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Published version information:

Citation: E Guerriero et al. Heat treatment procedure of the aluminium 6061-T651 for the Ariel telescope mirrors.. Proc SPIE 12180 (2022): 1218014. Is in proceedings of: Space Telescopes and Instrumentation 2022: Optical, Infrared, and Millimeter Wave, Montréal, Québec, Canada, 17-23 Jul 2022

DOI: 10.1117/12.2628178

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Event: SPIE Astronomical Telescopes + Instrumentation, 2022, Montréal, Québec, Canada

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ABSTRACT

The Atmospheric Remote-Sensing Infrared Exoplanet Large Survey (*Ariel*) is the M4 mission adopted by ESA's "Cosmic Vision" program. Its launch is scheduled for 2029. The purpose of the mission is the study of exoplanetary atmospheres on a target of $\sim$ 1000 exoplanets. Ariel scientific payload consists of an off-axis, unobscured Cassegrain telescope. The light is directed towards a set of photometers and spectrometers with wavebands between 0.5 and 7.8 μm and operating at cryogenic temperatures. The Ariel Space Telescope consists of a primary parabolic mirror with an elliptical aperture of 1.1$\cdot$ 0.7 m, followed by a hyperbolic secondary, a parabolic collimating tertiary and a flat-folding mirror directing the output beam parallel to the optical bench; all in bare aluminium. The choice of bare aluminium for the realization of the mirrors is dictated by several factors: maximizing the heat exchange, reducing the costs of materials and technological advancement. To date, an aluminium mirror the size of Ariel's primary has never been made. The greatest challenge is finding a heat

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Space Telescopes and Instrumentation 2022: Optical, Infrared, and Millimeter Wave, edited by Laura E. Coyle, Shuji Matsuura, Marshall D. Perrin, Proc. of SPIE Vol. 12180, 1218014 · © 2022 SPIE · 0277-786X · doi: 10.1117/12.2628178

treatment procedure that stabilizes the aluminium, particularly the Al6061T651 Laminated alloy. This paper describes the study and testing of the heat treatment procedure developed on aluminium samples of different sizes (from 50mm to 150mm diameter), on 0.7m diameter mirror, and discusses future steps.

Keywords: space telescope, Ariel mission, aluminium mirror, bare aluminium, Al6061T651, heat treatment, thermal cycle, laminated

1. INTRODUCTION

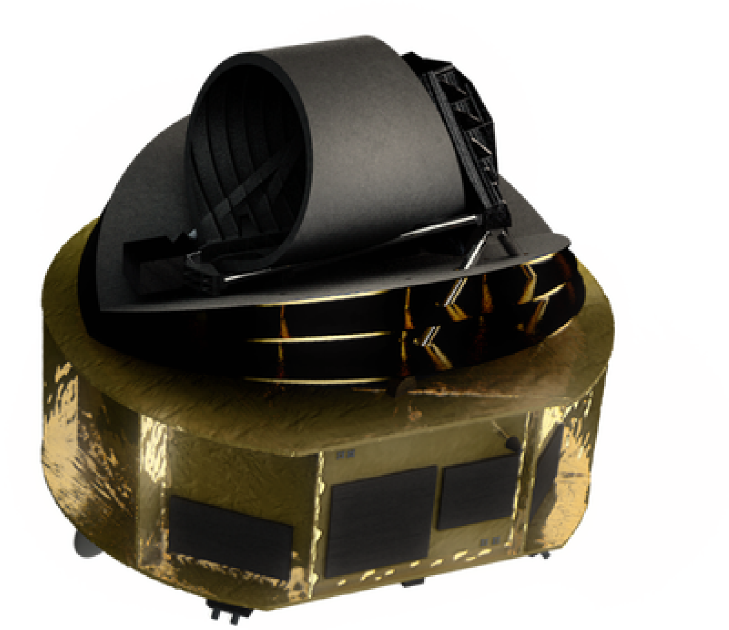


Figure 1. Artistic picture of Ariel. Credit: ESA, STFC, RAL Space, UCL, Europlanet-Science Office.

Ariel is the M4 mission adopted in 2020 by ESA as part of the "Cosmic Vision Program". Its launch is scheduled for 2029 (see Fig 1). The questions that the mission will seek to answer are; what exoplanets are made of and how planetary systems formed and evolved. To do this, Ariel will observe $\sim$ 1000 Neptunian exoplanets and Super-Earths, studying their atmosphere. The observations will take place in spectroscopy and photometry and will cover a range from 0.5μm to 7.8μm.[1]

Ariel's payload consists of a Cold Payload Unit (PLM) with an afocal, unobscured Cassegrain-type telescope inside. The PLM is passively cooled down to $\sim$55K and, through an active cooling system, can go $<$42K when needed.[2]

Optics and optical bench are entirely in Al6061T651 aluminium to maximize heat exchange and to have the same thermo-mechanical properties between the parts.

A mirror the size of Ariel's M1 (1.1·0.7m) has never been made of aluminium for the space. Therefore, there are no already consolidated manufacturing processes. Heat treatment is essential to stabilize a low-density material such as aluminium and make it mechanically workable.

2. ALUMINIUM RISKS OVERVIEW

Some technology development activities (TDA) was run during the project phase B to face and solve the technology risks related to the Ariel telescope aluminium mirrors and bringing the technology readiness level (TRL) of the M1 to 6.

These activities highlighted the main problems of the material, in particular the Al6061T651 Laminated aluminium of which M1 is made. The low density (2.7g/cm^3) makes it light and easily workable, but for that also malleable and elastic. Futhermore, the laminated alloy has internal defects that compromise the polishing of the surface.

2.1 Stress Deformation

The primary mirror is subjected to various kinds of stress throughout its manufacturing and putting into orbit process:

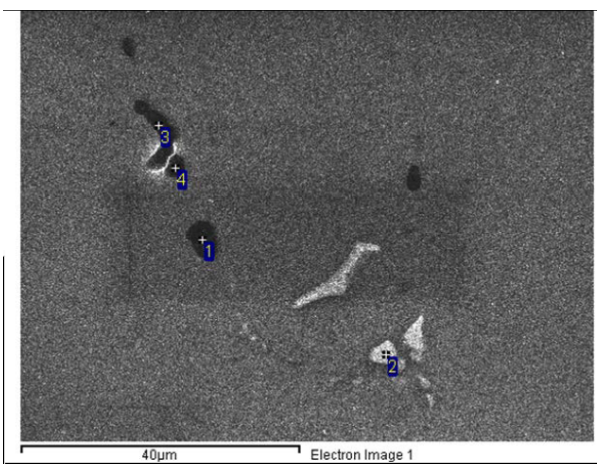
- the processing environment is at 1g; therefore, it is affected by its own weight (∼160Kg);
- launch operations stress the entire telescope up to 10g
- the same mechanical processes (machining, diamond turning, and polishing) add further stress while working the surface.

Stress, for low-density materials, tends to accumulate inside the machined piece and is released over time, modifying its shape and roughness; the result is that the mirror becomes out of specification. Therefore, the alloy needs to be tempered through a series of thermal cycles to be repeated after each processing. The treatment allows both to release the stress of the previous process (in a controlled environment) and to harden the alloy from time to time.

2.2 Si-Mg Aggregates

Ariel's primary mirror requires the use of Al6061T651 Laminated aluminium. Only the laminated processing allows creates blocks larger than 1.2m. There are other methods to produce the aluminium Al6061T651 whose different production makes the alloy better to realize mirrors, but it is not currently possible to create large blocks; e.g., for the RSA the overall billet dimensions are 57cm in diameter by 15.8cm thick, too little for M1.

However, the alloy produced by the rolling process has a strong presence of Si-Mg aggregates with dimensions to ∼1μm (see Fig 2). These affect the polishing of the optical surface. An aggressive polishing to improve the shape can tear off the aggregates leaving holes that generate a diffuse opacity over the entire surface and a marked increase in the roughness value (See Fig 3).



Processing option : All elements analysed (Normalised)

Spectrum	In stats.	O	Mg	Al	Si	Fe	Total
1	Yes	15.15	19.27	43.36	22.22		100.00
2	Yes			76.87		23.13	100.00
3	Yes	14.10	18.92	48.32	18.66		100.00
4	Yes	18.45		66.68	14.87		100.00
Max.		18.45	19.27	76.87	22.22	23.13	
Min.		14.10	18.92	43.36	14.87	23.13	

All results in weight%

Figure 2. Metallographic analysis of a sample of aluminium Al6061T65, with a scale of 40μm. The bright areas are aggregates of Al and Fe, while the dark areas are aggregates of Mg, Si, and O.

Aggregates are generated in the alloy because the rolling procedure requires heating the raw aluminium block to 400°C before each pass in the roll. The slow temperature variation allows the elements in solution with the

Figure 3. Normasky image obtained with the electron microscope and 5X magnification.The holes are due to the detachment of the aggregates.

aluminium to re-aggregate in structures, mainly Si, Mg and Fe. This defect is therefore intrinsic to the laminated alloy. It must be considered in the development of the heat treatment if we want to improve the polishing of the M1 mirror.

It was decided to perform a Solution treatment at 530°C to bring the aggregates back into the solution in the alloy.

3. HEAT TREATMENT SETUP

The developed heat treatment is based on the recipe developed by the NASA/Goddard Space Flight Center[3] and is distributed throughout the mirror production flow.

The whole heat treatment can be divided into three blocks (see Fig 4):

- the reproduction of the T6 process of the alloy with **Solution treatment** with **Rapid quench** and **Ageing**;
- the hardening of the alloy with the **Uphill quench**;
- the **Cold thermal cycles** before and after processing the optical surface and the **Figure test**.

3.1 Solution Treatment, Rapid Quench and Ageing

The mirror receives the first treatments after the Rough Machining, in which the shape of the surface with allowance is given, and the lightening pockets are made.

The Solution treatment and the Quench in water are made in the same process. The mirror is brought to a temperature of 530°C, maintained for 90min. After 90min, the furnace is opened to allow water to enter and gets the temperature to 29/35°C in 15s.

This treatment reduces the quantity and size of Si-Mg aggregates inside the rolled aluminium. The aggregates at temperatures above 500°C, in fact, dissolve and return to the solution with the alloy. The solution is subsequently frozen with the rapid cooling of the material, fixing the alloy.

Ageing is performed at 175°C in the furnace for 500min to stabilize the mirror after the Quench in water.

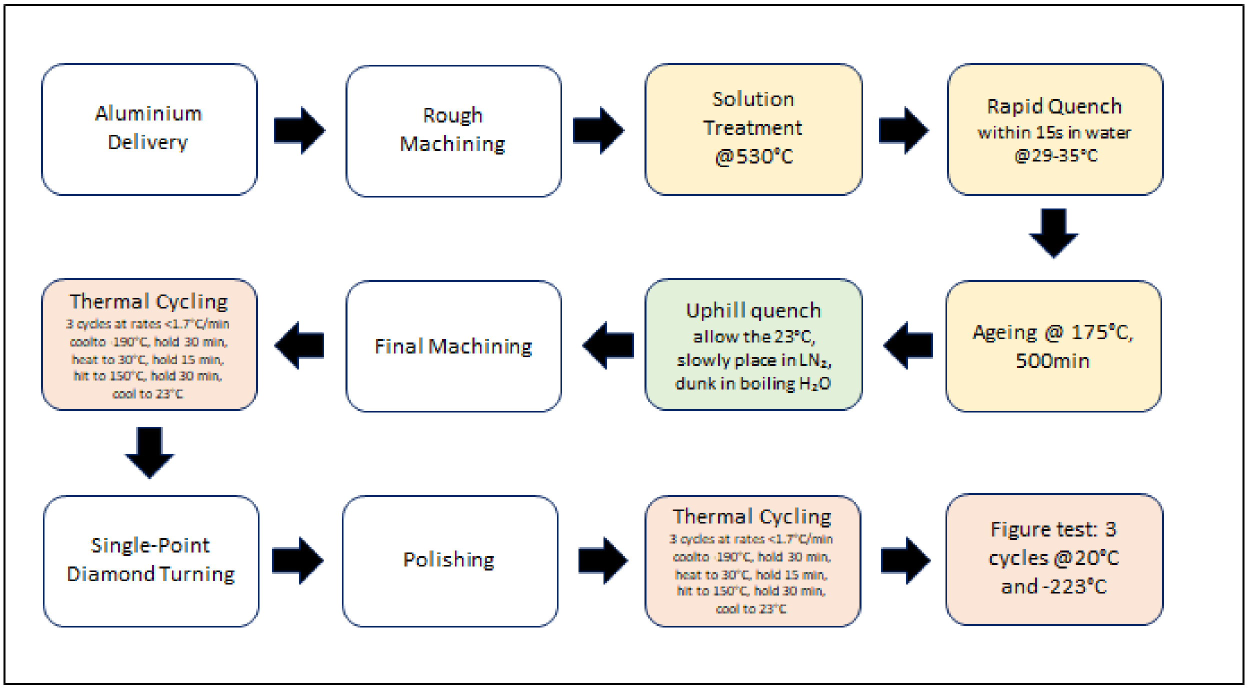


Figure 4. Manufacturing flow of the Ariel telescope mirrors based on Al 6061-T651

3.2 Uphill Quench

The Uphill quench is a cold transfer with thermal shock. The treatment involves cooling from 23°C to -190°C using liquid nitrogen. Once the temperature has stabilized, the mirror is immersed in another chamber with distilled water boiling at 100°C. The process hardens the material and releases internal stresses.

Once the Uphill quench is finished, the mirror is subjected to Final machining in which the stock is removed, corroded by the Rapid quench in water.

3.3 Thermal Cycles and Figure Test

The Thermal cycles are used to release the stress accumulated by the pressure exerted by mechanical processing. Cold thermal cycles are repeated two times during mirror manufacturing. The first time after Final machining, and the second time after Polishing.

The two thermal cycles are performed as follows.

3 cryogenic thermal cycles -190/+150°C:

- Cooling to -190°C (rates <1.7°C/min) from room temperature (with liquid nitrogen);
- Keeping at -190°C for 30 minutes;
- Heating at room temperature (rates <1.7°C/min);
- Keeping at room temperature for 15 minutes;
- Heating at 150°C (rates <1.7°C/min);
- Keeping at 150°C for 30 minutes;
- Cooling at room temperature (rates <1.7°C/min).

The Figure test consists of 3 cryogenic thermal cycles from 20°C to -223°C through liquid oxygen.

After the Diamond turning, the mirror surface has a reflectivity that can be measured at the interferometer to take the Surface error (SFE). By comparing these values, especially those of the second Thermal cycle and the Figure test, if these are very similar, it can be said that the mirror is stable.

4. HEAT TREATMENT APPLICATION

The heat treatment was first applied to disks with diameters from 50mm to 150mm, to understand how to handle aluminium and what to expect between one treatment and the next. Subsequently, it was applied to a second set of prototype mirrors, two breadboards (BB) with a circular shape instead of elliptical with a diameter of 0.7m. This is the maximum size of the available diamond turning machine (LT Ultra Precision, model MTC650). The machine for the larger elliptical mirror is still under development, and it will be ready to manufacture the M1 Engineering Qualification Model (EQM) (LT Ultra Precision, model MTC1200).

4.1 Disks

The disks were made from a block representative of those of the BBs. They were designed to simulate heat treatment on a small scale and develop a polishing recipe (in Media Lario S.r.l. agency). The heat treatment is considered representative of the M1, due to the similar thickness between the discs and the primary mirror with the lightening ($\sim$19mm). Therefore, they have the same heat penetration inside them. It was possible to learn how to handle aluminium before and after the treatments so as not to damage the surface and quantify the necessary excess metal $\sim$0.5mm (see Fig 5).

Figure 5. At left, disks with limescale deposit marks, footprints, and grid marks; at right, same disks after the Final machining and Diamond turning process, removing 0.5mm of excess metal.

4.2 BreadBoards Mirror

The two M1 breadboards are following different development tasks because it is needed for the Ariel program to obtain a preliminary technology assessment by the Payload Preliminary design review (PDR) (on September 2022), that will be completed by the Instrument PDR (on January 2023).

BB1 is needed to mitigate the risk on the overall manufacturing process and the performance of a large-size Al mirror; it will follow the same manufacturing process, as Ariel M1, including the heat treatment.

The mirror after the Diamond turning has a surface roughness S_q=10nm RMS and a shape error SFE=838nm RMS (see Fig 6). The specification of M1 is S_q <10nm RMS and SFE<80nm RMS. The polishing will have to work mainly on the shape, trying not to deteriorate the roughness. The heat treatment is expected to dissolve the aggregates of the alloy, making this process easier.

BB2 is needed to de-risk the manufacturing processes, Rough machining, Diamond turning, and Polishing without the heat treatment. Furthermore, it will be a means of comparison to quantify the effectiveness of the developed heat treatment.

The mirror after the Diamond turning has a surface roughness S_q=7nm RMS and SFE=348nm RMS (see Fig 6). Difficulty in achieving form specifications is expected due to undissolved aggregates.

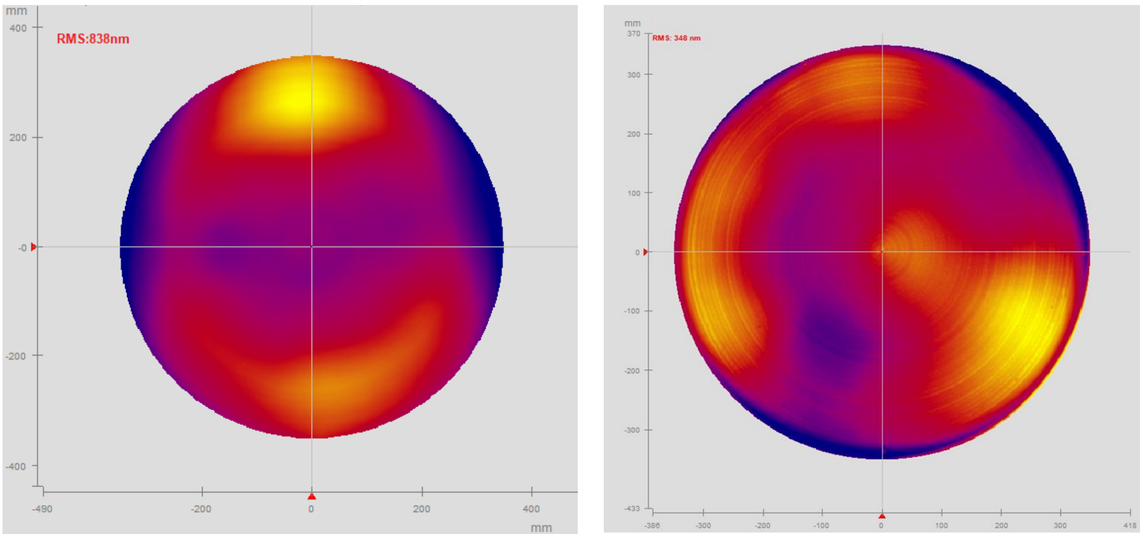


Figure 6. SFE interferometric measure of the BB1, at left , and BB2, at right.

5. CONCLUSIONS AND NEXT STEPS

The values obtained from the two BBs after the Diamond turning do not state that the processing is better in the BB2. The Diamond turning can bring an aluminium mirror to $S_q \sim 10$nm RMS and SFE$< 1\mu$m values. The final check on the effectiveness of the heat treatment on aluminium will be with polishing.

The mirrors will be polished between July and September 2022, primarily, the BB2, which is the de-risking mirror of the process, and then the BB1. Machining to shape specification of the BBs is expected to be faster in the BB1 than in the BB2, due to the solubilization of the aggregates and the tempering of the mirror. The SFE and Sq final values should be better in BB1 than in BB2. Once this result has been verified, it will be possible to assign TRL6 to the payload PDR to the heat treatment.

Once TRL6 is reached, it will be possible to apply the process to the EQM of the actual dimensions of Ariel's primary mirror scheduled in 2023.

6. ACKNOWLEDGMENTS

This activity has been realized under the Implementation Agreement n. 2021-5-HH.0 of the Italian Space Agency (ASI) and the National Institute for Astrophysics (INAF) Framework Agreement "Italian Participation to Ariel mission phase B2/C" and under the ASI contract n. 2021-21-I.0 "ARIEL TA Phase B Industrial Activities" to Leonardo S.p.A and Media Lario s.r.l. companies.

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