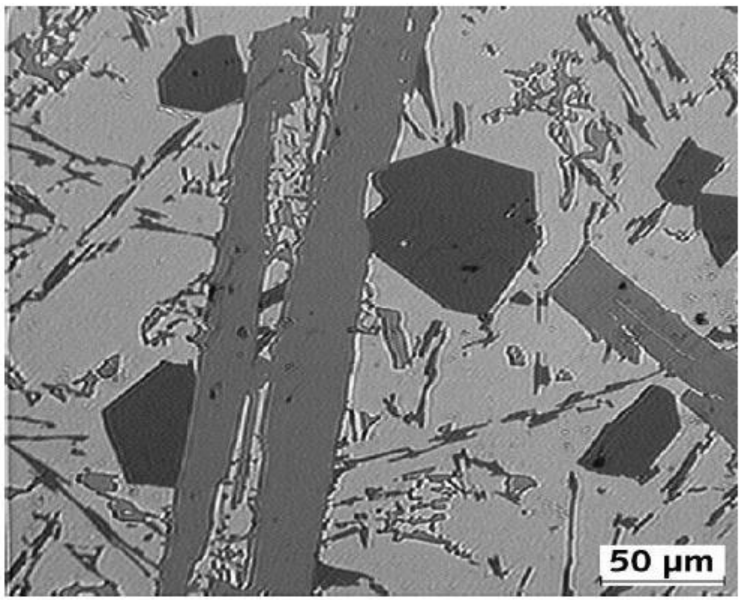
RSP alloys made by Melt Spinning: the enabling technology for tomorrow's solutions, available today.

RSP Technology BV Overview

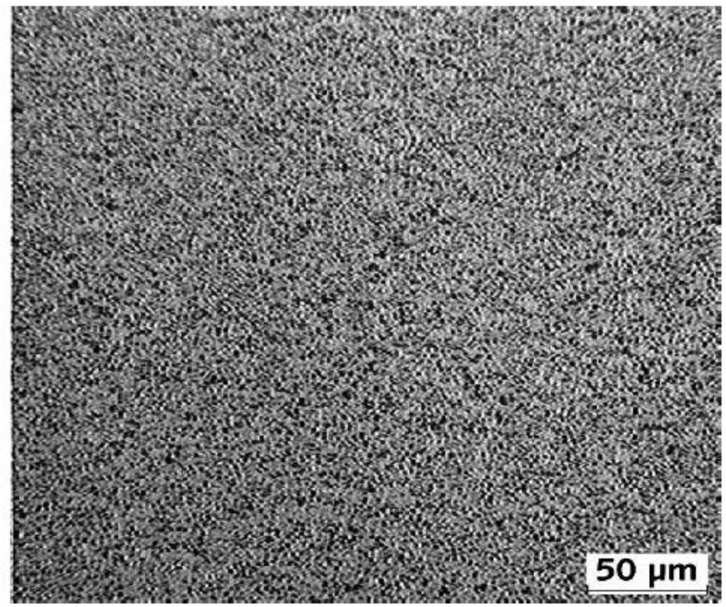


RSP Technology BV Overview

Microstructure: conventional vs Melt Spinning



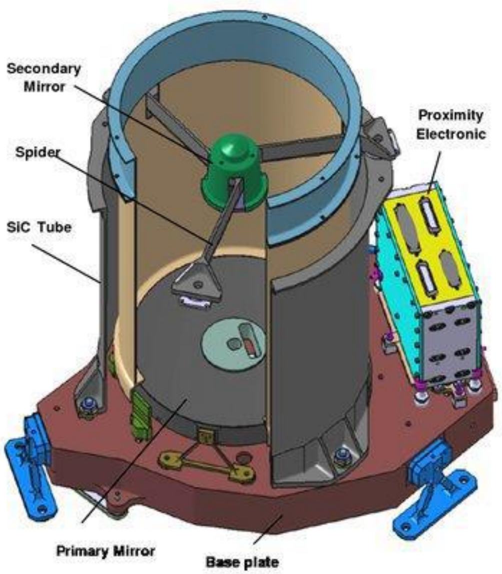
Conventional Microstructure



RSP Microstructure

RSP Technology BV Overview

Satellites frames and mirrors



Customer: Airubs DS
Mission: Instrument line of high-res imagers providing EO data.
Application: Frame, optical bench, mirrors.
Alloy: RSA-443 (replacing SiC)
Status: qualification finalized 2019
Production ramp up 2020

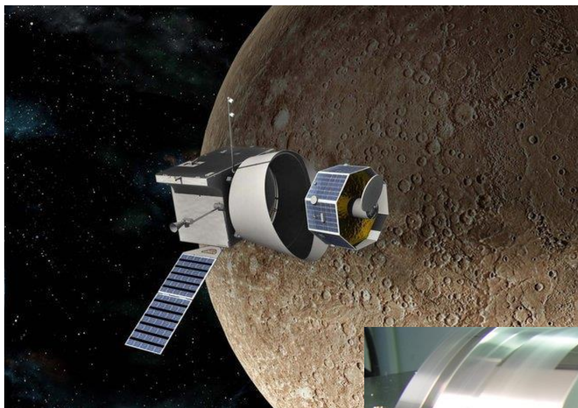
RSP Technology BV Overview

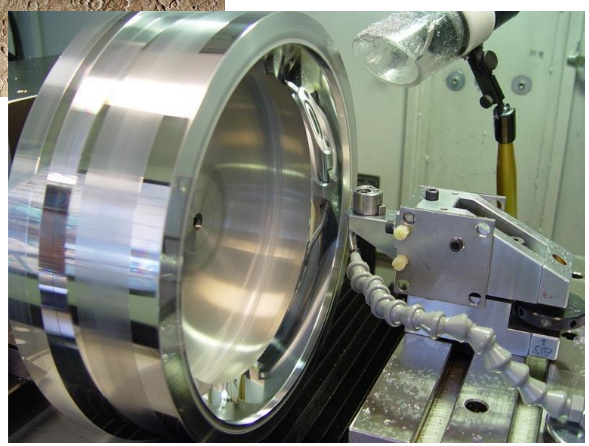
Mirrors and housings for optical communication terminals

Customer: Media Lario
Mission: Lasercom terminal
Application: Mirrors + Housing
Alloy: RSA-443
Status: Serial production 2023

RSP Technology BV Overview

Space mirrors

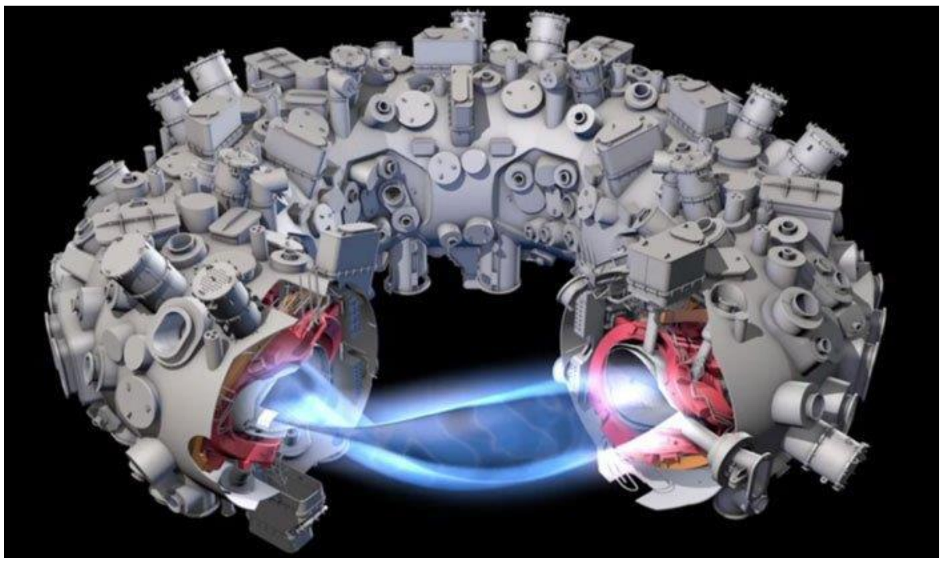




Customer: ESA, TNO
Mission: Bepi Colombo
Application: Light weighted, high accuracy baffle vane and mirrors
Alloy: RSA-6061
Status: Launched October 2018

RSP Technology BV Overview

High temperature camera system



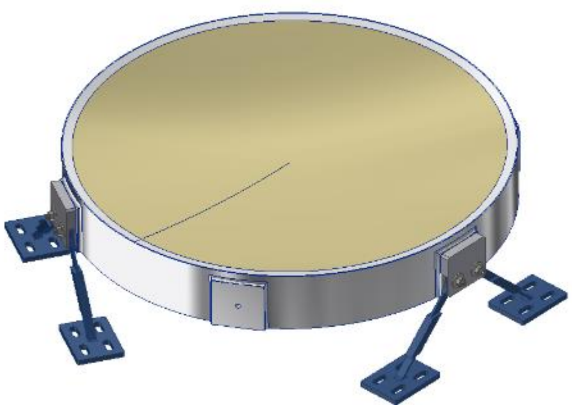
Customer: MPI für Plasmaphysik
Mission: Wendelstein7-X (100M °C)
Application: Mirrors for high temperature camera observing nuclear fusion plasma
Alloy: RSA-905
Status: First mirrors 2019

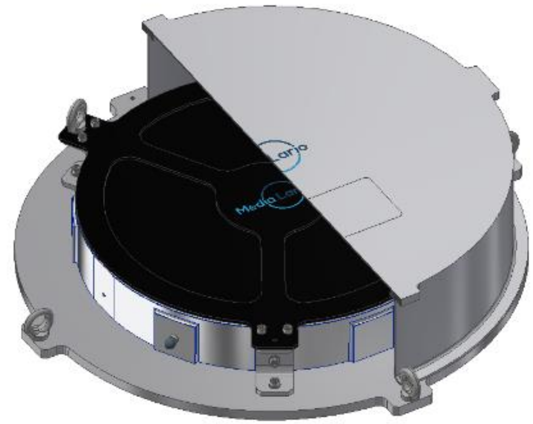
Breadboard Mirror Design

Breadboard Mirror Design Overview

Ref. Doc. DBM-ML-TN-003-Iss.1-Rev.0 - Mirror Design Report

- The DBM design is based on Media Lario heritage on mirror light-weighting approach
- A standard back-pocket design has been chosen to reduce mass down to 60 kg/m2
- An adjustable mount has been adopted to support the mirror during horizontal-axis metrology
- A bipod concept has also been designed to support the mirror
- A dedicated transport container was also designed and manufactured

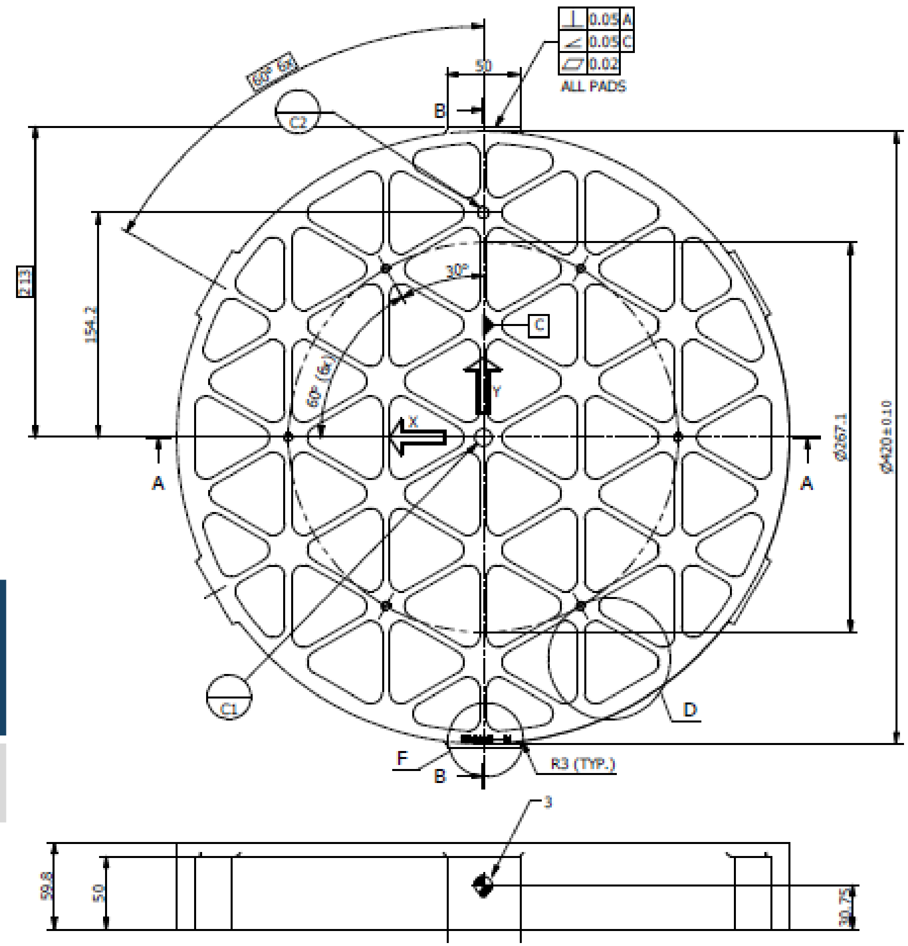




Breadboard Mirror Design

- The DBM mirror is a circular, aspherical, on-axis mirror made in Al-RSP-RSA6061 T6
- Open back triangular lightening pattern has been designed to obtain a light-weighting ratio of 55%
- Final mass is 8.4 kg, corresponding to an areal mass of 60 kg/m2

Volume claim [mm³]	CAD Mass [kg]	Optical surfaces area [m²]	Areal mass [kg/m²]	Mirror mass w/o pockets [kg]	Lightening ratio
Ø420 x 59.8	8.4	0.139	60.4	18.7	55.1%

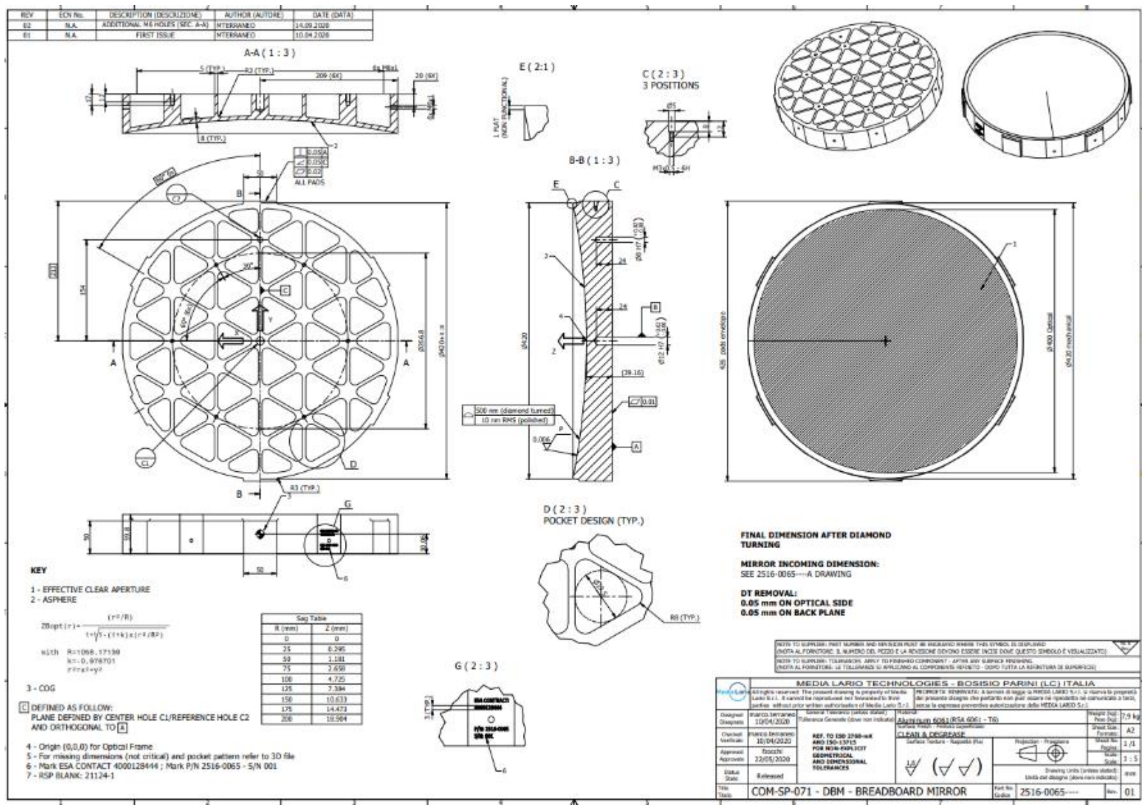


R = 1058.17139
k = 0.976071

Breadboard Mirror Design

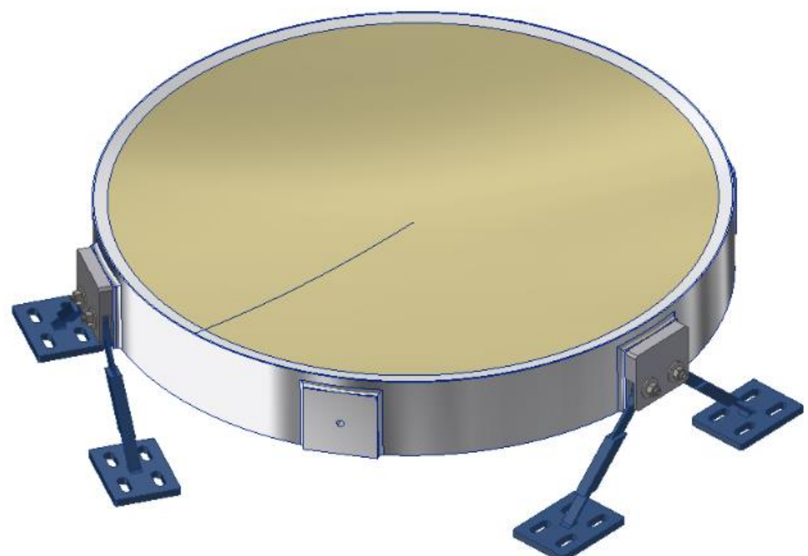
Ref. Doc. DBM-ML-TN-003-Iss.1-Rev.0 - Mirror Design Report

- BB Mirror dimensions: Diameter 430 mm, height 60mm
- Mass: 7,9 Kg



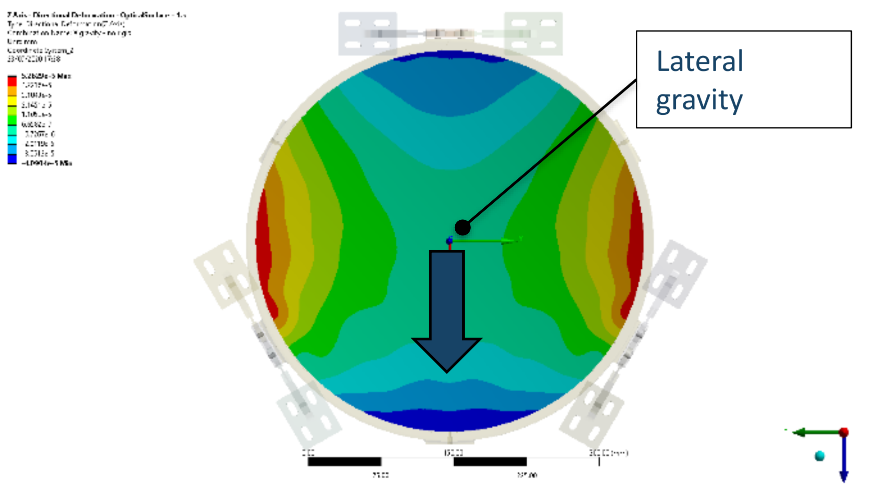
Main support design

- The mirror support is realized by adjustable bipods, glued to the mirror pads.
- The proposed design is optimized for horizontal-axis metrology setup.
- The support system is designed to be:
  - **Adjustable**, in order to search for the neutral fiber position of the mirror, minimizing the gravity deformation RMS of the optical surface
  - **Flexible**, in order to introduce the less stress possible into the mirror while measured.
  - **Low sensitive to planarity** of the base plate and to screwing of the head into the pad, given by the flexures, and low sensitivity to screwing of the bipod heads into the pad.



Main support design FEA

- FEA has been performed to check:
  - Optical surface deformation induced by gravity
  - Optical surface deformations induced by interface planarity errors (2µm)

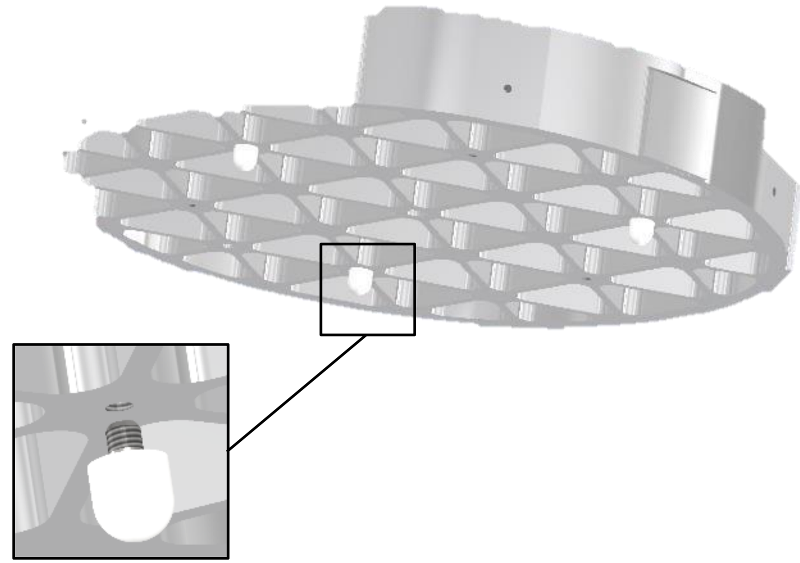


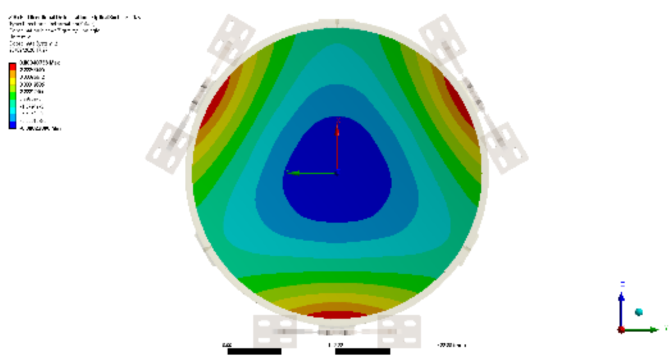
Parameter	Lateral gravity
PTV [nm]	94
RMS [nm]	18.4

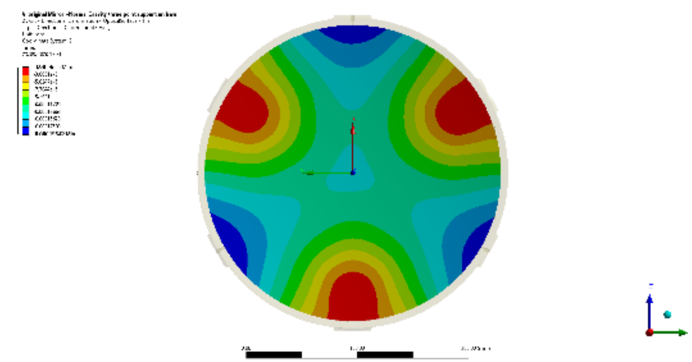
Additional support design and FEA

- An additional support concept has been developed for vertical-axis metrology setup
- Design is based on a three-point support
- FEA shows that this configuration is more effective and induce lower deformations

Parameter	Normal gravity (bipods)	Normal gravity (3-points)
PTV [nm]	637	176
RMS [nm]	140	42



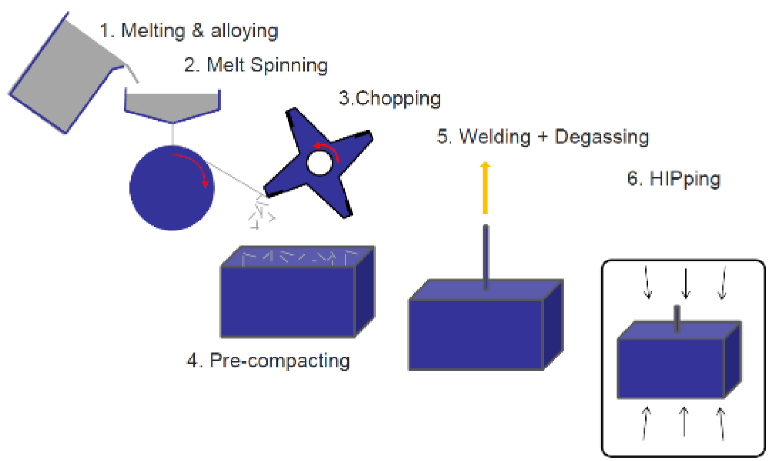




Rapid Solidification Process

RSP Manufacturing Process

- RSP Technology has developed a line of Aluminium alloys produced by rapid solidification process (RSP) providing superior qualities for optical applications, resulting in lower surface roughness, better shape stability, higher strength and low thermal expansion.
- In the RSP process, a melt spun ribbon is chopped in fine grains that are subsequently compacted and solidified in a Hot Isostatic Press (HIP) at a cooling rate of 1,000,000 °C/s, thus "freezing" the liquid alloy in a material with ultra-fine microstructure.
- After HIP, the resulting billets have standard dimensions of 200/300mm in diameter and 500mm in length.



Raw material production process for RSA alloys

RSP Diffusion Bonding Process

- The same process can be used to join raw material segments into a larger substrate. This process is more correctly known as diffusion bonding and is achieved by means of a Hot Isostatic Press.
- The raw material segments are placed into the can
- The empty spaces are filled with selected Aluminium Flakes
- The segments are degassed and bonded by re-HIPping. The result is a diffusion bonded billet

Example of material preparation before re-HIPing

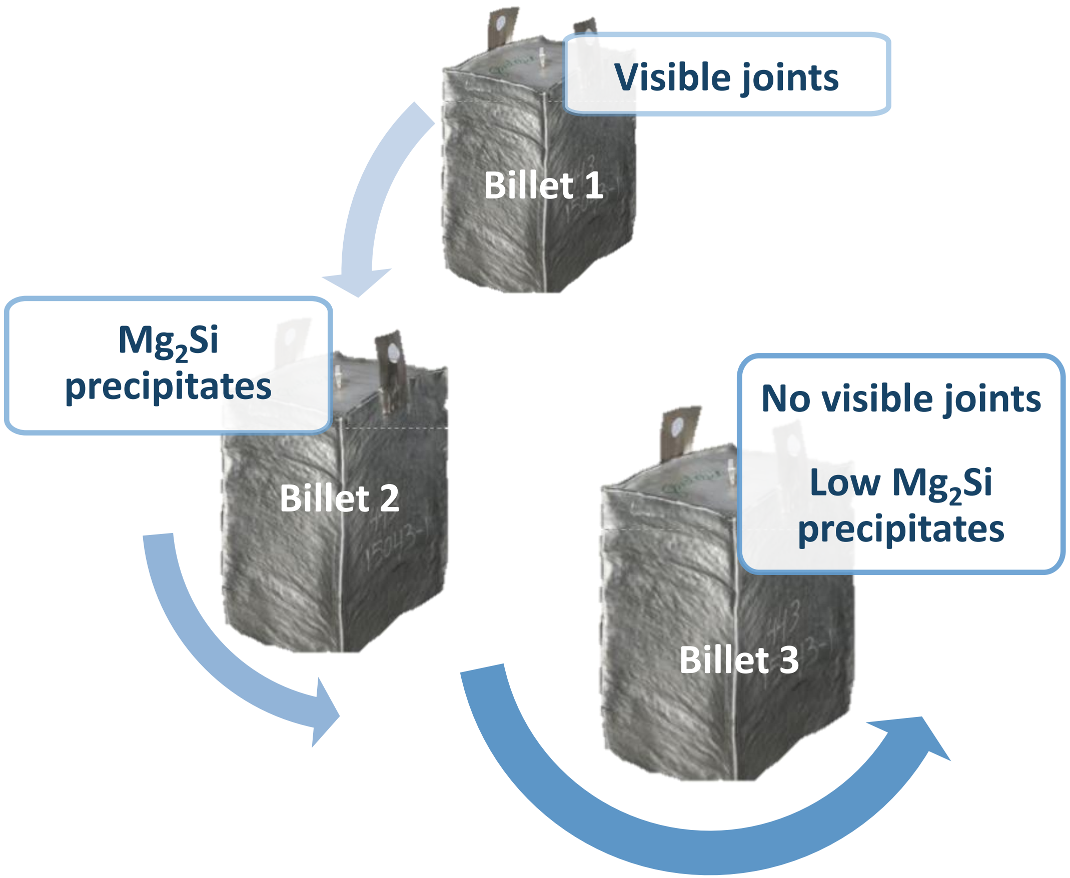
Diffusion Bonding Development

Diffusion Bonding Development

A trade-off for the RSA alloy selection was performed with candidates being Al RSA-6061T6, Al RSA-443, Al RSA-905. Al RSA-6061T6 was selected and 3 billets were produced.

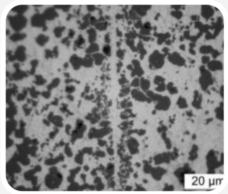
Diffusion Bonding Development

The third billet was accepted: Mg_2Si precipitates were still present, but the joint is not visible by interferometric inspections. This billet was used for the manufacturing the breadboard.



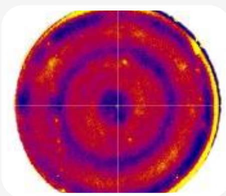
Diffusion Bonding Optimization

Interferometers, optical and Nomarsky microscopes are the best tools to inspect large areas rapidly detecting discontinuities on the polished surfaces and to compare them among samples.



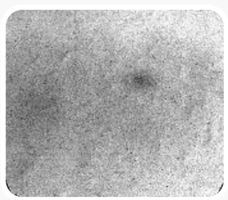
Optical Microscopes

- High magnification
- Finer detail resolution



Interferometers

- Large field of view
- Highest sensitivity for heights



Nomarski Microscopes

- Best to inspect finish and small features
- Mid-range field of views

Diffusion Bonding Optimization

Only materials with an acceptable number of precipitates can be used for joining.

The core parameters that allow controlling the Mg_2Si precipitates in bonded material are:

- ✓ Mg_2Si precipitates and mechanical properties of the base material and flakes
- ✓ Vacuum during re-HIPping: shall be reached at any location in the billet
- ✓ Thickness of the joint: 8 mm
- ✓ Presence in the can of a top and bottom layer of flakes (8 mm each)

Diffusion Bonding Optimization Conclusions

Lessons learned:

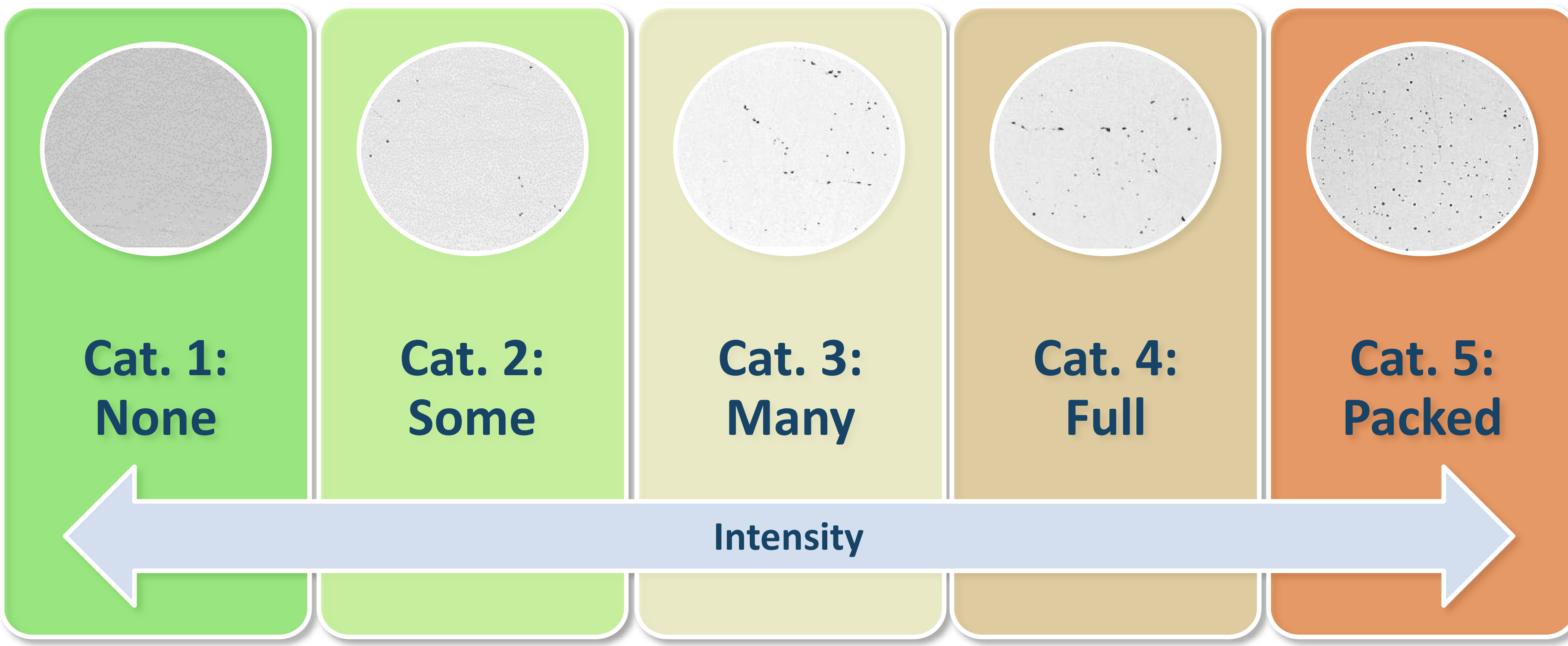
- Al RSA-6061-T6 has precipitates.
- **Start from a base material with precipitates in class 1 (see next slides) to have diffusion bonded substrates free from discontinuities**.
- **Add flakes in the joints of the separate RSA blocks.**

Open point:

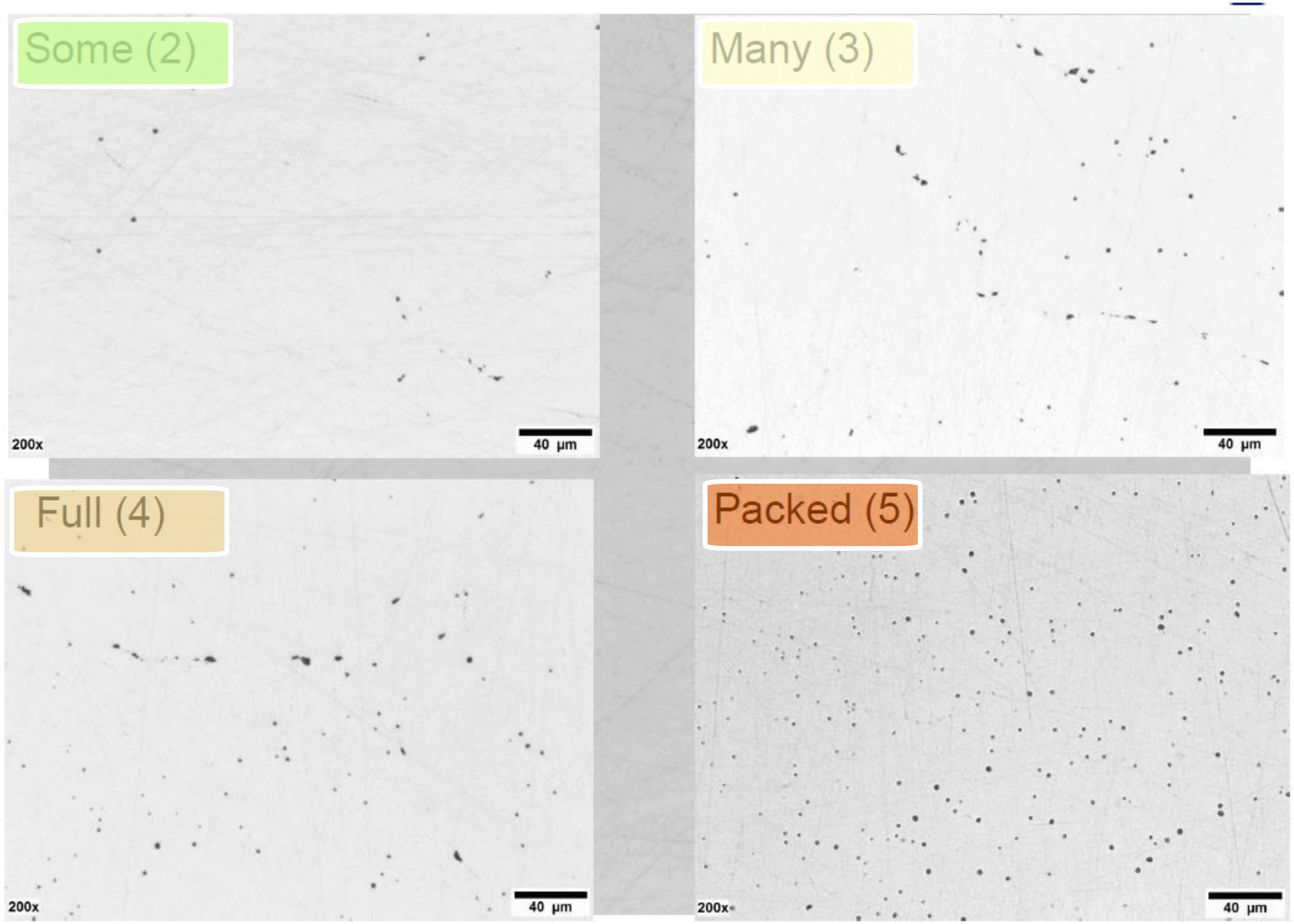
- Improvement of the joining process to minimize the presence of precipitates in the jointed material.

RSP Material Selection

Five categories are identified based on the concentration of precipitates.



RSP Categories Overview



Characterization of the Bonded Material

Summary

- The diffusion bonding process optimized has been used to produce two new diffusion bonded Billets of RSA6061 T6 with the dimensions required for the manufacturing of the BB mirror: Billet-4 Batch 21123-1 and Billet-5 Batch 21124-1.
- The diffusion bonded material has been fully characterized. The results obtained are reported in the Media Lario Presentation “DBM-ML-PRE-007-Iss.1-Rev.0-Diffusion Bonded Mirror DR close-out” annexed to the DR close-out MOM “DBM-ML-MOM-012-Iss.1-Rev.0 - Design Review Close-out MoM_with Annex” and in the Media Lario document “DBM-ML-STR-001 Iss.1 Rev.0 - DBM Specimen Test Report”, deliverable STP
- Micrographs and Mechanical tests performed on Billet-4 Batch 21123-1 have showm that there is a correlation between the concentration of Mg2Si precipitates and the mechanical properties of the bonded material. The results have been confirmed on tests performed on Bilet-5 used for the Mirror Breadboard manufacturing
- The results obtained are reported in the following slides

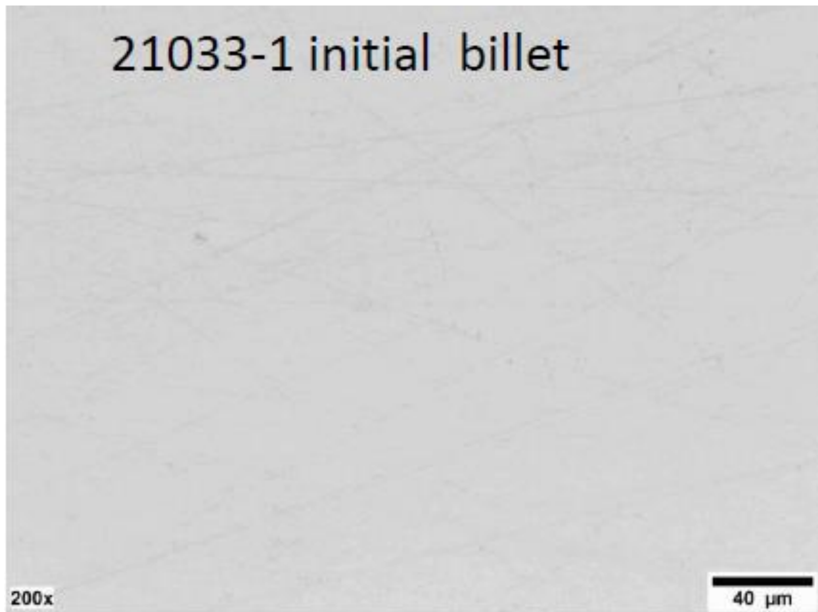
Diffusion Bonded Billet-4 Batch 21123-1

Ref. ANNEX to DBM-ML-MOM-012-Iss.1-Rev.0 - Design Review Close-out MoM_with Annex

- Billet-4 Batch 21123-1 has been used for tensile tests of samples including the joint
- Billet-4 has been derived from the Raw Material RSA-6061T6 Batch 21033-1 and the Aluminum Flakes Batch 22124-2
- Micrographic characterization of the selected raw material and flakes batch performed before bonding: Mg_2Si category for: 1 (No Precipitates)
- 6 blocks of raw material used to produce the diffusion bonded Billet-4 batch 21123-1
- Billet-4 batch 21124-1 size: 450 mm diameter and 70 mm length
- Micrographic characterization of the diffusion bonded Billet-5 batch 21124-1: Mg_2Si category 3 in the bulks and 2 in the joint. The movement from category 1 to category 2 and 3 can be related to multiple cycles of degassing plus HIPping that might impact the presence of precipitates.

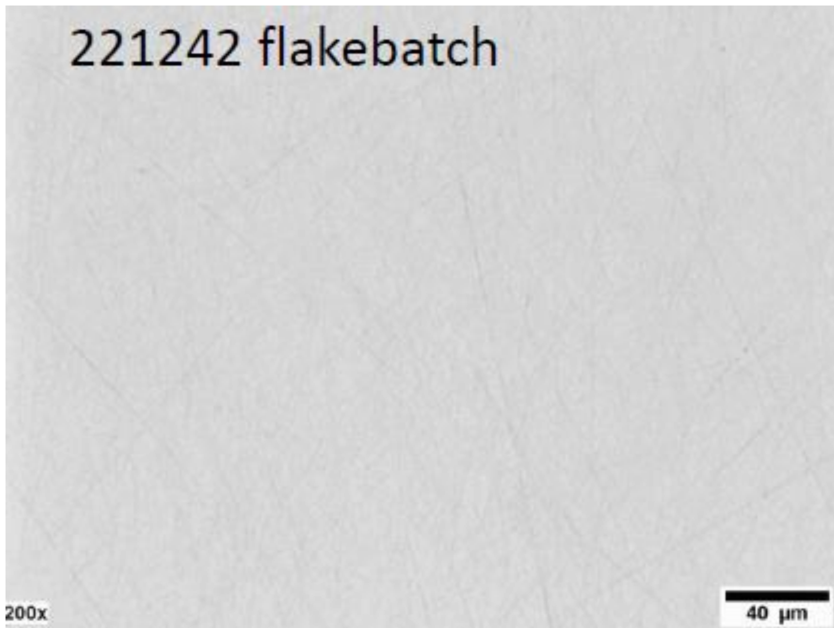
Raw Material 21033-1 Micrographs

- The Mg content is controlled by alloying
- The Mg_2Si Precipitates are checked by optical microscope and chemical analysis by SEM
- Mg_2Si category for Raw Material RSA-6061T6 Batch 21034-1 : 1 (No Precipitates)



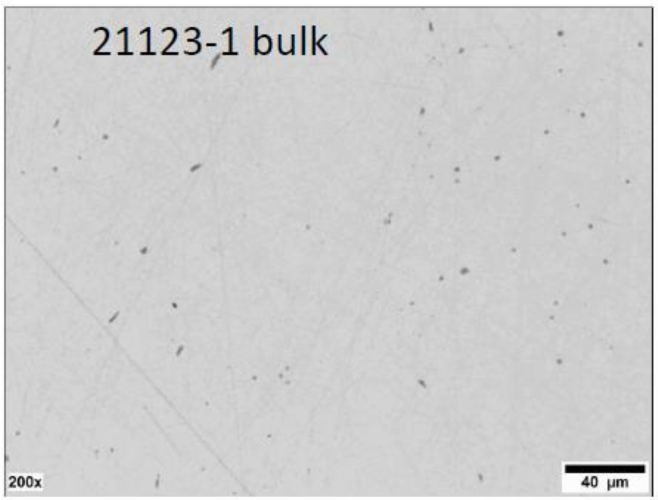
Aluminium Flakes Batch 22124-2 Properties

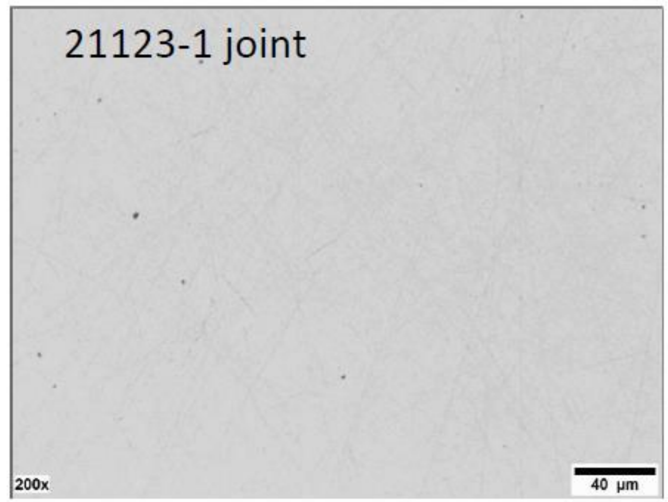
- The Mg content is controlled by alloying
- The Mg_2Si Precipitates are checked by optical microscope and chemical analysis by SEM
- Mg_2Si category for Aluminium Flakes Batch 221242: 1 (No Precipitates)



Billet-4 Batch 21123-1 Micrographs

- Mg_2Si category for matrix of re-HIPped billet RSA-6061T6 Batch 21123-1: 3
- Mg_2Si category for joint of re-HIPped billet RSA-6061T6 Batch 21123-1: 2
- Joints Undetectable (vertical in the micrographs)





Raw Material Batch 21033-1 Tensile Results

- 29/07/2022: Data from DBM-ML-PRE-007-Iss.1-Rev.0-Diffusion Bonded Mirror DR close-out
- Raw Material RSA-6061T6 Batch 21033-1 mechanical properties (average of three samples)

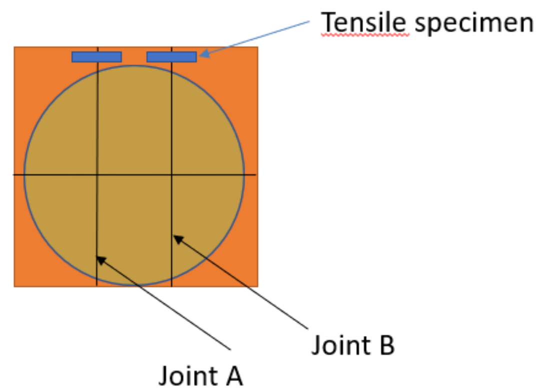
UTS	YS	e	Batch
359	326	10,8%	21033-1

- Mechanical properties in compliance with the specifications of the aluminium 6061T6
- Raw material 21033-1 used for the production of the re-HIPped Billet-4 Batch 21023-1

Billet-4 Batch 21123-1 Tensile Results: 1st campaign

- 29/07/2022: Data from DBM-ML-PRE-007-Iss.1-Rev.0-Diffusion Bonded Mirror DR close-out
- Billet-4 Batch 21123-1 for testing mechanical properties (average of three samples): First Campaign

UTS	YS	e	Batch
299	292	0,8%	21123-1 Joint A
297	288	1,7%	21123-1 Joint B

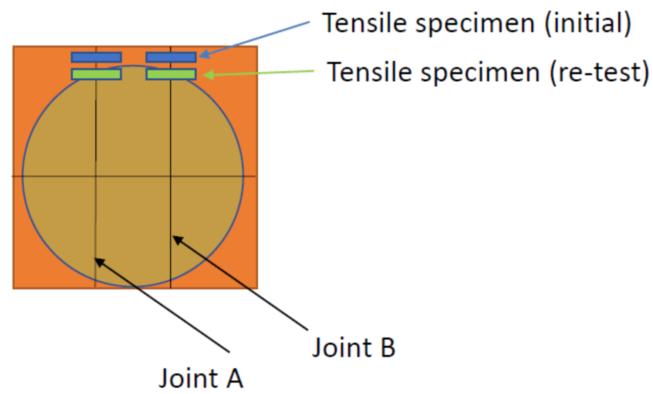


- Samples derived from the edge, joint included
- The brittle behaviour (low elongation) can be related to edge effects: test specimens derived outside the disk of 450 mm diameter
- Additional tensile tests performed with samples including the joint and derived from the disk of 450 mm performed in a second campaign

Billet-4 Batch 21123-1 Tensile Results: 2nd campaign

- Billet-4 Batch 21123-1 for testing mechanical properties (average of three samples): Second Campaign

UTS	YS	e	Batch
287	276	1,8%	21123-1 Joint A
278	271	1,7%	21123-1 Joint B



- Samples derived from the disk of 450 mm, 20mm from the edge, joint included
- The brittle behaviour (low elongation) can be related to the joint. Additional contribution from edge effects can not be excluded.
- Results are consistent with the ones obtained during the first campaign and are representative of the properties of the material
- The process for deriving the specimens has been destructive and required to sacrifice a large portion of the billet. Consequently, Billet-4 Batch 21123-1 will no longer be a possible back up for the manufacturing of the BB mirror

Billet-4 Batch 21123-1 Tensile Results: 3rd campaign

- 13/10/2022: Data provided by RSP
- Billet-4 Batch 21123-1 for testing mechanical properties (average of three samples): third Campaign on samples from the bulk

UTS	YS	e	Batch	Date of Test
330	274	4,2%	21123-1 Bulk	13/10/2022
359	326	10,8%	Raw material 21033-1	29/07/2022 (from slide 11)

- Samples derived from the d the disk of 450 mm outside the joint area (sketch with the position of the samples to be provided by RSP)
- Lower reduction of elongation with respect to the parent Raw Material RSA-6061T6 Batch 21033-1 confirmed
- UTS level from parent Raw Material RSA-6061T6 Batch 21033-1 slightly decreased
- YS level from parent Raw Material RSA-6061T6 Batch 21033-1 decreased as in the areas with the joint

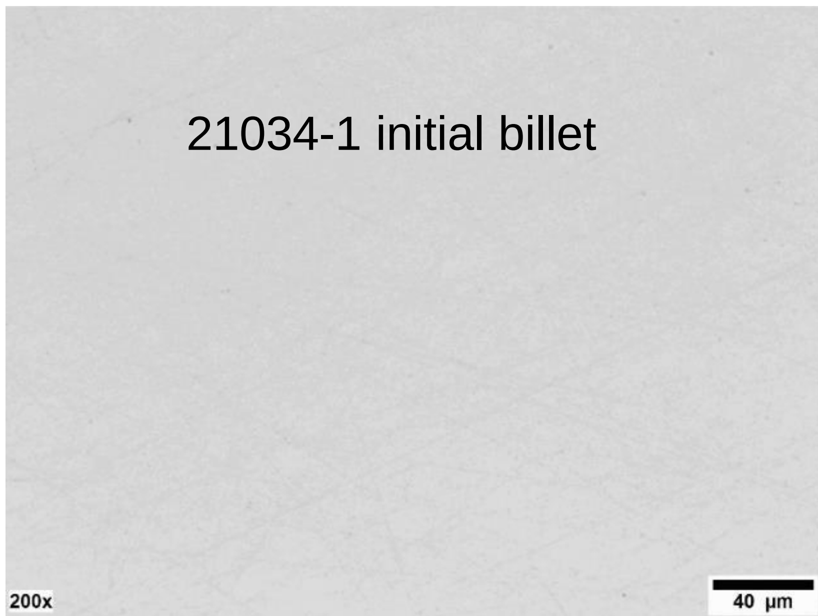
Diffusion Bonded Billet-5 Batch 21124-1

Ref. ANNEX to DBM-ML-MOM-012-Iss.1-Rev.0 - Design Review Close-out MoM_with Annex

- Billet-5 Batch 21124-1 has been used for the Mirror Breadboard manufacturing
- Billet-5 has been derived from the Raw Material RSA-6061T6 Batch 21034-1 and the Aluminum Flakes Batch 22124-2
- Micrographic characterization of the selected raw material and flakes batch performed before bonding: Mg_2Si category for: 1 (No Precipitates)
- 6 blocks of raw material used to produce the diffusion bonded Billet-5 batch 21124-1
- Billet-5 batch 21124-1 size: 450 mm diameter and 70 mm length
- Micrographic characterization of the diffusion bonded Billet-5 batch 21124-1: Mg_2Si category 4 (Full of Precipitates). The movement from category 1 to category 4 can be related to multiple cycles of degassing plus HIPping that might impact the presence of precipitates.

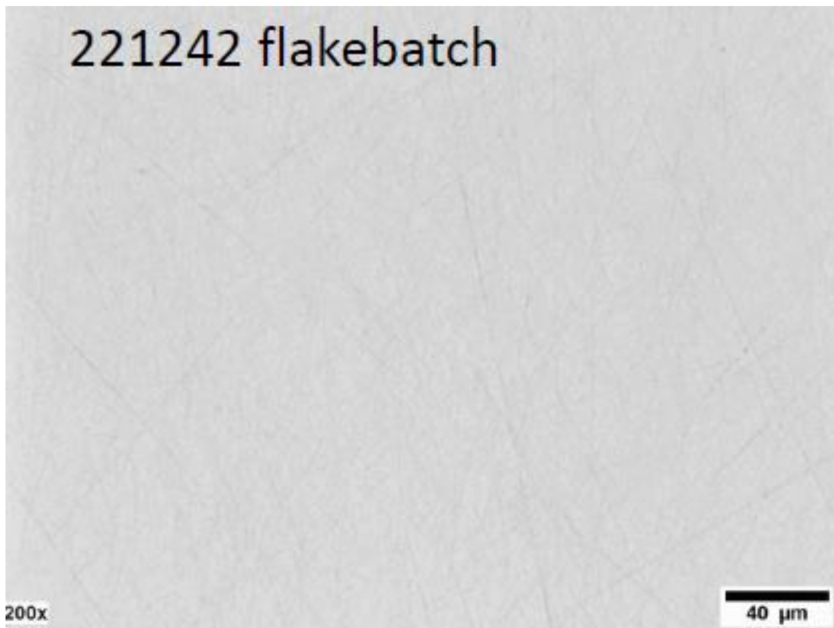
Raw Material 21034-1 Micrographs

- The Mg content is controlled by alloying
- The Mg_2Si Precipitates are checked by optical microscope and chemical analysis by SEM
- Mg_2Si category for Raw Material RSA-6061T6 Batch 21034-1 : 1 (No Precipitates)



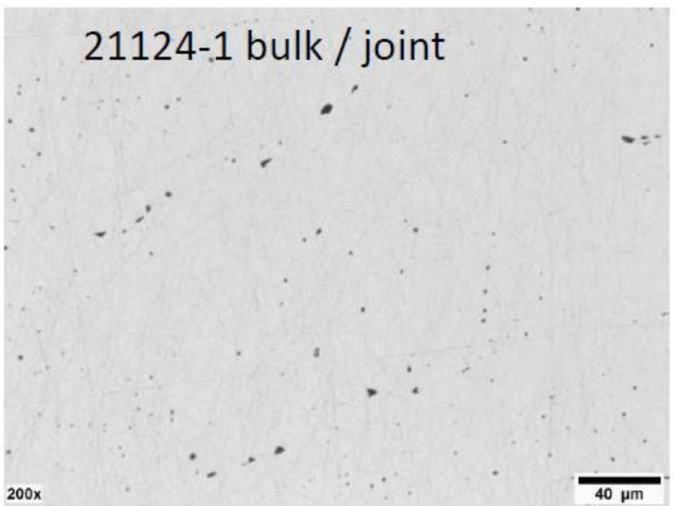
Aluminium Flakes Batch 22124-2 Properties

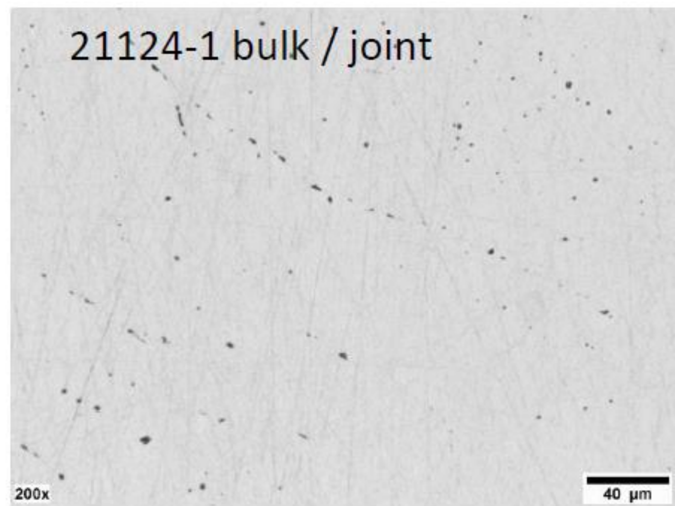
- The Mg content is controlled by alloying
- The Mg_2Si Precipitates are checked by optical microscope and chemical analysis by SEM
- Mg_2Si category for Aluminium Flakes Batch 221242: 1 (No Precipitates)



Billet-5 Batch 21124-1 Micrographs

- Mg_2Si category for matrix of re-HIPped billet RSA-6061T6 Batch 21124-1: 4
- Mg_2Si category for joint of re-HIPped billet RSA-6061T6 Batch 21124-1: 4
- Joints Undetectable (vertical in the micrographs)
- Category 4 is on the edge, impact to be evaluated by BB mirror manufacturing.





Raw Material Batch 21034-1 Tensile Results

- Raw Material RSA-6061T6 Batch 21034-1 mechanical properties (average of three samples

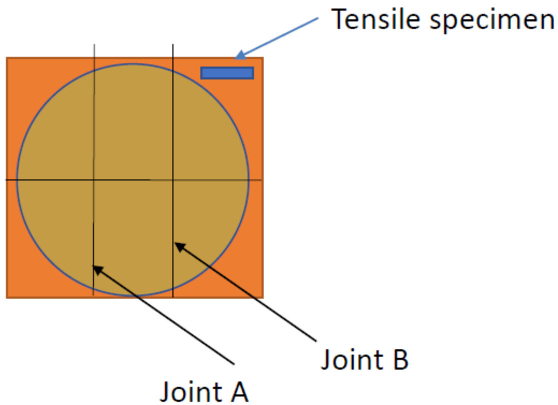
UTS	YS	e	Batch
358	334	8,3%	21034-1

- Mechanical properties in compliance with the specifications of the aluminium 6061T6
- Raw material 21034-1 used for the production of the re-HIPped Billet-5 Batch 21024-1

Billet-5 Batch 21124-1 Tensile Results

- 29/07/2022: Data from DBM-ML-PRE-007-Iss.1-Rev.0-Diffusion Bonded Mirror DR close-out
- Billet-5 Batch 21124-1 for the manufacturing of the BB Mirror mechanical properties (average of three samples

UTS	YS	e	Batch
349	323	4,9%	21124-1 Bulk



- Samples derived from the corners of the square billet in order to not destroy the billet, joint not included
- Billet-5 Batch 21124-1 produced by RSP for the manufacturing of the BB Mirror

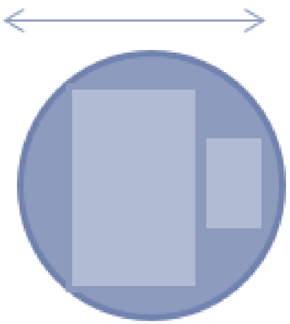
Tensile Results of the Bulks Summary

UTS	YS	e	Batch	Date of Test
359	326	10,8%	Raw material 21033-1	29/07/2022
330	274	4,2%	Billet-4 21123-1 Bulk	13/10/2022
358	334	8,3%	Raw material 21034-1	29/07/2022
349	323	4,9%	Billet-5 21124-1 Bulk	29/07/2022

Diffusion Bonded Billet-4 and Billet-5 Manufacturing

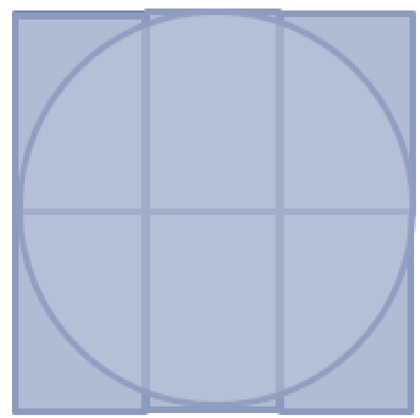
Standard available billets 2x:
Diameter 300mm
2* (6 slices L= 80 mm)

Billet nrs:
21033-1
21034-1



2* (6 blocks 230 x 153 x L80mm)

Flakes for the joints
Batch nr: 221242



2* billets
460 x 460 x 80 mm

Machined to (waterjet)
1 substrate / each:
D450 mm L70 mm

Batch nrs:
21123-1
21124-1

2 x can: 484 x 491 x 96mm

Billet-4 and Billet-5 Before Cutting

The billets before cutting

Billet-4 After Cutting

The billet after cutting

Billet-5 After Cutting

The billet after cutting

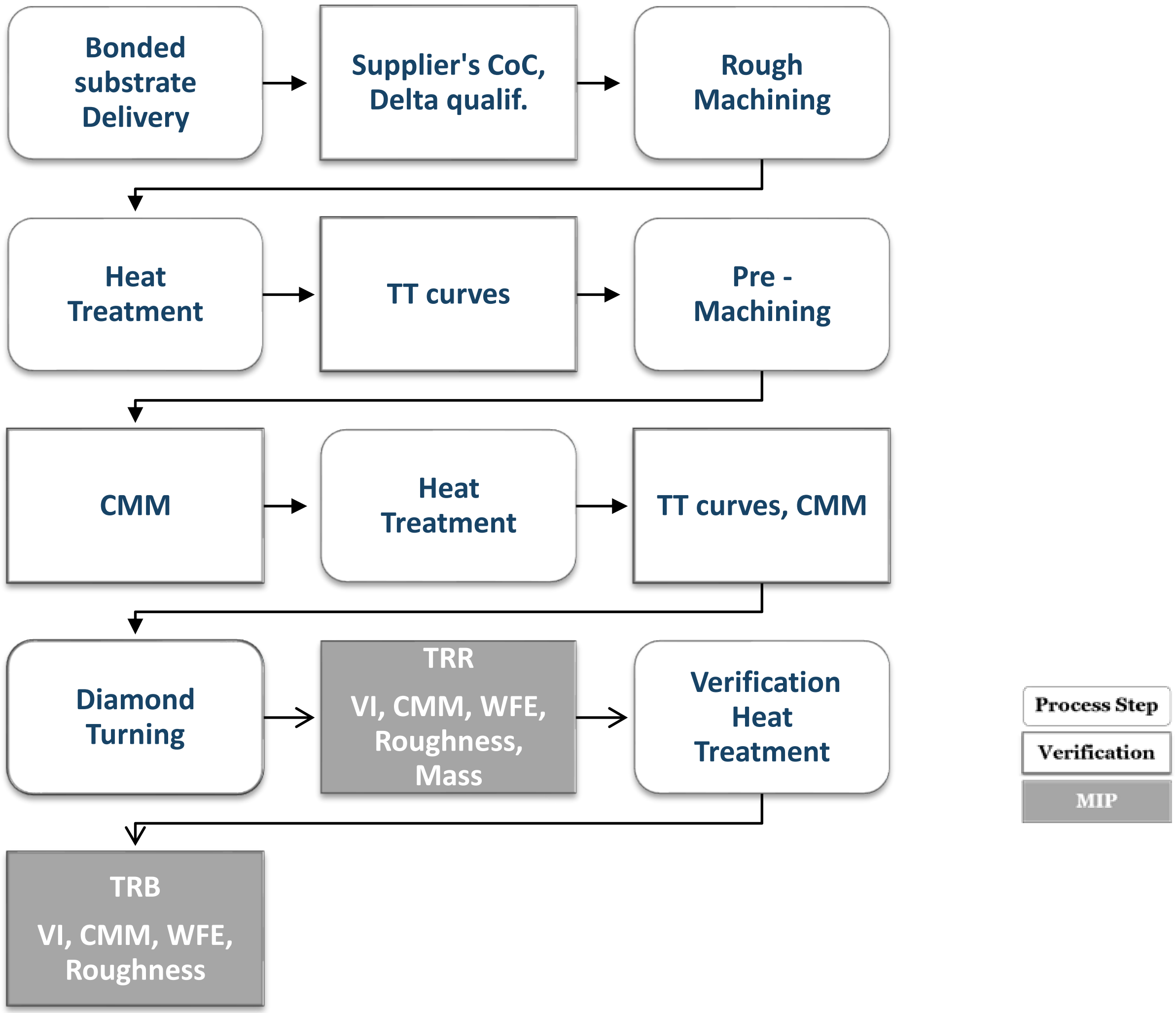
Conclusions

- CTE, density, hardness and mechanical stiffness of the diffusion bonded material are in compliance with the specifications, both in the bulk and joint areas.
- For both the diffusion bonded Bilet-4 Batch 21123-1 and Billet-5 Batch 21124-1 no porosities or discontinuities have been observed and the Joint is not visible.
- Micrographs have shown that multiple cycles of degassing plus Hipping have an impact on the presence of the Mg2Si precipitates, leading to an increase of the precipitates.
- In turn, the increase of the Mg2Si precipitates has an impact on the mechanical properties, as it results in a decreasing of the elongation and a decreasing also of the strength in the joint area. The effects of these variations will have to be evaluated during the manufacturing of the BB Mirror.

Manufacturing of the Breadboard Mirror

Manufacturing Flow for the Mirror Breadboard

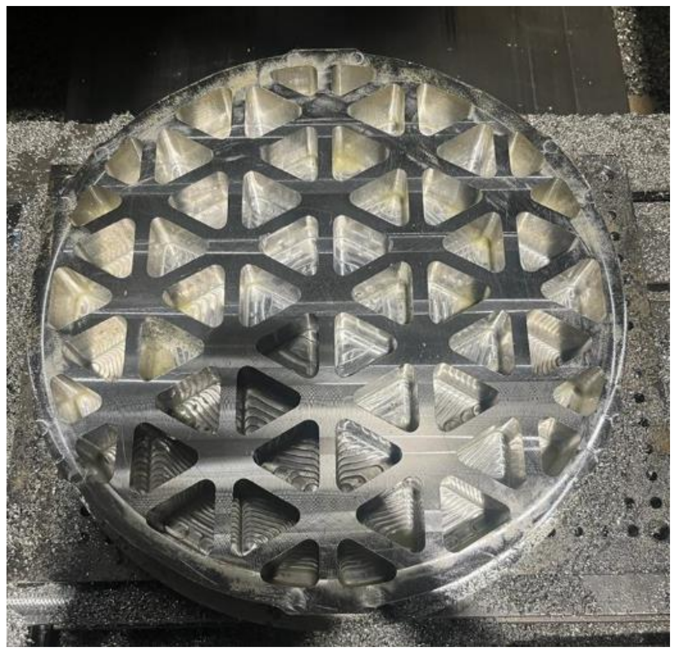
Ref. Doc. DBM-ML-TP2-001-Iss.2-Rev.0 - Test plan for mirror breadboard



BB Mirror Manufacturing

Ref. Doc. DBM-ML-TN-004-Iss.1-Rev.0 - Preliminary Test Report

Rough machining was performed leaving extra material to reduce manufacturing stresses



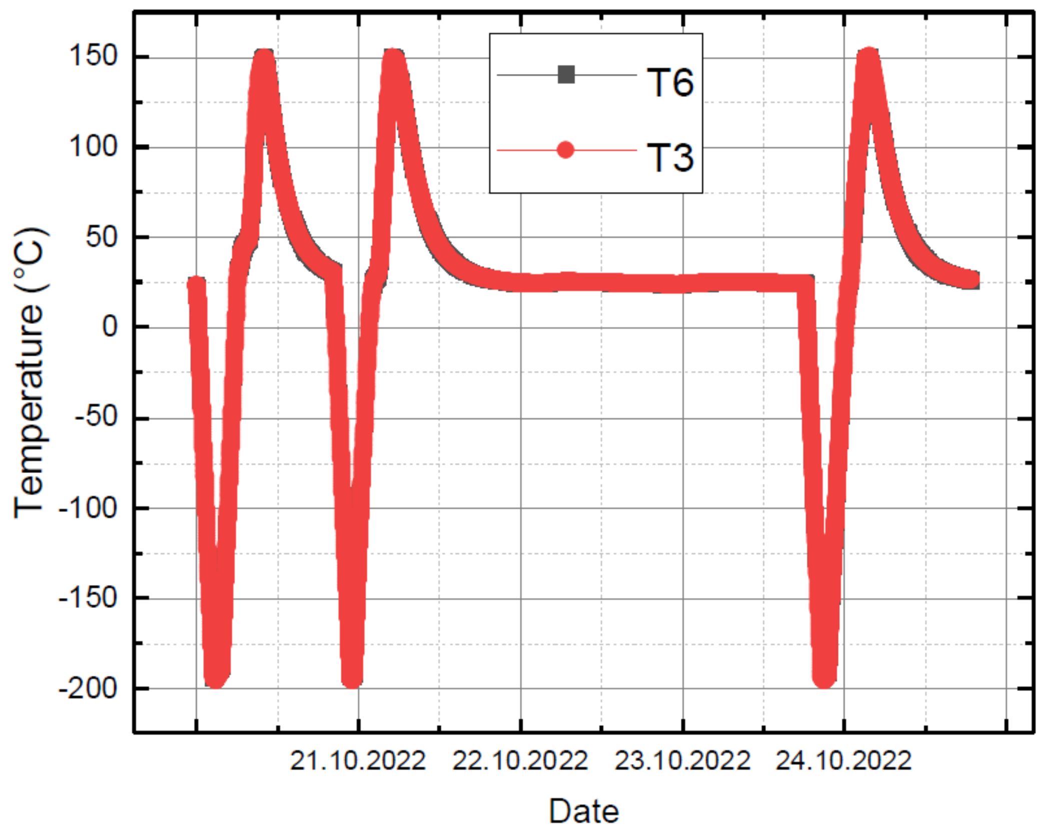
BB Mirror during rough-machining

BB Mirror Manufacturing

Visual Inspection after rough machining

BB Mirror Manufacturing

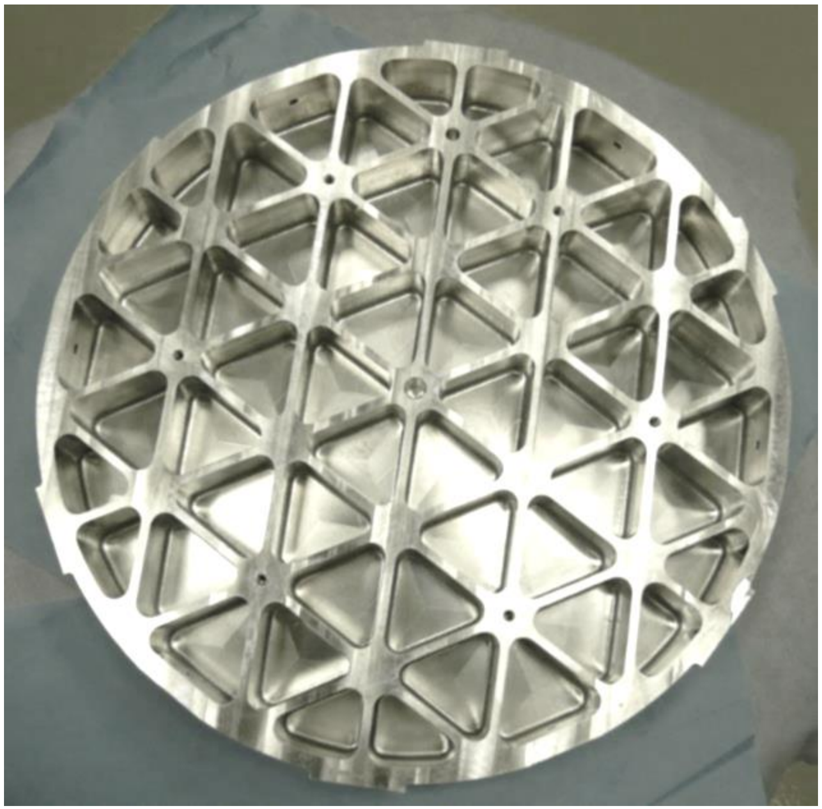
The first Heat Treatment was performed after rough machining

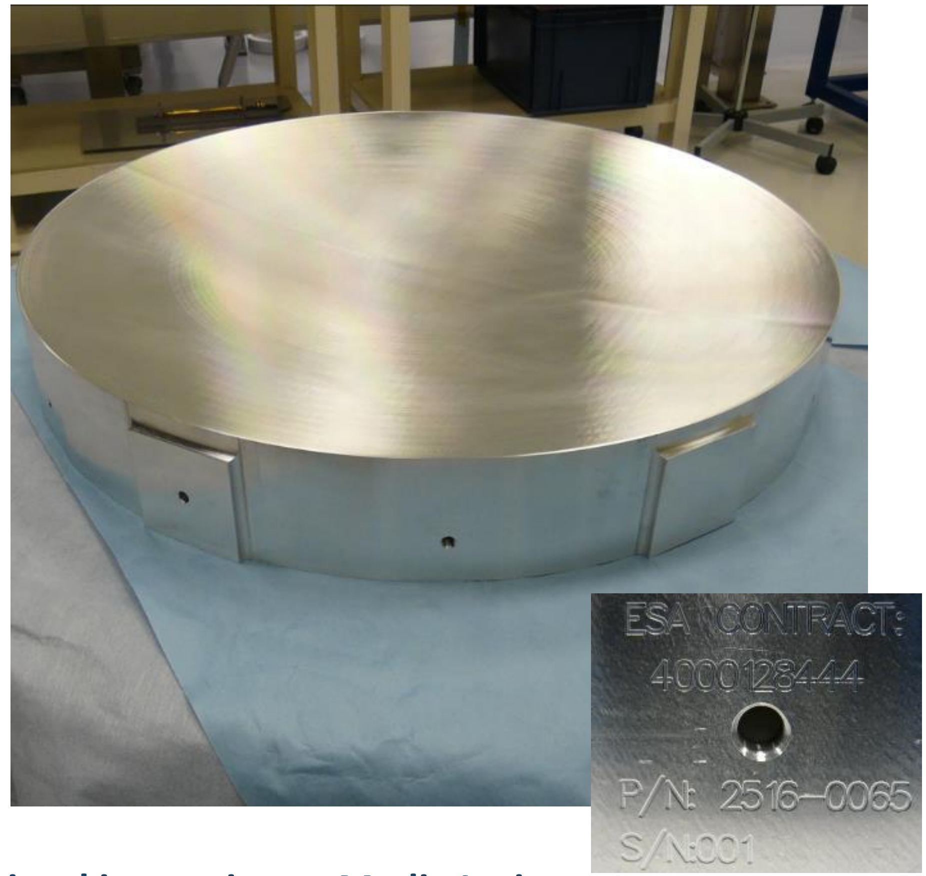


TT curves of the first heat treatment

BB Mirror Manufacturing

With the pre-machining phase the substrate was led to mechanical specs

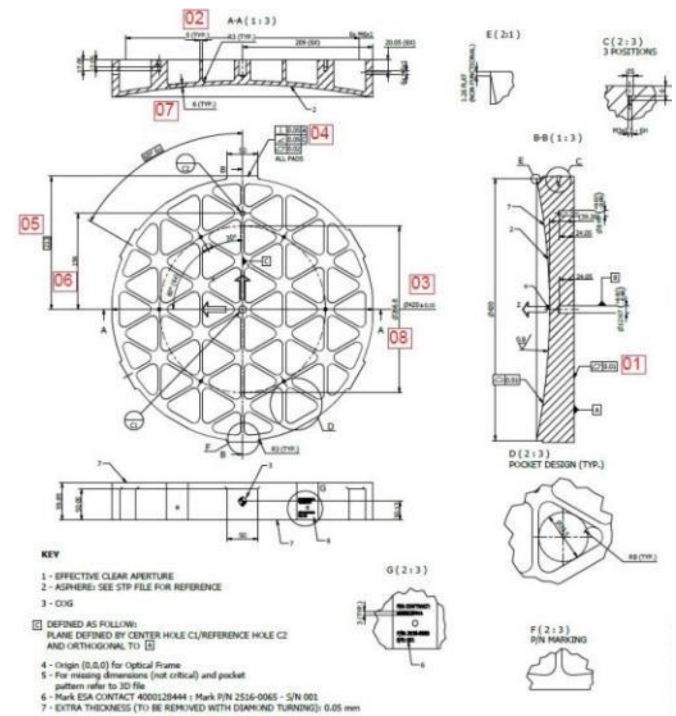




BB Mirror after Pre-machining during visual inspection at Media Lario

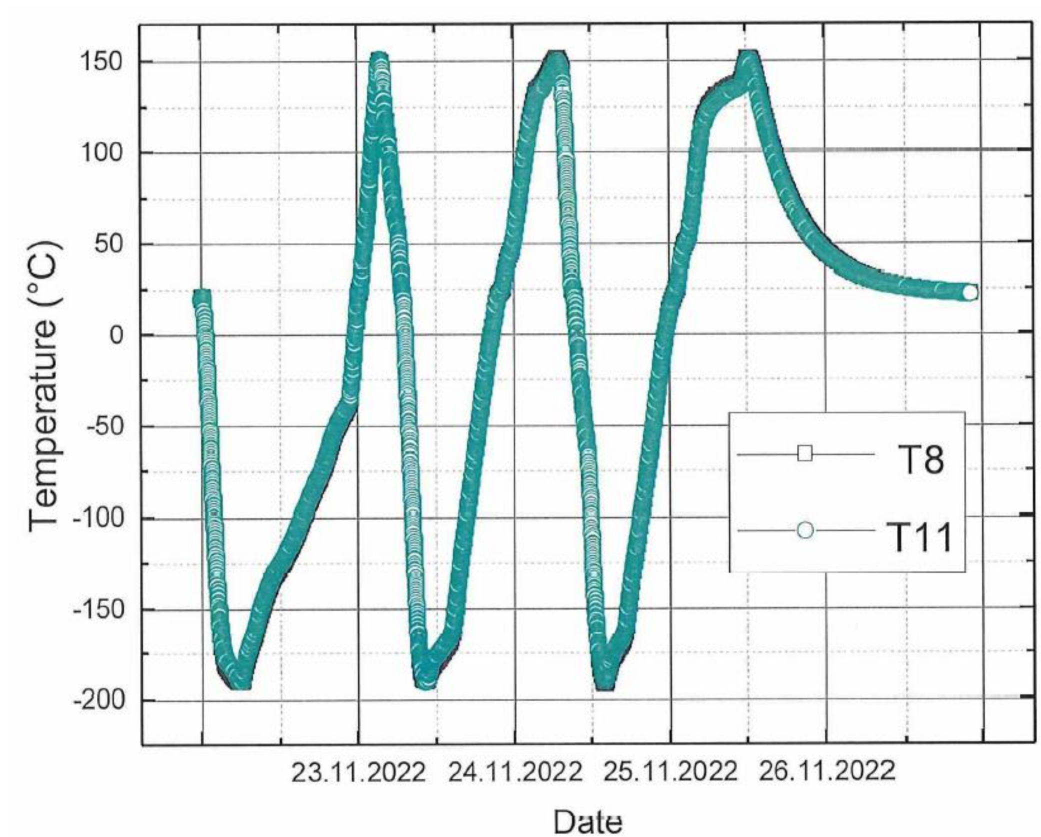
BB Mirror Manufacturing

Characteristic	Actual	Nominal	Upper Tol	Lower Tol	Deviation	
01. Flatness A 0.01	0.023	0.000	0.010	0.000	0.023	Recoverable via SPDT
02. Rib1_5 ±0.1	5.001	5.000	0.100	-0.100	0.001	
02. Rib2_5 ±0.1	4.961	5.000	0.050	-0.050	-0.039	
02. Rib3_5 ±0.1	4.992	5.000	0.050	-0.050	-0.008	
02. Rib4_5 ±0.1	4.995	5.000	0.050	-0.050	-0.005	
02. Rib5_5 ±0.1	5.006	5.000	0.050	-0.050	0.006	
02. Rib6_5 ±0.1	4.989	5.000	0.050	-0.050	-0.012	
02. Rib7_5 ±0.1	5.011	5.000	0.050	-0.050	0.011	
02. Rib8_5 ±0.1	5.011	5.000	0.050	-0.050	0.011	
03. D420 ±0.1	420.015	420.000	0.100	-0.100	0.015	
04. Perpendicularity 0.05 A_Y+	0.007	0.000	0.050	0.000	0.007	
04. Inclination 0.05_C Y+	0.056	0.000	0.050	0.000	0.056	Recoverable via SPDT
04. Flatness 0.02 Y+	0.001	0.000	0.020	0.000	0.001	
04. Perpendicularity 0.05 A_X-Y+	0.006	0.000	0.050	0.000	0.006	
04. Inclination 0.05_C X-Y+	0.049	0.000	0.050	0.000	0.049	
04. Flatness 0.02 X-Y+	0.002	0.000	0.020	0.000	0.002	
04. Perpendicularity 0.05 A_X-Y-	0.004	0.000	0.050	0.000	0.004	
04. Inclination 0.05_C X-Y-	0.052	0.000	0.050	0.000	0.052	Recoverable via SPDT
04. Flatness 0.02 X-Y-	0.002	0.000	0.020	0.000	0.002	
04. Perpendicularity 0.05 A_Y-	0.009	0.000	0.050	0.000	0.009	
04. Inclination 0.05_C Y-	0.050	0.000	0.050	0.000	0.050	Recoverable via SPDT
04. Flatness 0.02 Y-	0.001	0.000	0.020	0.000	0.001	
04. Perpendicularity 0.05 A_X+Y-	0.003	0.000	0.050	0.000	0.003	
04. Inclination 0.05_C X+Y-	0.050	0.000	0.050	0.000	0.050	Recoverable via SPDT
04. Flatness 0.02 X+Y-	0.000	0.000	0.020	0.000	0.000	
04. Perpendicularity 0.05 A_X+Y+	0.007	0.000	0.050	0.000	0.007	
04. Inclination 0.05_C X+Y+	0.046	0.000	0.050	0.000	0.046	
04. Flatness 0.02 X+Y+	0.002	0.000	0.020	0.000	0.002	
05. Measure 213 Y+	212.947	213.000	0.500	-0.500	-0.053	
05. Measure 213 X-Y+	213.004	213.000	0.500	-0.500	0.004	
05. Measure 213 X-Y-	213.053	213.000	0.500	-0.500	0.053	
05. Measure 213 Y-	213.088	213.000	0.500	-0.500	0.088	
05. Measure 213 X+Y-	213.031	213.000	0.500	-0.500	0.031	
05. Measure 213 X+Y+	212.945	213.000	0.500	-0.500	-0.055	
06. Coord 154 D8	154.038	154.000	0.500	-0.500	0.038	
07. Optical Thickness 6_1	6.076	6.000	0.100	-0.100	0.076	
08. D226.8	266.918	266.800	0.500	-0.500	0.118	



BB Mirror Manufacturing

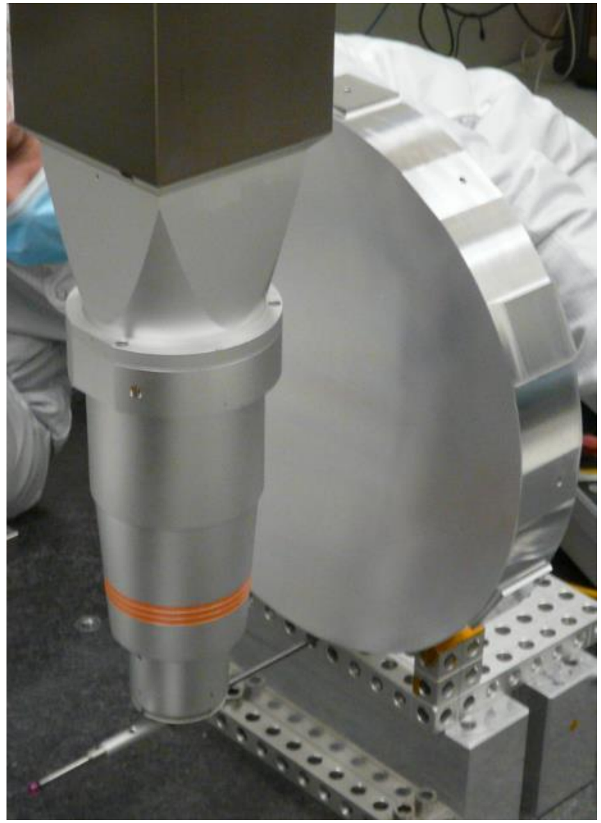
An additional Heat Treatment was performed to stabilize the substrate releasing all internal stresses potentially left by machining



TT curves of the second heat treatment

BB Mirror Manufacturing

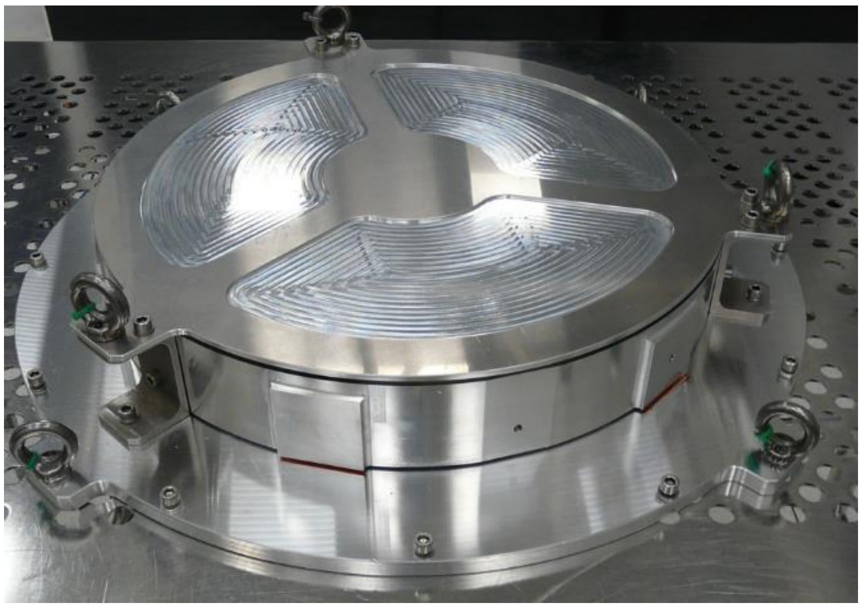
Characteristic	Actual	Nominal	Upper Tol	Lower Tol	Deviation	
01. Flatness A 0.01	0.023	0.000	0.010	0.000	0.023	Recoverable via SPDT
02. Rib1_5 ±0.1	5.002	5.000	0.100	-0.100	0.002	
02. Rib2_5 ±0.1	4.960	5.000	0.050	-0.050	-0.040	
02. Rib3_5 ±0.1	4.992	5.000	0.050	-0.050	-0.008	
02. Rib4_5 ±0.1	4.994	5.000	0.050	-0.050	-0.006	
02. Rib5_5 ±0.1	5.006	5.000	0.050	-0.050	0.006	
02. Rib6_5 ±0.1	4.988	5.000	0.050	-0.050	-0.013	
02. Rib7_5 ±0.1	5.012	5.000	0.050	-0.050	0.012	
02. Rib8_5 ±0.1	5.012	5.000	0.050	-0.050	0.012	
03. D420 ±0.1	420.012	420.000	0.100	-0.100	0.012	
04. Perpendicularity 0.05 A_Y+	0.007	0.000	0.050	0.000	0.007	
04. Inclination 0.05_C Y+	0.048	0.000	0.050	0.000	0.048	
04. Flatness 0.02 Y+	0.001	0.000	0.020	0.000	0.001	
04. Perpendicularity 0.05 A_X-Y+	0.005	0.000	0.050	0.000	0.005	
04. Inclination 0.05_C X-Y+	0.049	0.000	0.050	0.000	0.049	
04. Flatness 0.02 X-Y+	0.002	0.000	0.020	0.000	0.002	
04. Perpendicularity 0.05 A_X-Y-	0.005	0.000	0.050	0.000	0.005	
04. Inclination 0.05_C X-Y-	0.052	0.000	0.050	0.000	0.052	Recoverable via SPDT
04. Flatness 0.02 X-Y-	0.002	0.000	0.020	0.000	0.002	
04. Perpendicularity 0.05 A_Y-	0.008	0.000	0.050	0.000	0.008	
04. Inclination 0.05_C Y-	0.057	0.000	0.050	0.000	0.057	Recoverable via SPDT
04. Flatness 0.02 Y-	0.001	0.000	0.020	0.000	0.001	
04. Perpendicularity 0.05 A_X+Y-	0.002	0.000	0.050	0.000	0.002	
04. Inclination 0.05_C X+Y-	0.051	0.000	0.050	0.000	0.051	Recoverable via SPDT
04. Flatness 0.02 X+Y-	0.000	0.000	0.020	0.000	0.000	
04. Perpendicularity 0.05 A_X+Y+	0.010	0.000	0.050	0.000	0.010	
04. Inclination 0.05_C X+Y+	0.046	0.000	0.050	0.000	0.046	
04. Flatness 0.02 X+Y+	0.003	0.000	0.020	0.000	0.003	
05. Measure 213 Y+	212.948	213.000	0.500	-0.500	-0.052	
05. Measure 213 X-Y+	213.005	213.000	0.500	-0.500	0.005	
05. Measure 213 X-Y-	213.051	213.000	0.500	-0.500	0.051	
05. Measure 213 Y-	213.083	213.000	0.500	-0.500	0.083	
05. Measure 213 X+Y-	213.026	213.000	0.500	-0.500	0.026	
05. Measure 213 X+Y+	212.942	213.000	0.500	-0.500	-0.058	
06. Coord 154 D8	154.036	154.000	0.500	-0.500	0.036	
07. Optical Thickness 6_1	6.081	6.000	0.100	-0.100	0.081	
08. D226.8	266.916	266.800	0.500	-0.500	0.096	

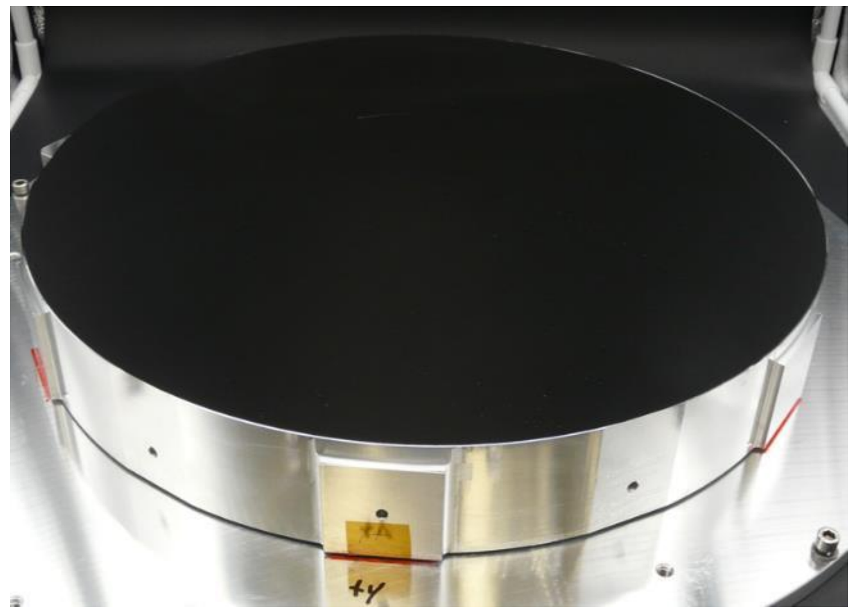


BB Mirror after Pre-machining during 3D CMM measurements at Media Lario

BB Mirror Manufacturing

The mirror was finally Diamond turned





BB Mirror after Diamond Machining during incoming at Media Lario

BB Mirror Before Verification Cryogenic Treatment

Visual Inspection was performed at 2000 lx against matte-black background (ISO 14997)

One light scratch already highlighted by LT ULTRA accepted with no impact

BB Mirror Before Verification Cryogenic Treatment

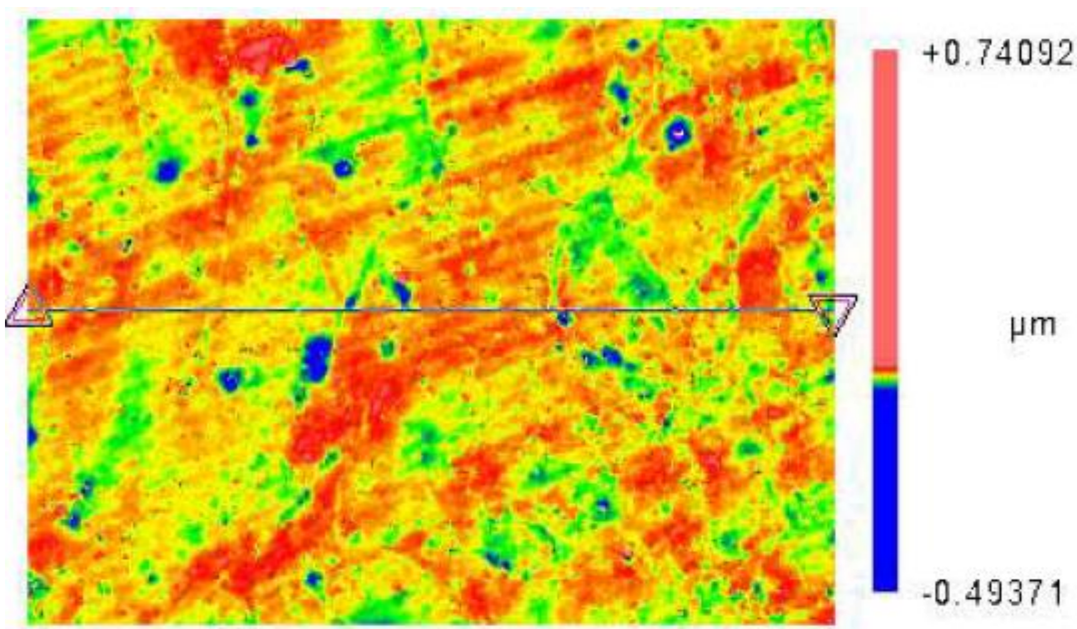
Characteristic	Actual	Nominal	Upper Tol	Lower Tol	Deviation
01. Flatness A 0.01	0,001	0,000	0,010	0,000	0,001
02. Rib1_5 ±0.1	5,001	5,000	0,100	-0,100	0,001
02. Rib2_5 ±0.1	4,959	5,000	0,050	-0,050	-0,041
02. Rib3_5 ±0.1	4,992	5,000	0,050	-0,050	-0,008
02. Rib4_5 ±0.1	4,995	5,000	0,050	-0,050	-0,005
02. Rib5_5 ±0.1	5,005	5,000	0,050	-0,050	0,005
02. Rib6_5 ±0.1	4,990	5,000	0,050	-0,050	-0,011
02. Rib7_5 ±0.1	5,008	5,000	0,050	-0,050	0,008
02. Rib8_5 ±0.1	5,010	5,000	0,050	-0,050	0,010
03. D420 ±0.1	420,017	420,000	0,100	-0,100	0,017
04. Perpendicularity 0.05 A_Y+	0,008	0,000	0,050	0,000	0,008
04. Inclination 0.05_C Y+	0,048	0,000	0,050	0,000	0,048
04. Flatness 0.02 Y+	0,004	0,000	0,020	0,000	0,004
04. Perpendicularity 0.05 A_X-Y+	0,006	0,000	0,050	0,000	0,006
04. Inclination 0.05_C X-Y+	0,047	0,000	0,050	0,000	0,047
04. Flatness 0.02 X-Y+	0,005	0,000	0,020	0,000	0,005
04. Perpendicularity 0.05 A_X-Y-	0,006	0,000	0,050	0,000	0,006
04. Inclination 0.05_C X-Y-	0,047	0,000	0,050	0,000	0,047
04. Flatness 0.02 X-Y-	0,005	0,000	0,020	0,000	0,005
04. Perpendicularity 0.05 A_Y-	0,005	0,000	0,050	0,000	0,005
04. Inclination 0.05_C Y-	0,045	0,000	0,050	0,000	0,045
04. Flatness 0.02 Y-	0,004	0,000	0,020	0,000	0,004
04. Perpendicularity 0.05 A_X+Y-	0,005	0,000	0,050	0,000	0,005
04. Inclination 0.05_C X+Y-	0,049	0,000	0,050	0,000	0,049
04. Flatness 0.02 X+Y-	0,004	0,000	0,020	0,000	0,004
04. Perpendicularity 0.05 A_X+Y+	0,010	0,000	0,050	0,000	0,010
04. Inclination 0.05_C X+Y+	0,044	0,000	0,050	0,000	0,044
04. Flatness 0.02 X+Y+	0,005	0,000	0,020	0,000	0,005
05. Measure 213 Y+	212,950	213,000	0,500	-0,500	-0,050
05. Measure 213 X-Y+	213,005	213,000	0,500	-0,500	0,005
05. Measure 213 X-Y-	213,055	213,000	0,500	-0,500	0,055
05. Measure 213 Y-	213,080	213,000	0,500	-0,500	0,080
05. Measure 213 X+Y-	213,029	213,000	0,500	-0,500	0,029
05. Measure 213 X+Y+	212,947	213,000	0,500	-0,500	-0,053
06. Coord 154 D8	154,040	154,000	0,500	-0,500	0,040
07. Optical Thickness 6_1	5,984	6,000	0,100	-0,100	-0,016
08. D226.8	266,897	266,800	0,500	-0,500	0,097

3D CMM measurements after Diamond Machining

BB Mirror Before Verification Cryogenic Treatment

Surface Roughness after Diamond Machining

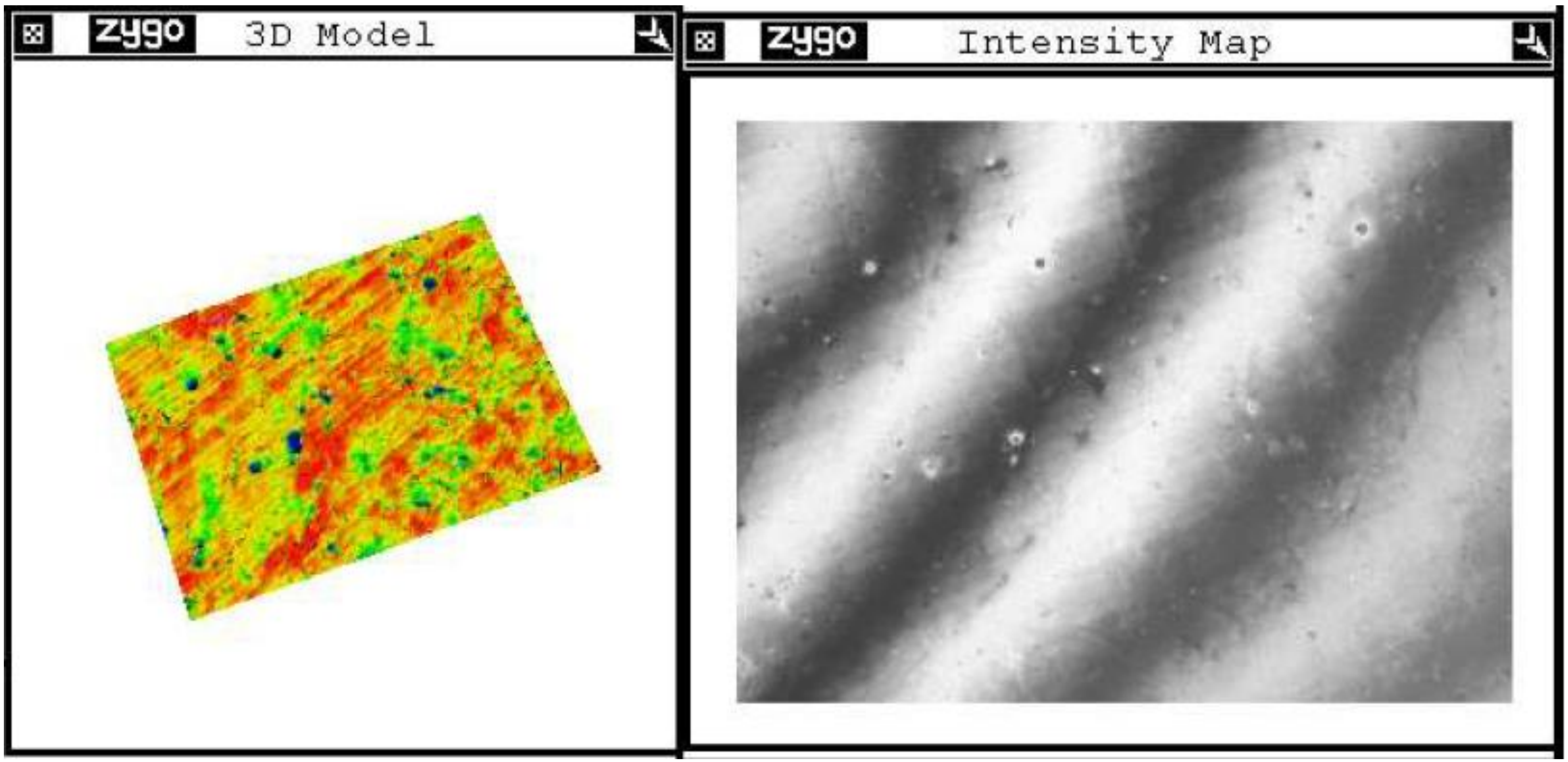
Sq	11.495	nm
Sa	6.438	nm
Size X	0.34	mm
Size Y	0.26	mm



Sq: 11.495 nm rms in line with the commitment from the diamond machining supplier

BB Mirror Before Verification Cryogenic Treatment

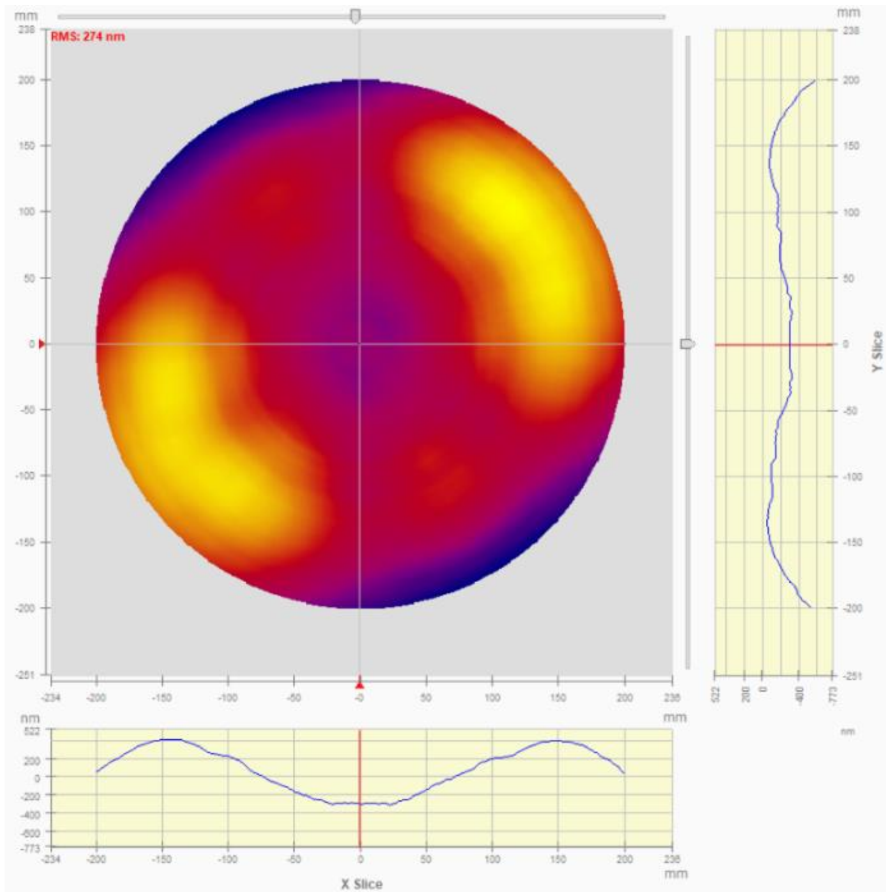
Surface Map after Diamond Machining



Presence of discontinuities that can be related to Mg_2Si precipitates removed during machining

BB Mirror Before Verification Cryogenic Treatment

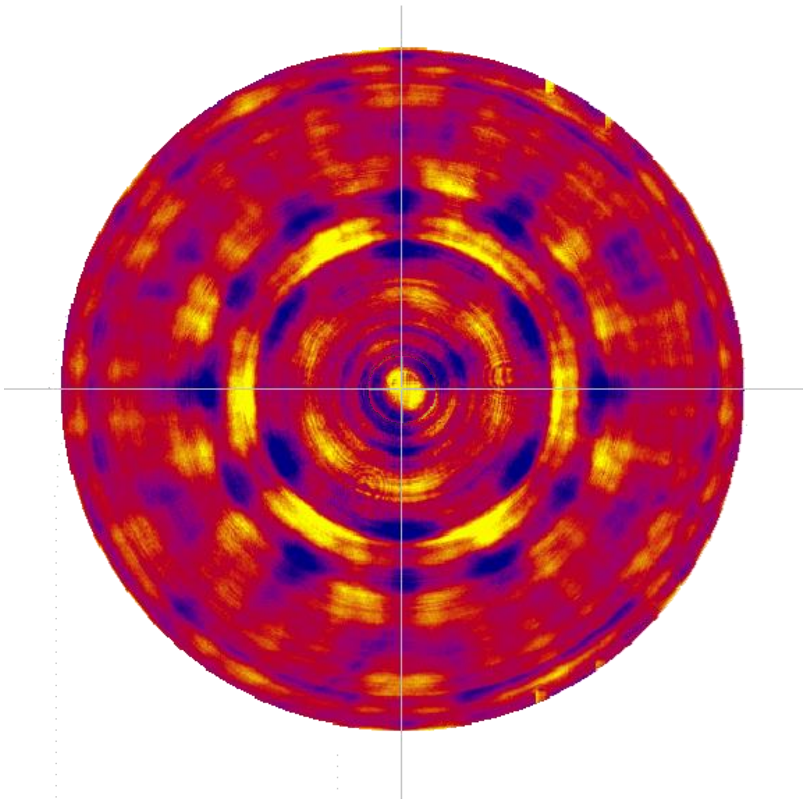
Interferometric measurement were performed on the full mirror aperture



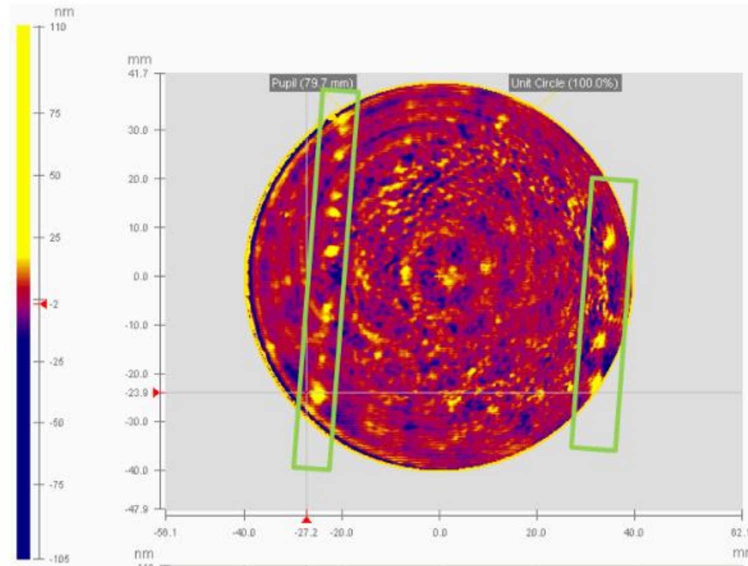
274 nm SFE in line with the commitment from the diamond machining supplier

BB Mirror Before Verification Cryogenic Treatment

120 Zernike polynomials were removed from the map to highlight discontinuities but no presence of joints is detected



2023 results:
120 Zernike polynomials removed



Same interferometer analysis of sample 122D from billet 1 produced in May **2020**. No HTs performed on the sample. The joints are clearly visible by the residual surface (green box) after preliminary polishing without thermal stress.

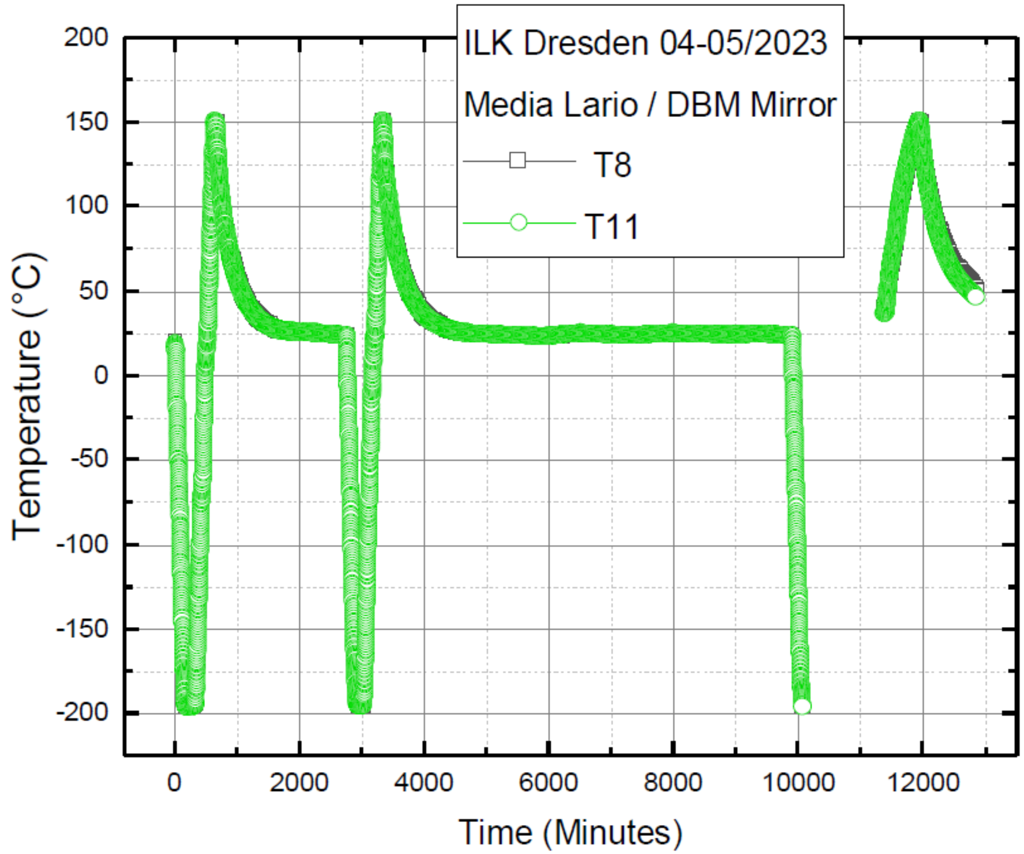
Summary

- The mirror was manufactured up to the DT phase meeting relevant requirements.
- The segment joints are not detectable by interferometry and the optical surface is free from discontinuities.
- The BB Mirror SFE is 274 nm with a surface roughness of 11 nm RMS, all results are in line with the commitment received from the diamond machining supplier.
- The surface topography measured via WLI shows the presence of pits that can be related to Mg_2Si precipitates removed during machining, typical for bare Al DT surfaces.
- Polishing could certainly lead to a lower SFE but to the cost of an increased roughness due to the formation of more pits.
- Given the achieved SFE, it has been agreed to proceed to environmental testing.

Cryogenic Verification Cycling

Cryogenic Verification Cycles

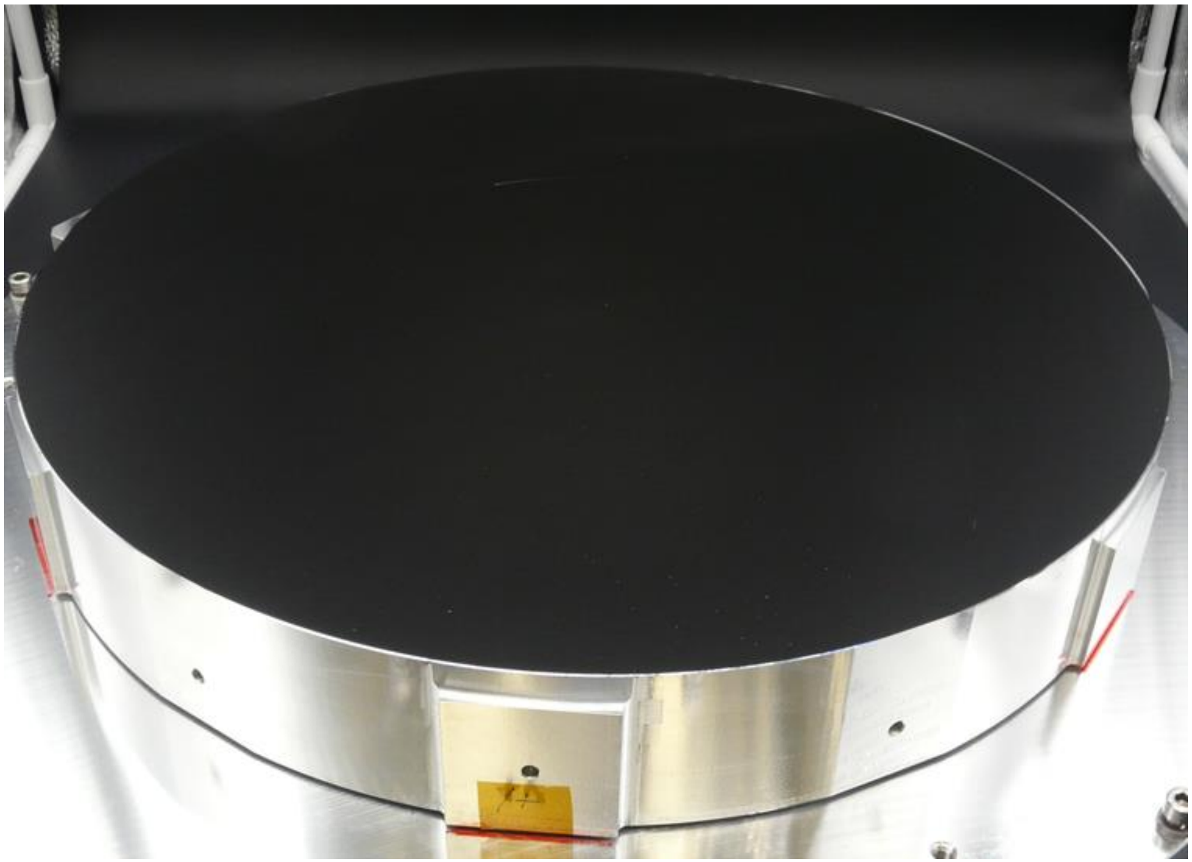
The Verification Cycles were performed after diamond machining



TT curves of the verification cycles

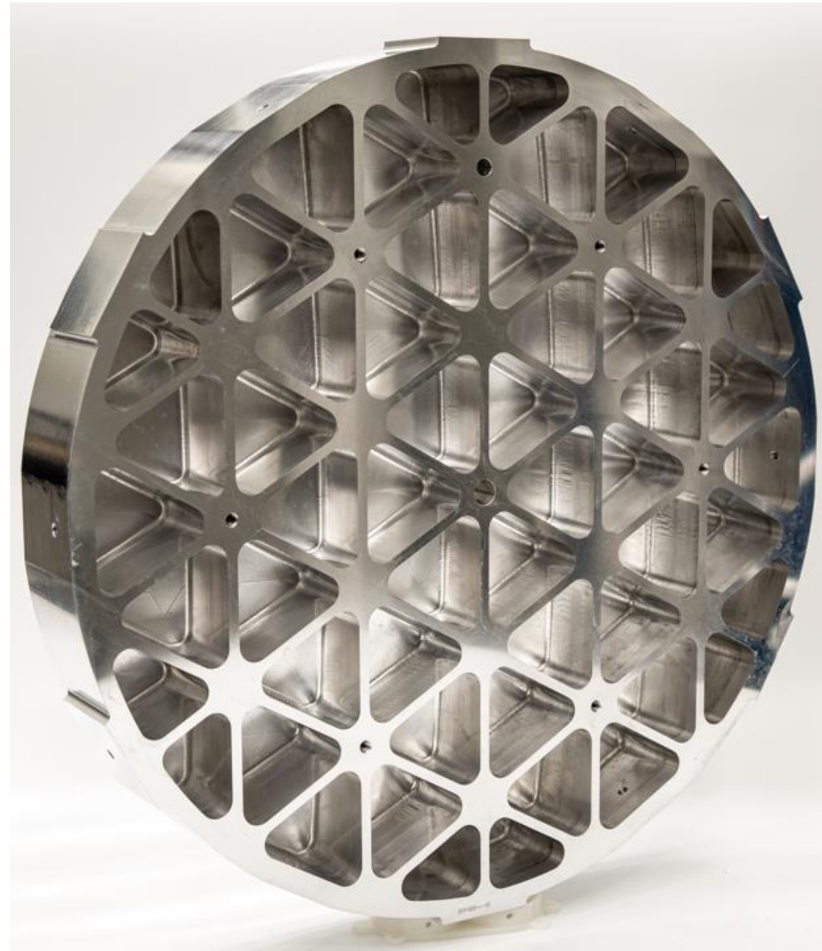
BB Mirror After Cryogenic Verification Cycles

Visual Inspection was performed at 2000 lx against matte-black background (ISO 14997)



Same scratch observed before the heat treatment still visible

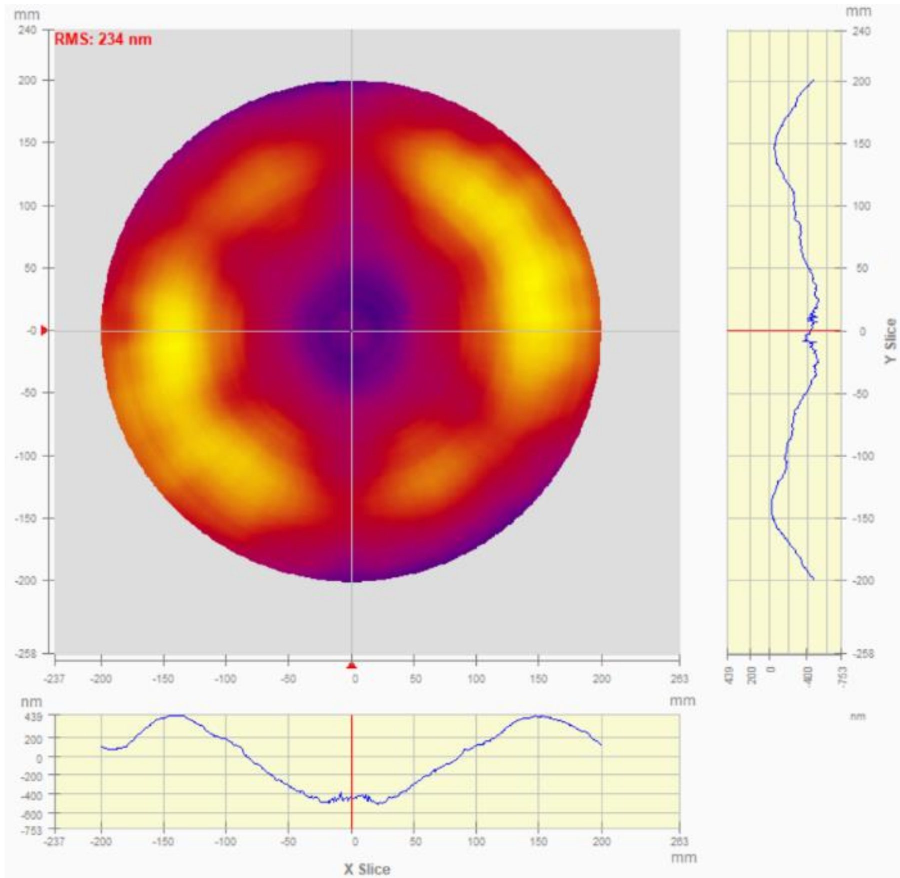
BB Mirror After Cryogenic Verification Cycles



DBM front surface and lightweighted back

BB Mirror After Cryogenic Verification Cycles

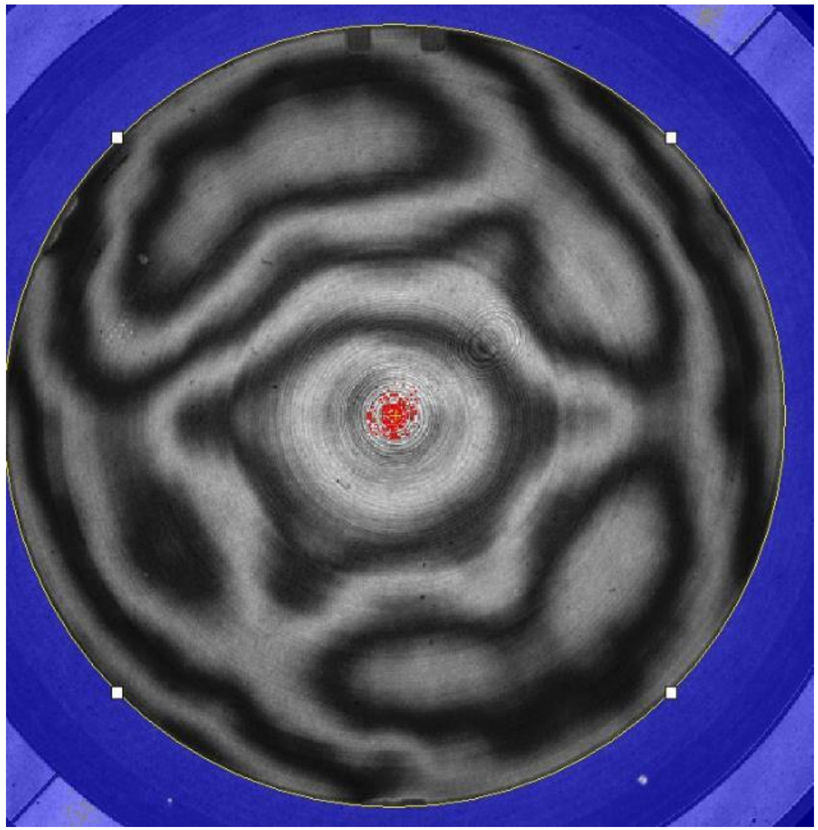
Interferometric measurement were performed on the full mirror aperture



234 nm RMS (SFE) with light relaxation of the machining fixation I/F

BB Mirror After Cryogenic Verification Cycles

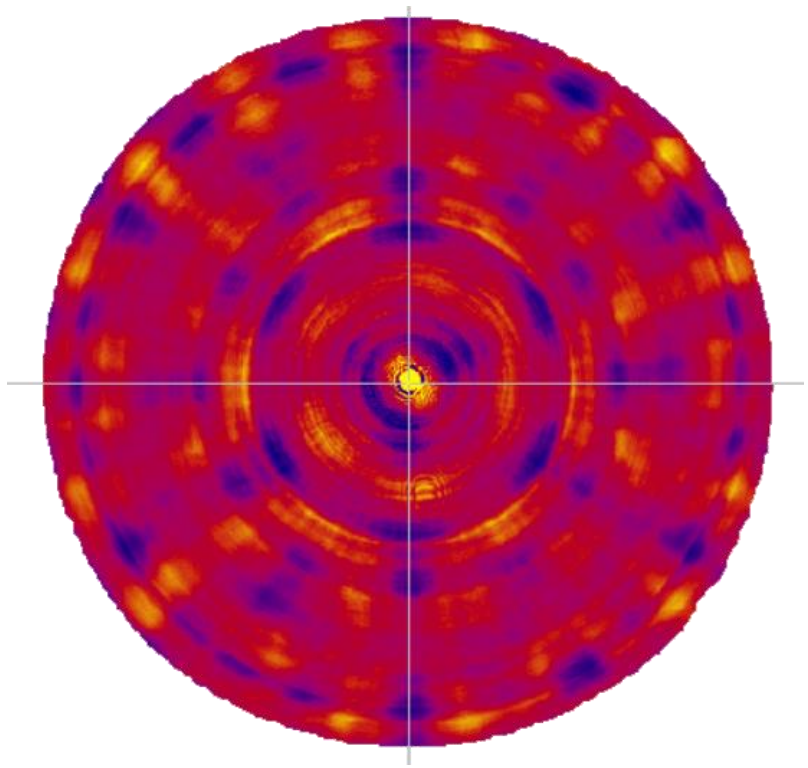
No presence of joints can be detected during interferometric testing



DBM Interferometric fringes after verification cycles

BB Mirror After Cryogenic Verification Cycles

120 Zernike polynomials were removed from the map to highlight discontinuities, but no presence of joints can be detected



120 Zernike polynomials removed

BB Mirror Verification Matrix

Requirement Label	Subject	Specified Value	As Built / Measured	Comp.
1010- 1011-1012	Material	Diffusion bonded RSA-6061 cast by metal spinning device and joined by Diffusion Bonding and in T6 condition	As Built	C
1210	Reflection Spectral Range	450 nm – 3 µm	≥ 84% from 450-1000 nm ≥ 94% from 1000-3000 nm	C
1220_A	Type	Aspheric with k: -0.976701	As Built	C
1220_B	Radius of Curvature (ROC)	1058.17139 ± 1 mm	1058.2401 mm	C
1230	Clear Aperture	400 mm	400 mm	C
1240	Number of Mirror Segments	≥ 3	6 segments	C
1270	Surface Roughness	≤ 6 nm	Sq: 11.495	NC
1215	WFE	< 200 nm RMS	234 nm RMS	NC
1250	light-weighting ratio of 55%	greater than 50%	55% Mass: 7,9 Kg	C

BB Mirror Verification Matrix

Requirement Label	Subject	Specified Value	As Built / Measured	Comp.
3100	Operational T range	From 55 to 293 °K	As Built	C
4100 - 4200	Handling and shipping container	The mirror shall be equipped with adequate means for handling. The mirror transport container shall protect the mirror and the blanks from contamination and damage.	See Handling, Packing and Shipping Procedure	C
5300	T cycling from 90 to 320 °K	From 90 K to 320 °K	See previous slides	C
5400	WFE measurements	WFE shall be measured before and after thermal cycling	See previous slides	C

BB Mirror Manufacturing Conclusions

- The mirror was manufactured and tested.
- The segment joints are not detectable by interferometry and the optical surface is free from discontinuities.
- Interferometric maps of the BB Mirror have been collected by CGH before and after the cryogenic environmental cycles.
- Given the achieved SFE and stability, the manufacturing and testing of the BB Mirror is considered completed.
- The surface topography measured via WLI (White Light Interferometer) shows the presence of pits that can be related to Mg_2Si precipitates removed during machining. The precipitates are typical of the 6061 alloy and cannot be avoided but could be minimized by means of a further development of the diffusion bonding process outside the scope of the current contract.

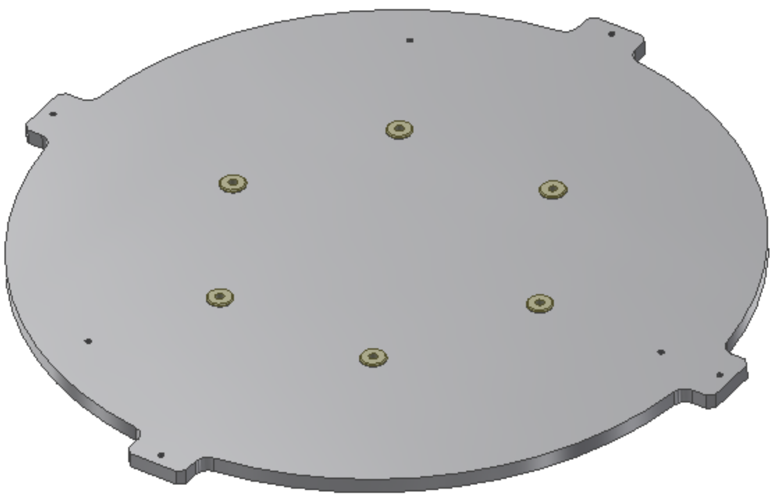
Handling, Packing and Shipping Procedure

Handling and shipping tools/procedure

Ref. Doc. DBM-ML-PR-001-Iss.1-Rev.0 - Handling, Packing and Shipping Procedure

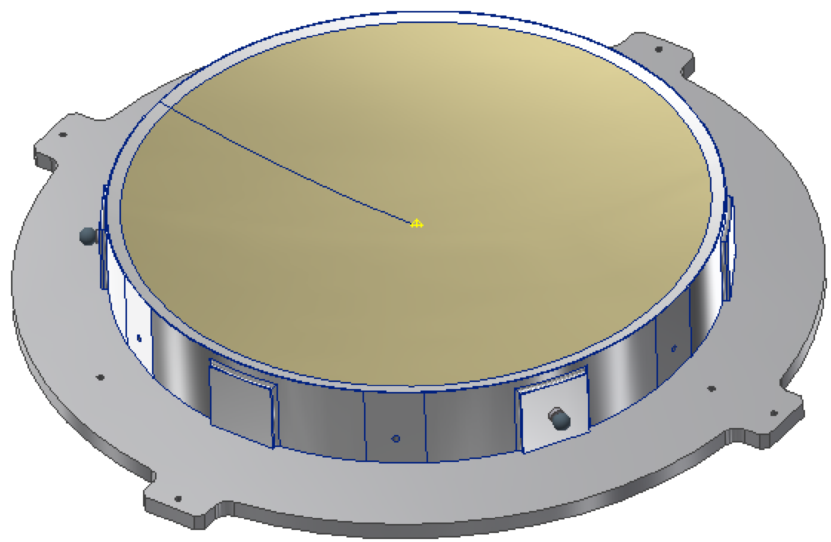
STEP 1

- A shipping interface is prepared, including teflon/moplen rings to avoid damage on the mirror
- Diameter (including pads): 600mm
- Mass: 7.8 kg



STEP 2

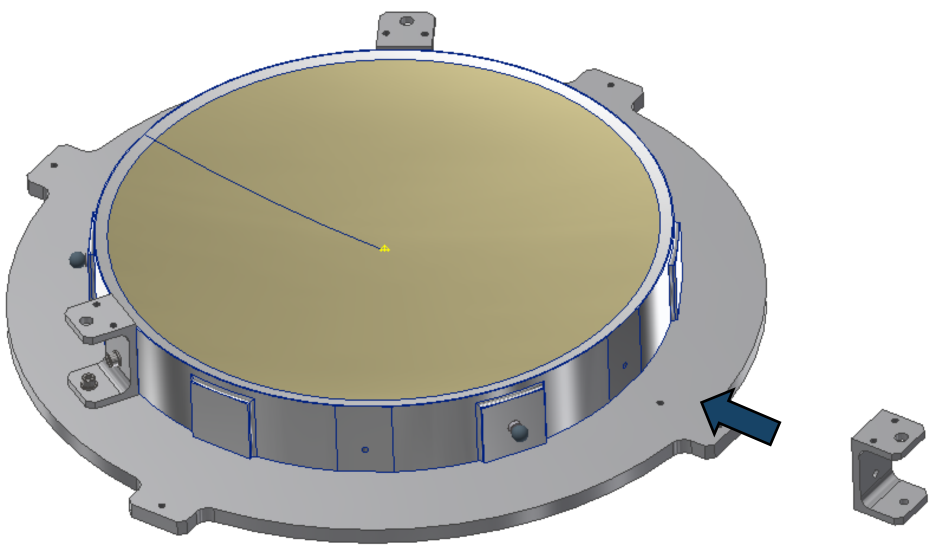
- Mirror is placed on the shipping plate
- Mirror mass: 8.4 kg



Handling and shipping tools/procedure

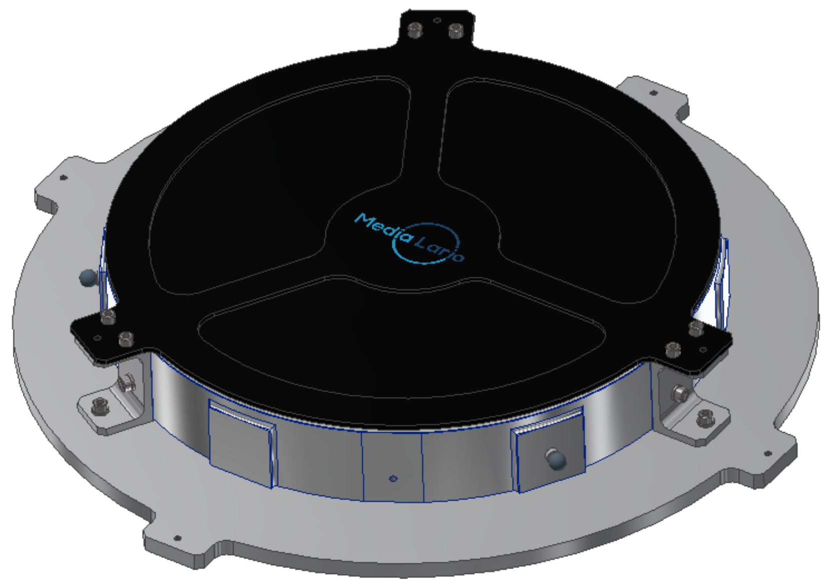
STEP 3

- Mounting/interface bracket are installed on the mirror side



STEP 4

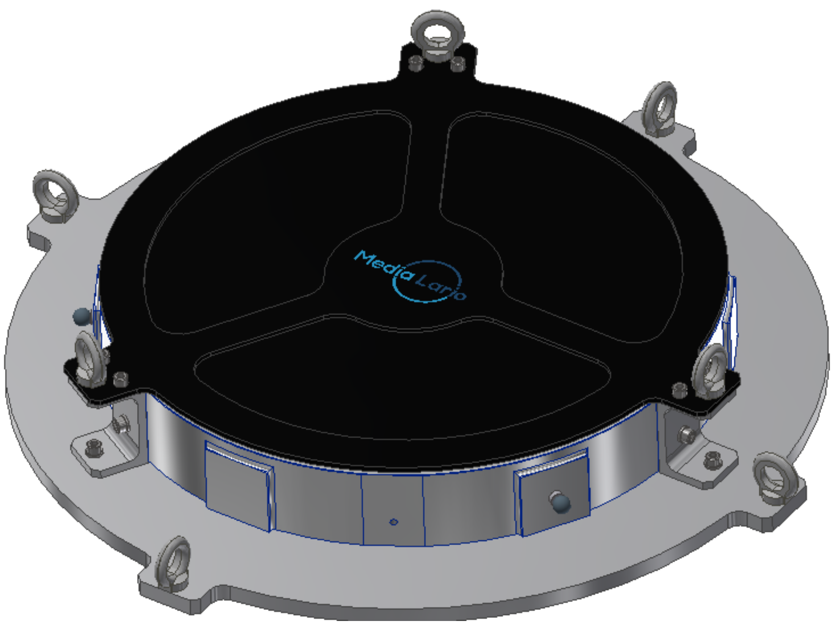
- A black anodized aluminum cover is placed on the mirror
- Cover is not in contact with the optical surface
- Mirror doble bagged in LDPE foils



Handling and shipping tools/procedure

STEP 5

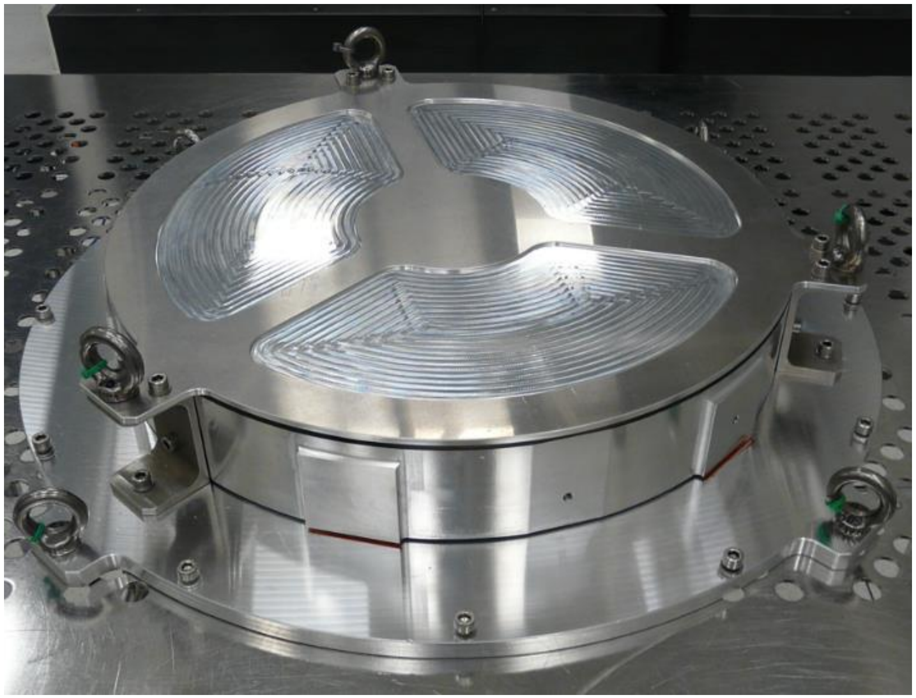
- Lifting device are kept in place
- Mirror-only or full system handling are both possible



STEP 6

- Transport cover is placed
- Mirror is ready for storage or transport
- Total mass: 19 kg

Breadboard Mirror in the Shipping Container



Up-scale Roadmap

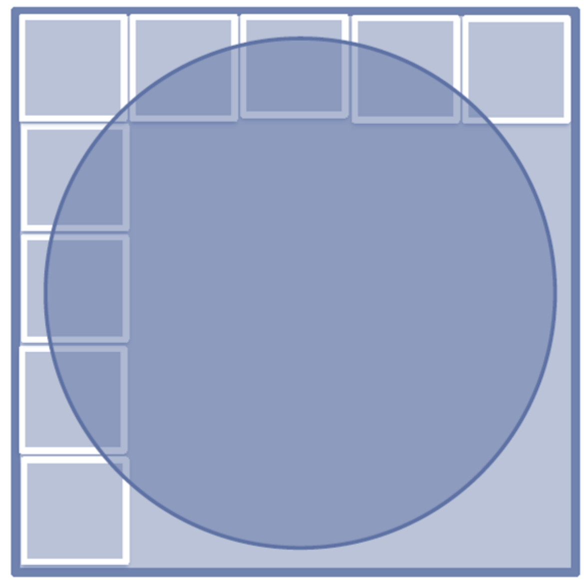
DB Up-scaling on RSA-6061T6

Alternative approaches for realizing a 1mtr mirror

- Configuration alternative 1:

Standard available billets 5x:
Diameter 300mm

25x blocks 200 x 200 x L100?mm)
+ flakes for the joints

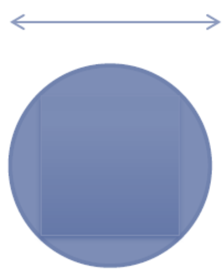


cansize: 1.100 x 1.100 x 100mm (310kg)

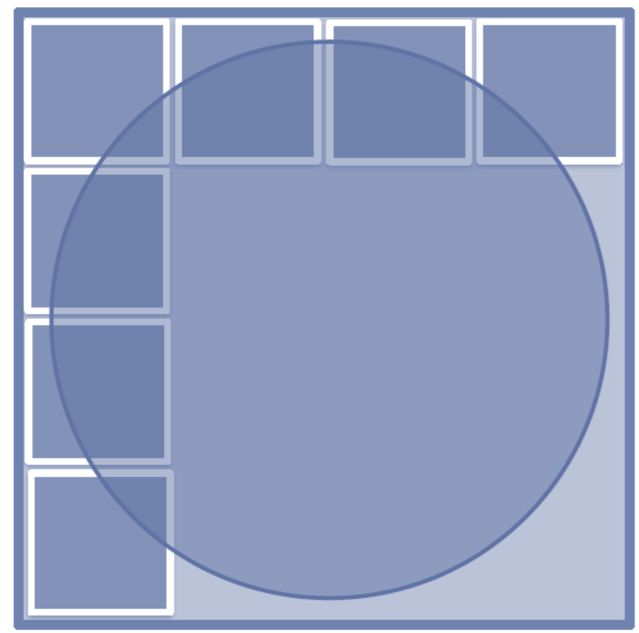
DB Up-scaling on RSA-6061T6

- Configuration alternative 2:

Standard available billets 4x:
Diameter 360mm



16 blocks 250 x 250 x L100?mm)
+ flakes for the joints

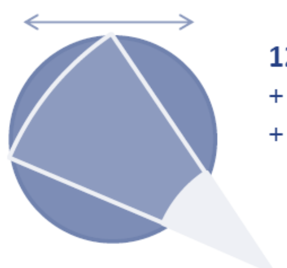


cansize: 1.100 x 1.100 x 100mm (310kg)

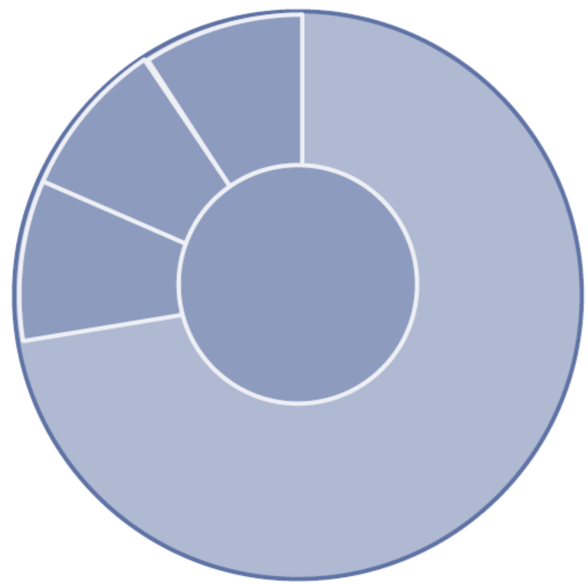
DB Up-scaling on RSA-6061T6

- Configuration alternative 3:

Standard available billets 4x:
Diameter 360mm



12 blocks circle segment
+ disk D420mm
+ flakes for te joints

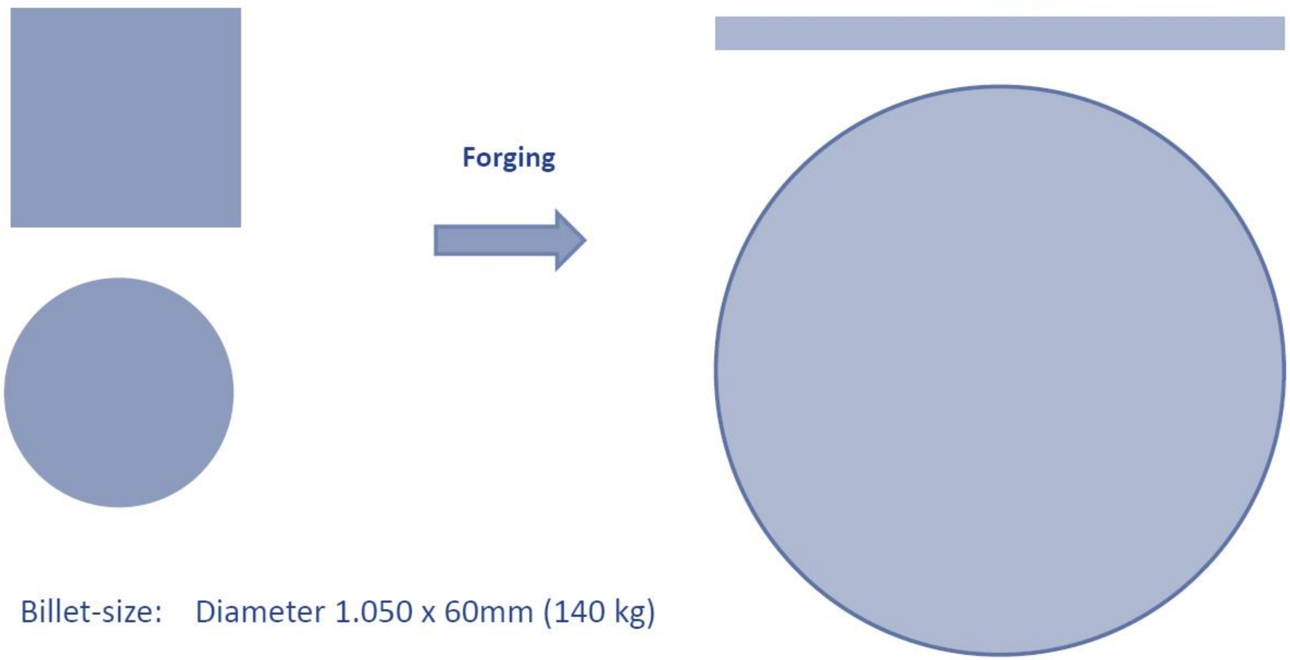


cansize: Diameter 1.050 x 100mm (234 kg)

DB Up-scaling on RSA-6061T6

- Configuration alternative 4:

Non-standard billet 1x:
Diameter 420mm x 400mm (appr. 150kg)



Billet-size: Diameter 1.050 x 60mm (140 kg)

DB Up-scaling on RSA-6061T6

Critical areas to be improved in the diffusion bonding of the RSA-6061T6 alloy:

1. Presence of precipitates: the material shows the presence of Mg_2Si precipitates that are removed during machining thus creating pits on the optical surface of the mirrors. The precipitates are typical of the 6061 alloy and cannot be avoided but shall be minimized by means of a further development of the diffusion bonding process. Main parameters to be controlled:
   - the concentration of Mg, that shall remain within a tight range
   - the T6 treatment of the billets, given the difficult uniform distribution of temperatures inside the material.

DB Up-scaling on RSA-6061T6

Critical areas to be improved in the diffusion bonding of the RSA-6061T6 alloy:

2. Dimensional restrictions: the main restriction is due to the behaviour of the flakes impacting the mechanical pre-compaction. Consequently:
    - The T6 treatment is not homogeneous in large substrates and the result is different, depending on location. Based on these differences, a certain amount of internal stresses can be created, resulting also in differences in microstructure
    - The precursor billets required to build the bonded substrate are limited in size (200/300 mm in diam. and 500 mm in length)
    - There is need for many blocks (16x), and so, many joints for the manufacturing of mirrors um to 1 meter diameter (6 blocks used for the manufacturing of the 430 mm Mirror Breadboard). If many blocks and joints are used, the risk of a failure increases.

DB Up-scaling on RSA-6061T6

Critical areas to be improved in the diffusion bonding of the RSA-6061T6 alloy:

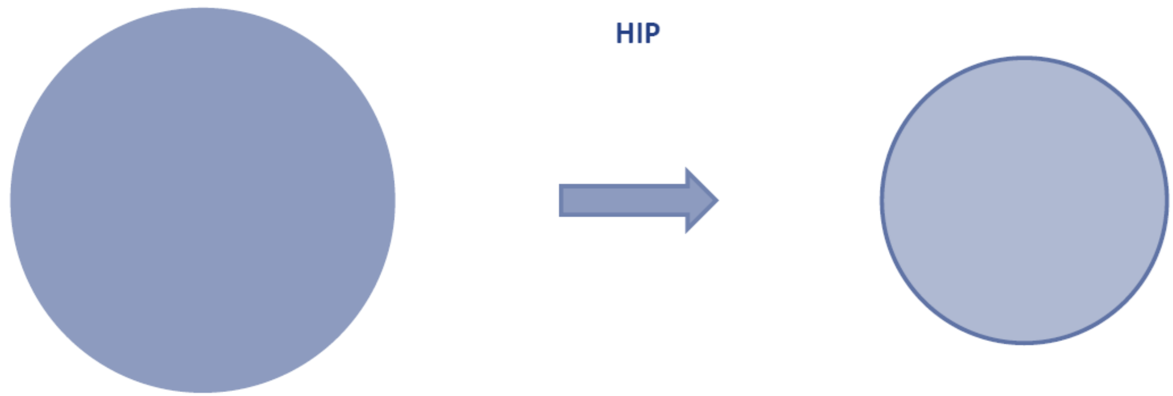
3. Billets, flakes and cans are shipped to HIP facilities and chances are that the flakes in the joints are re-located.

Alternative solution for Up-scaling

Alternative approach for realizing a 1mtr mirror

- Configuration alternative 5:

Alternative alloy: RSA-902
1 non-standard billet
Diameter 1.020mm x 200mm (appr. 250kg)



Scale 1 : 2 !

Cansize initial billet: Diameter 1.350 x 200mm (appr. 250 kg)

Alternative solution for Up-scaling

- RSA-6061T6 was selected against RSA 905 and 443
- RSP Technology BV has recently introduced a new type of RSA alloy called 902
- RSA-902 alloy could be an alternative candidate for the diffusion bonding up-scaling
- Possible advantages related to the RSA-902:
  - RSA-902 vs. RSA-6061T6: Due to the behaviour of the flakes, this alloy does not require mechanical pre-compaction. Consequently:
    - ✓ The dimensions of the initial billets are not restricted
    - ✓ There is no need for bonding and re-HIPping
- The maximum size of 500 mm was applicable also for the RSA-902 at the beginning of the current project. During these years of development of the diffusion bonding process for the RSA-6061T6, RSP has also improved the process and the facilities for the manufacturing of other RSA alloys. The results is that today, RSP can produce billets of RSA-902 up to 1 meter in one production step only, that is without the need of the diffusion bonding

Alternative solution for Up-scaling

Possible advantages related to the RSA-902:

- RSA-902 has no need for T6 treatment: RSA-902 is a dispersion strengthen alloy, which does not need any kind of hardening (T6) process. Consequently:
    - stress relieve cycling can be carried out at a higher temperature: a material in T6 condition cannot be stress relieved at a high temperature (typically 170° C instead of 380°C). The higher temperature is much more effective
    - dimensional stability is better
- RSA-902 additional properties:
    - the surface finish of the RSA-902 after Single Point Diamond Turning (SPDT) is supposed to be comparable or slightly better than the RSA-6061
    - RSA-902 offers enhanced mechanical/physical properties: higher E-modulus, slightly lower CTE
    - Strength properties are comparable with RSA-6061

Mirrors Manufacturing and Testing Up-scaling

Media Lario and its supply chain is equipped with all the facilities needed for the manufacturing and testing of mirrors up to 1.2 meter:

- Tooling for machining of the blank
- Facilities for thermal treatments
- Facilities for cryogenic thermal treatments
- Machine for Single Point Diamond Turning of the optical surface
- Machine for polishing
- 3D CMM machine for mechanical tolerances measurements
- Interferometer for shape accuracy measurement
- White Light Interferometer for surface roughness measurements
- Tooling for handling, cleaning and visual inspection
- Facility for Cryogenic testing (Centre Spatial de Liège)

DBM Project Conclusions

Conclusions

- A mirror breadboard in RSA-6061T6 diffusion bonded has been produced and tested in laboratory conditions after three cryogenic cycles. At the end of the manufacturing process, the mirror was intact and in line with the specifications. The feasibility of the diffusion bonding of the RSA-6061T6 material has been demonstrated.
- Although the results obtained with the diffusion bonding of the RSA-6061T6 alloy in the current project are very promising, some critical areas to be improved have been identified. The upscaling approach of the bonded substrates using RSA-6061 alloy gives some challenges and restrictions.
- A possible alternative solution for large substrates in the range of 1 meter is to consider development and upscaling of the aluminium alloy RSA-902. Based on the properties and manufacturing process of the material, the RSA-902 could offer advantages respect to the RSA-6061T6 for the manufacturing of large substrates.

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