DBM Executive Summary Report

DBM ESR

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1 INTRODUCTION AND SCOPE

The Executive Summary Report (ESR) is an applicable document that concisely summarise the findings of the ESA Contract n°4000128444-19-NL-AR - COM-SP071, “JOINING PROCESS FOR MANUFACTURING OF LARGE ALUMINIUM-BASED OPTICAL MIRRORS” [AD1] and relevant SOW [AD2].

The document is submitted to the Agency in support of the project Final Review.

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, i.e. currently considered to be approximately 500 mm.

The need for larger aluminium mirrors is coming from scientific missions that require a large collecting area.

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.

The open point is what process ca be used for the bonding of segments of aluminium-based alloys to obtain large segmented optical mirrors.
Conventional fusion welding techniques applied on aluminium alloys would melt the parent metals and compromise the fine-grained structure of the rapidly solidified alloy. As a consequence, the polishing of the mirror will result in non-homogeneous surface roughness in the weld areas.
A possible solution is to use the same rapid solidification process to bond segments to form larger billets. This process is also known as Diffusion Bonding (DB).

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.

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

The objective of this activity is to develop the diffusion bonding process to enable the production of large RSA Aluminium mirror blanks obtained by joining smaller segments. This process has been demonstrated on a breadboard mirror of 430 mm diameter.

2 REFERENCES

2.1 Applicable Documents

[AD1] ESA contract n°4000128444-19-NL-AR - COM-SP071, "JOINING PROCESS FOR MANUFACTURING OF LARGE ALUMINIUM-BASED OPTICAL MIRRORS"

[AD2] Statement of Work, ESA document code ESA-TRP-TECMMO-SOW-013477, Issue 1, Rev. 0 dated 01/04/2019.

2.2 Reference Documents

[RD1] DBM-ML-FR-001-Iss.1-Rev.0 - Final Report

2.3 Acronyms and Abbreviations

AD	Applicable Document
c.f.	see
CGH	Computer Generated Hologram
DBM	Diffusion Bonded Mirror
DT	Diamond Turning (Diamond Turned)
DR	Design Review
FP	Final Presentation
HT	Heat Treatment
ML	Media Lario S.r.l.
PA	Product Assurance
PV	Peak to Valley
QA	Quality Assurance
RMS	Root Mean Square
SFE	Surface Form Error
SoW	Statement of Work
SRR	System Requirement Review
TRR	Test Readiness Review
TRB	Test Review Board
VI	Visual Inspection
WLI	White Light Interferometer

3 DEVELOPMENT PLAN

3.1 Project Team

Media Lario is the authority for the application scope, the design, the manufacturing, the optical process and the cryogenic testing of the mirror breadboard. Media Lario is responsible for meeting the objectives of the ITT, i.e. large aluminium mirrors for space applications.

RSP Technology is the authority for the material manufacturing and for the diffusion bonding process. 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 are from RSP Technology BV.

3.2 Work logic

The activity consists of the following technological steps:

- Optimisation of the joining technology
- Manufacturing and testing of the mirror breadboard

The activity started with the definition of the requirements for the breadboard mirror and the jointed material together with the trade-off to select the material suitable for the joining process and trials on specimen to optimise the joining process.
In parallel, ML worked on the design of the breadboard mirror to be manufactured.

4 TRADE-OFF OF JOINING PROCESS AL-BASE MATERIALS

4.1 Joint Technologies selection

Five candidates for the joining technology have been investigated: Laser welding; e-Beam welding; Friction welding; Furnace brazing; Diffusion Bonding.
The Diffusion Bonding process achieved by Hot Isostatic pressure is the joining process selected.
RSP Technology has developed a manufacturing process to produce highly homogeneous Aluminium alloy billets by high pressure compaction (Hot Isostatic Pressing) of selected Aluminium Flakes produced by Melt-spinning process. 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.

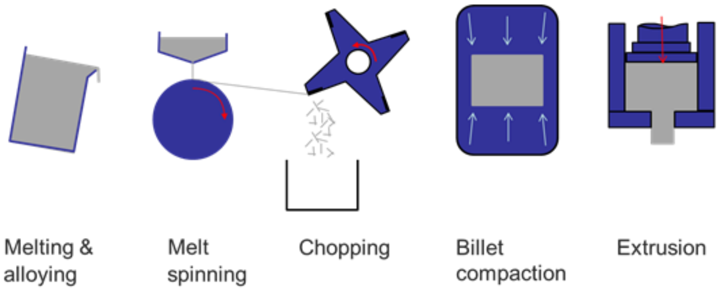

Figure 4-1. Raw material production process for RSA alloys.

4.2 Material selection

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.

The RSA-6061, as all the RSA alloys, has 10x to 50x finer structure than conventional Aluminium, with very high purity (Figure 4-2). Thanks to this fine and homogeneous microstructure, RSP Aluminium mirrors can be diamond turned to a surface roughness at least 50% lower than conventional Aluminium mirrors.

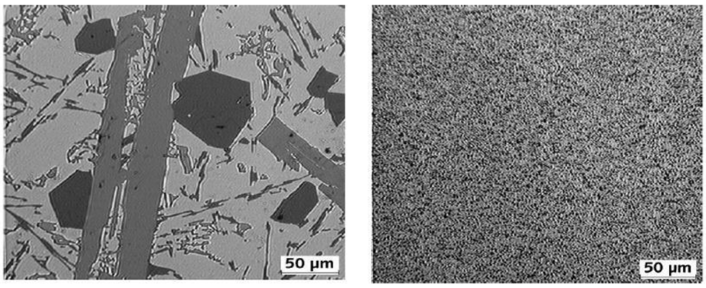

Figure 4-2. conventional microstructure (on the left) vs. RSP microstructure (on the right)

5 BRADBOARD MIRROR DESIGN

The Diffusion Bonded Breadboard Mirror (DBM) is a circular, aspherical, on-axis mirror made of Aluminum Al-RSP-RSA6061T6.
A mirror weight of 8.4 kg has been achieved, corresponding to an approximately light-weighting ratio of 55% and areal mass of 60 kg/m^2. The mirror drawing is illustrated in Figure 5-1.

Table 5-1. Mirror dimension and mass data

Volume claim [mm^3]	CAD Mass [kg]	Optical surfaces area [m^2]	Areal mass [kg/m^2]	Mirror mass without lightening pockets [kg]	Lightening ratio
∅420 x 59.8	8.4	0.139	60.4	18.7	55.1%

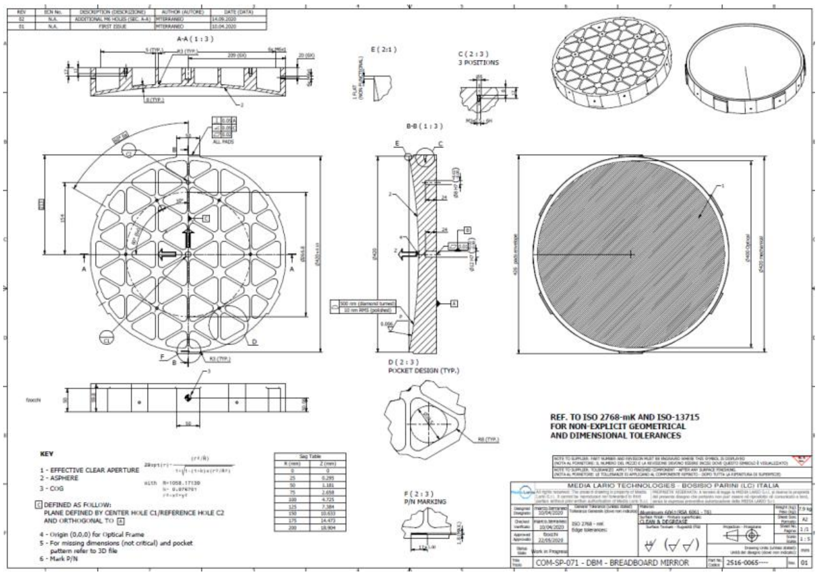

Figure 5-1. DBM Mirror Drawing

6 DIFFUSION BONDING PROCESS DEVELOPMENT

The RSP standard manufacturing process is illustrated in chapter 4.1. The same RSP standard manufacturing process can be used to join raw material of RSA segments into a larger substrate. This process is more correctly known as diffusion bonding and is achieved by means of a Hot Isostatic Press. Diffusion bonding can be applied to any number of segments configured to obtain larger and/or thicker substrates. Moreover, since the individual RSA segments have already gone through a HIP furnace cycle during raw material production, the HIP cycle performed to realize the diffusion bonded joint does not cause any further compaction of the material. Therefore, the final dimension of the diffusion bonded substrate corresponds to the full size of the HIP facility, thus the HIP facility is the only size limiter.

The process consists of placing the raw material segments into a container, named can, to fill the empty spaces between adjacent segments with selected Aluminium Flakes and to perform the degassing and bonding of the segments by re-HIPping. The bonded material is then cut in the require shape.

The scope of the joining process development was to highlight and tune the core process parameters for the manufacturing of diffusion bonded materials in RSA-6061T6 adequate for the manufacturing of optical mirrors for cryogenic applications.

Three RSA-6061T6 diffusion bonded billets have been produced during the diffusion bonding process development. The third one was accepted and used for the manufacturing of the Breadboard Mirror.

7 BREADBOARD MIRROR MANUFACTURING AND TESTING

7.1 Diffusion Bonded Mirror Breadboard Manufacturing

Rough machining was performed leaving extra material to reduce manufacturing stresses.
A first heat treatment of 3 thermal cycles in the range -190 ÷ +150 °C was performed after rough machining.
With the pre-machining phase the substrate was led to mechanical specs. A second heat treatment of 3 thermal cycles in the range -190 ÷ +150 °C was performed after pre machining.
The mirror was finally Diamond turned and subjects to verification treatment. The verification treatment consists of 3 thermal cycles in the range -190 ÷ +150 °C
TT curves of the cryogenic treatments are reported in Figure 7-1.

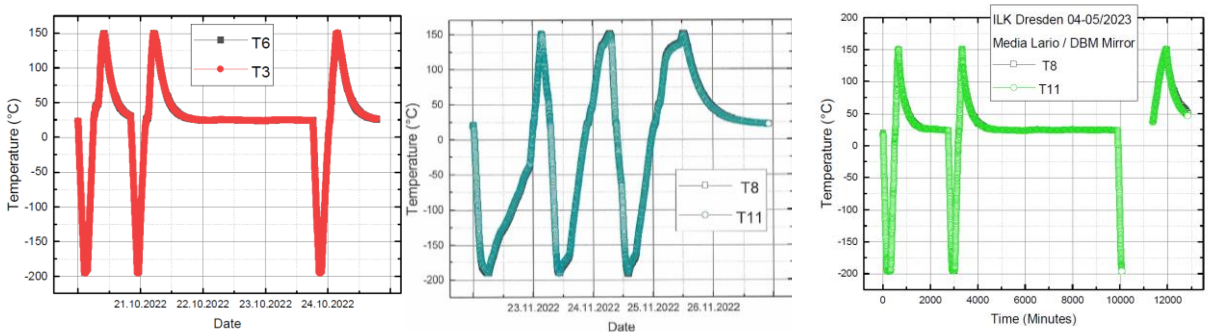

Figure 7-1. TT curves of the first(left), second (centre) and verification (right) heat treatments

7.2 Diffusion Bonded Mirror Testing

7.2.1 Compliance 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
1110	Surface roughness	≤ 6 nm	Sq: 11.495	NC[1]
1210	Reflection spectral range	450nm-3µm	≥ 84% from 450-1000 nm ≥ 94% from 1000-3000 nm	
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
1215	Wave front error	< 200 nm RMS	234 nm RMS	NC[1]
1250	light-weighting ratio of 55%	greater than 50%	55% Mass: 7,9 Kg	C

[1]Although not compliant with SOW indications, these changes have agreed with ESA

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.	Handling and shipping container produced. Handling, Packing and Shipping Procedure issued.	C
5300	T cycling from 90 to 320 °K	From 90 K to 320 °K	As Built	C
5400	WFE shall be measured before and after thermal cycling	WFE measurements	SFE measurement by interferometer and CGH at room temp.	C

7.2.2 MSE Maps

Interferometric maps have been collected by CGH before and after cryogenic verification cycling in the range - 190 ÷ +150 °C. The accuracy of the CGH, certified by the supplier, is 8 nm RMS. Measured Surface Figure Errors were 274 nm RMS before and 236 nm RMS after verification cycles. Results are reported here in the following Figure 7-2.

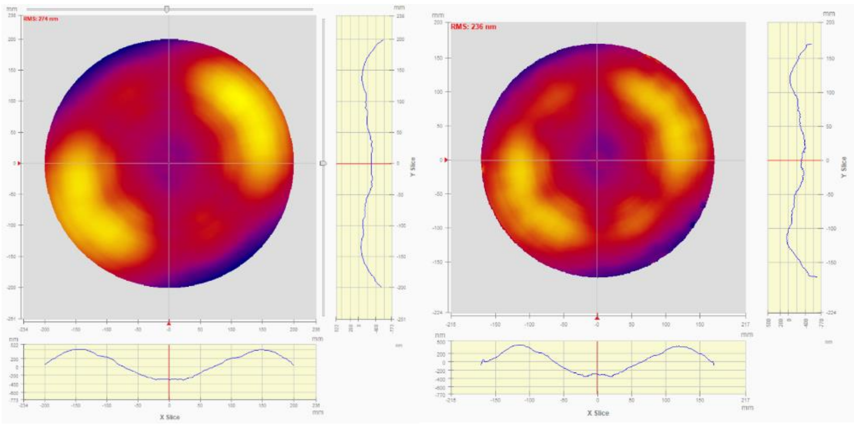

Figure 7-2. Interferometric maps before and after verification cycles

The data collected have been analysed by removing 120 Zernike polynomials from the maps to highlight possible discontinuities in the jointed areas: no presence of joints can be detected. Results are reported in Figure 7-3.

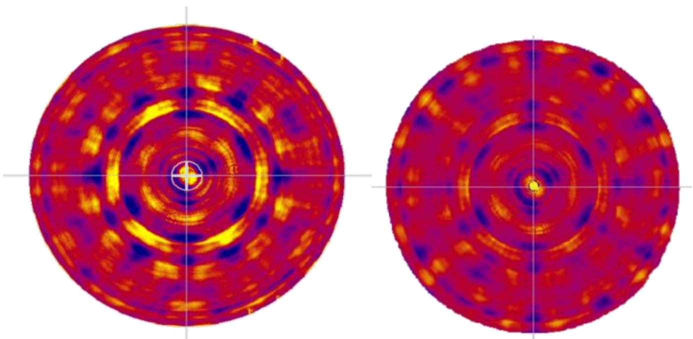

Figure 7-3. 120-Zernike residuals before and after verification cycles

The same interferometer analysis was performed of sample 122D from billet 1 produced in May 2020. The joints were clearly visible from the residual surface (green box) just after preliminary polishing. No heat treatments had been performed on the sample before polishing. Results are reported in Figure 7-4.

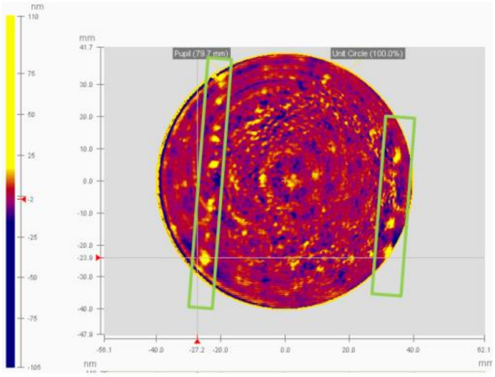

Figure 7-4. Interferometric measurement of the sample 122D from billet 1 produced in May 2020. *The green boxes highlight the joints*

7.2.3 Roughness Measurements

The surface roughness achieved shows a Sq of 11.495 nm rms in line with the commitment from the diamond machining supplier and very near to the specification of 10 nm rms.
The Surface Map after Diamond Machining shows the presence of discontinuities that can be related to Mg2Si precipitates removed during machining. These precipitates are typical of the aluminum 6061 and cannot be avoided but can be minimized by a further development of the diffusion bonding process to be performed outside the scope of the present work.
Results are shown here in Figure 7-5.

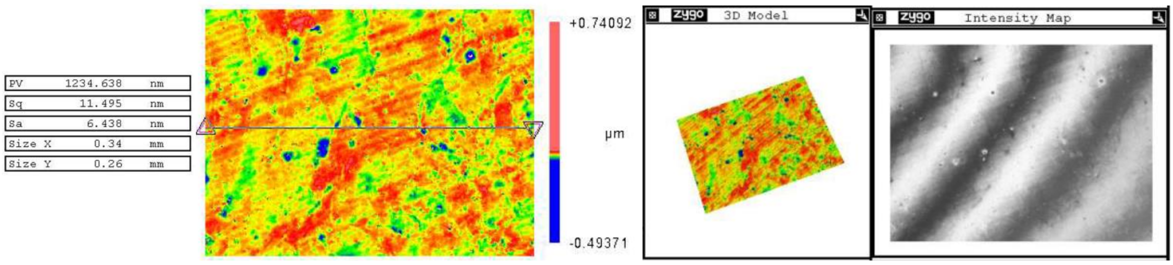

Figure 7-5. WLI Measured Surface (left) and Surface Map after Diamond Machining (right)

7.2.4 Visual Inspection

Visual inspection was carried out according to ISO 10110 standard against a dark background under an illumination of 2000 lux. One scratch was found inside the optical area. The defect was already observed before the thermal cycling just after diamond machining . Defects similar to the one observed are typically introduced during the diamond machining of big mirrors due to the wear of the tip of the turning tool. The acceptability of the defect has been agreed with ESA.
Pictures of the mirror are shown here in Figure 7-6.

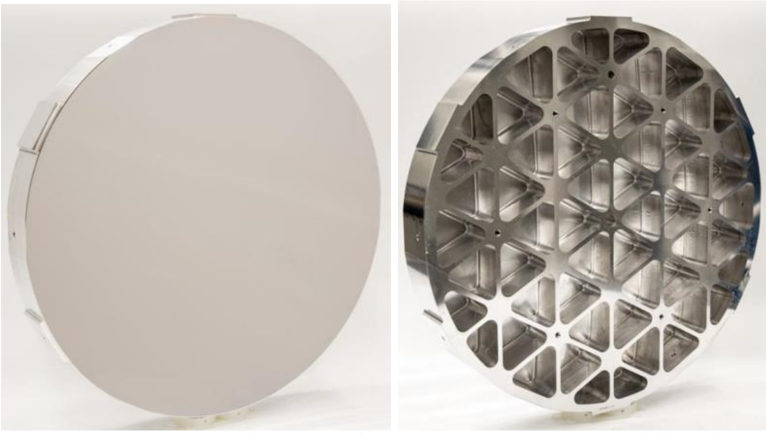

Figure 7-6. Mirror Breadboard after the cryogenic verification cycling

8 FUTURE ROAD-MAP FOR UP-SCALING AND CRYOGENIC TESTING

This Future road-map and cryogenic testing is aimed to the identification of the critical area in the manufacturing process of diffusion bonded mirrors and possible way for improvement for manufacturing and cryogenic testing of rapid solidified Al-based mirrors with diameter up to 1 meter.

8.1 Up-scaling of Diffusion Bonding of the RSA-6061T6 alloy

We have produced a bonded mirror that underwent three cryogenic thermal cycles and, at the end, was intact and in line with the specifications.
Four configurations have been proposed by RSP for the manufacturing of diffusion bonded billets up to 1 meter diameter in RSA6061.
Some critical areas still to be improved have been identified in the diffusion bonding of the RSA-6061T6 alloy. These critical areas are mainly related to the presence of precipitates and dimensional restrictions of the diffusion bonded billet.

8.2 Alternative Solution for diffusion bonding process Up-scaling

Two alternative solutions have been proposed by RSP for the upscaling.
The first one is the RSA.902 instead of the RSA6061. 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 with no need of diffusion bonding This solution has been considered interesting but not fully in line with the scope of the present work.
The second one is based on the use of conventional AA6061 alloy plus RSA-6061 selected flakes. This solution covers most of the potential issues related to the up-scaling with RSA-6061T6 and is based on the feasibility of bonding solid material and flakes proven during the current study.

8.3 Road map for up-scaling the manufacturing and testing

Media Lario and its supply chain is equipped with all the facilities needed for the manufacturing and cryogenic testing temperature of mirrors up to 1 meter.

9 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 except for minor NCs for SFE and surface roughness, considered acceptable by ESA given the good results achieved. 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, restrictions and potential learning curve effects.