Protected silver coating for Ariel telescope mirrors: study of ageing effects

Ines Ypi[a,b], Paola Zuppella[b,c], Paolo Chioetto[b,c], José Antonio Araiza-Durán[c], Umberto Barozzi[e], Lorenzo Barubiani[e], Georgia Bishop[f], Pasquale Bonfà[d], Daniele Brienza[d], Anna Brucalassi[c], Matteo Burresi[e], Andrew Caldwell[f], Fabio D'Anca[h], Alexander Davidson[f], Lucile Desjonqueres[f], Marco Di Giampietro[e], Rachel Drummond[f], Paul Eccleston[f], Paolo Ferro[a], Debora Ferruzzi[c], Enrico Fossati[e], Gabriele Grisoni[i], Elisa Guerriero[h], Lucia Ianni[e], Lorenzo Maddii Fabiani[e], Giuseppe Malaguti[j], Giuseppina Micela[h], Federico Miceli[e], Emanuele Pace[k], Enzo Pascale[l], Raffaele Piazzolla[d], Paolo Picchi[k], Carlo Pompei[e], Giovanni Postiglione[e], Giampaolo Preti[l], Mario Salatti[d], Antonio Scippa[g], Caroline Simpson[f], Giovanna Tinetti[m], Elisabetta Tommasi[d], Leonardo Tommasi[e], Andrea Tozzi[c], and Dervis Vernani[i]

[a]Department of Management and Engineering, University of Padova, Stradella S. Nicola 3, 36100 Vicenza, Italy

[b]CNR-Institute of Photonics and Nanotechnology of Padova, Via Trasea 7, 35131 Padova, Italy

[c]Astrophysical Observatory of Arcetri, INAF, Largo E. Fermi 5, 50125 Firenze, Italy

[d]ASI-Italian Space Agency, Via del Politecnico snc, Roma, Italy

[e]Leonardo S.p.A., Via delle Officine Galileo 1, 50013 Campi Bisenzio, Firenze, Italy

[f]RAL Space, STFC Rutherford Appleton Laboratory, Didcot, Oxon, OX11 0QX, UK

[g]Department of Industrial Engineering, University of Florence, via di Santa Marta n.3, 50139 Firenze, Italy

[h]Astrophysical Observatory of Palermo, INAF, Piazza del Parlamento 1, Palermo, 90134, Italy

[i]MediaLario S.r.l., Via al Pascolo 10, Bosisio Parini (LC), 23842, Italy

[j]Astrophysics and Space Science Observatory of Bologna, INAF, Via Piero Gobetti 93/3, Bologna, 40129, Italy

[k]Department of Physics and Astronomy, University of Florence, Largo E. Fermi 2, Firenze, 50125, Italy

[l]Department of Physics, La Sapienza University of Rome, Piazzale Aldo Moro 2, Roma, 00185, Italy

[m]Department of Physics and Astronomy, University College London, Gower Street, London, WC1E 6BT, UK

ABSTRACT

The Atmospheric Remote-sensing Infrared Exoplanet Large-survey (Ariel), selected as ESA's fourth medium-class mission in the Cosmic Vision program, is set to launch in 2029. The objective of the study is to conduct spectroscopic observations of approximately one thousand exoplanetary atmospheres for better understanding the planetary system formation and evolution and identifying a clear link between the characteristics of an exoplanet and those of its parent star.

The realization of the Ariel's telescope is a challenging task that is still ongoing. It is an off-axis Cassegrain telescope (M1 parabola, M2 hyperbola) followed by a re-collimating off-axis parabola (M3) and a plane fold mirror (M4). It is made of Al 6061 and designed to operate at visible and infrared wavelengths. The mirrors of the telescope will be coated with protected silver, qualified to operate at cryogenic temperatures.

Further author information:
Ines Ypi: E-mail: inesypi@pd.ifn.cnr.it

Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation VI,
edited by Ramón Navarro, Ralf Jedamzik, Proc. of SPIE Vol. 13100, 1310067
© 2024 SPIE · 0277-786X · doi: 10.1117/12.3017768

The qualification of the coating was performed according to the ECSS Q-ST-70-17C standard, on a set of samples that have been stored in ISO 6 cleanroom conditions and are subjected to periodic inspection and reflectance measurements to detect any potential performance degradation. The samples consist of a set of Aluminum alloy Al 6061-T651 disks coated with protected silver.

This paper presents the results of the morphological characterization of the samples based on Atomic Force Microscopy (AFM) and the reflectivity measurement in the infrared by Fourier Transform Infrared (FTIR) spectroscopy.

Keywords: Ariel mission, AFM, FTIR, silver coating.

1. INTRODUCTION

Ariel (Atmospheric Remote-sensing Infrared Exoplanet Large-survey) was selected as the candidate for the fourth medium-class mission (M4) under the ESA (European Space Agency) "Cosmic Vision" program in June 2015.[1]

As of the time of writing, Ariel has successfully completed the payload Preliminary Design Review (PDR) with a planned launch scheduled for 2029. Its ultimate destination is the Sun-Earth Lagrange point 2 (L2), situated approximately 1.5 million kilometers beyond Earth in the direction away from the Sun.

The primary objective of Ariel is to conduct an extensive survey by observing the atmospheres of a set of exoplanets and the characteristics of their parent star using near-infrared spectroscopy. Scientists aim to utilize this data to address various questions related to understanding the processes leading to the formation and evolution of planets. This will also contribute to our understanding of our own Solar System.[2]

To fulfill its mission, Ariel features a reflective telescope, with a primary mirror (M1) of 1.1 m by 0.73 m elliptical aperture. This is followed by a hyperbola (M2), a re-collimating off-axis parabola (M3) and a plane fold mirror (M4).

All mirrors are made of Al 6061-T651 aluminum alloy and optical bench structures of Al 6061-T652. This selection aims to maintain the necessary stability and precision for accurate pointing by mitigating the effects of thermoelastic deformations, particularly at the interfaces of different structural components, induced by temperature gradients and fluctuations over Ariel's operational lifespan at cryogenic temperatures (50 K).[3]

Moreover, to increase and maintain the reflectance of the optical surface in the VIS-IR operating wavelength (0.5 µm-7.8 µm), a coating made of protected silver developed by CILAS (Cilas Ariane Group S.A.) has been applied. A dedicated qualification campaign has allowed the coating to reach Technology Readiness Level (TRL) 6 according to ISO 16290.[4]

The samples of Al 6061-T651 with a protected Ag coating used for the coating qualification campaign, are disks of 25 mm of diameter, 6 mm of thickness. All samples have been cut from the same plate of rolled Al 6061-T651 which was initially used in the fabrication of the prototype for the primary mirror. The protected silver coating of the mirrors is a stack, consisting of an adhesion layer of NiCr, a reflective Ag layer and at the top a nanostructured protective layer.

The reason for studying the possible aging effect lies in the characteristics of silver: on one hand silver is the prime candidate for high performance applications in both visible and infrared mirror technology because of its high reflectivity, low emissivity, and lowest polarization splitting of all metals. However the presence of common atmospheric pollutants initiates tarnishing and corrosion processes in silver, leading to a deterioration in reflectivity and an escalation in scatter, thereby significantly compromising its optical performance. Silver coatings are particularly vulnerable to damage from humidity, sulfur, and chlorine pollutants, which are present even in controlled cleanroom settings.[5]

Therefore it's crucial to make sure that the coating stays intact from the moment it's applied to the telescope mirrors until launch (approx. 3 years), in order to maintain its performance over time.

2. EXPERIMENTAL

Since the samples have undergone different sets of qualification tests, five of them have been selected as representative, as seen in Figure 1.

	Humidity	Thermal	Adhesion Level 2	Cryotest	Cleaning	Abrasion
SN1			✓	✓	✓	
SN02M(L02)			✓			
SN04M(L04)	✓		✓			
SN06M(L06)			✓	✓		
SN08M(L08)	✓	✓	✓	✓	✓	✓

*all samples have undergone visual inspection and spectral relative reflectivity

Figure 1. Qualification tests to which the samples have been subjected.

Sample SN1 is part of the first deposition run conducted on April 3rd, 2019 by CILAS, whereas the remaining samples are from the qualification run carried out on December 12th, 2019 by CILAS.

The ECSS-Q-ST-70-17C standard, developed by the European Cooperation for Space Standardization (ECSS), gives a minimum set of testing techniques to validate the coating process and also gives some meaningful criteria results about exposure of the coating in its operating environment, which are essential for ensuring the durability of coatings for space applications.[6] The specifications of the test conducted on the samples are found in Figure 2.

	Specifications
Visual inspection	ISO 9211-4 Annex C
Humidity	ISO 9022-2 Method 12 Severity 06, test duration of 24h, 90 % RH, 24 h, 55±3 °C (no condensation)
Thermal	ISO 9022-2 T. range: -40 °C / +70 °C, T. change rate: 2°C/min, Dwell time: 15 min, Nr of cycles: 30
Adhesion lv. 2	ISO 9211-4 Method 2 Severity 2
Cryotest	ECSS-Q-ST-70-04C T. range: 54 K / 293 K, T. change rate: 5°C/min, Dwell time: 15 min, Vacuum : < 10-4 mbar
Cleaning	Testing using supplier's procedure at room temperature and ambient pressure
Abrasion	ISO 9211-4 Method 01 Severity 01

Figure 2. Specification of processes and treatments employed.

To verify that performance of the coating hasn't been compromised (aging effect) during storage in ISO6 cleanroom, the following paragraphs describe the verification methods that have been employed. All of the test were performed at the Institute for Photonics and Nanotechnologies of the National Research Council (CNR-IFN) in Padova, Italy.

2.1 Visual inspection

The first method used for the analysis is the Visual Inspection (VI) conducted according to ISO 9211-4 Annex C.

The purpose of this inspection is to identify any defects present on the optical surface of the samples. During this process, all samples have been handled with cleanroom gloves and protective mask, at room temperature and ambient pressure.

2.2 Atomic Force Microscopy

For qualitative analysis of surface topography and surface roughness measurement, an Atomic Force Microscope (AFM) was employed.

AFM surface imaging is achieved by scanning the surface with a cantilever featuring a nanometer-sharp silicon tip. The instrument was operated in non-contact mode, meaning that the cantilever is vibrated near the sample's surface while maintaining a distance of 1-10 nm, in the region of attractive interaction forces.

The scans (10 µm x 10 µm, 256^2 pixels) were taken with a Park System XE-Series 70 and Park NX10 microscopes and processed with XEI, the provided proprietary software.

To assess any morphology variation, the required criteria for M1 is to maintain surface roughness below 10 nm RMS.

2.3 Fourier Transform Infrared Spectroscopy

The IR spectra reported were all recorded by a Nicolet i5s FTIR spectrometer interfaced to a '10Spec' specular reflectivity accessory by Pike Technologies, and processed with the Nicolet 'OMNIC' software. The spectra were recorded at 4 cm^{-1} resolution, 16 scans per spectra. The specular reflection configuration offers a non-destructive approach for measuring reflectance of thin reflective coatings .

In the employed configuration, infrared light was directed onto the Al 6061 samples at an Angle of Incidence (AOI) of 10 degrees. The reflected light was then collected and analyzed. Measurements were ratioed against a background reference obtained from a calibrated aluminum sample (ALREF-21017) provided by Filmetrics, which offers a reflectance standard in the range of 0.165 µm to 2.2 µm.

Reflectance standards are essential for establishing a spectrometer baseline. Starting from calibrated curves initially provided by the manufacturer within a narrow range, a set of optical constants was determined to best characterize the optical properties of the reference sample. Once these optical constants were established, they were used to calculate reflectance in the range of 2.5 µm to 20 µm and normalize the reference signal over the extended range.

For reflectance performance the specification limit is 90%, while the goal is 95%.

3. RESULTS

3.1 Result of visual inspection

The criteria followed for visual inspection is that during the check, no degradation should be evident by eye compared to the initial inspection.

A detailed comparison was made using photographs of the samples and drawings of the visible defects. When comparing the images from April 2022 with those taken in October 2023, no signs of degradation were observed after the storage period and no new defects were apparent.

Representative photos of the samples are shown in Figures 3 and 4. On the left side of the image is reported the sample before the storage period and on the right side the same sample at the end of the test.

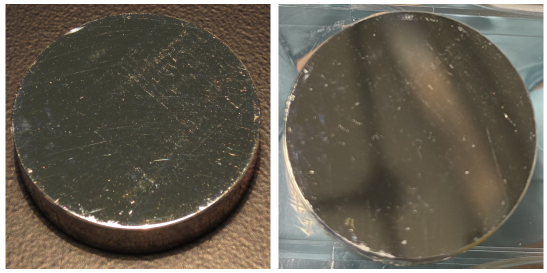


Figure 3. Photographs of SN1 before (left) and after (right) the storage period.

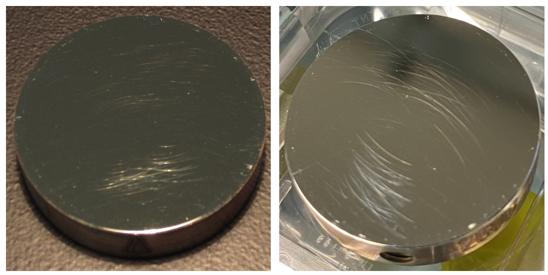


Figure 4. Photographs of SN02M before (left) and after (right) the storage period.

3.2 AFM Roughness Analysis

The analyzed samples were SN02M, SN04M, SN06M, and SN08M because they had been previously measured at CNR-IFN in Padova, allowing for a meaningful comparison. Figure 5 shows the topography of a representative area (5 µm x 5 µm) of sample SN06M.

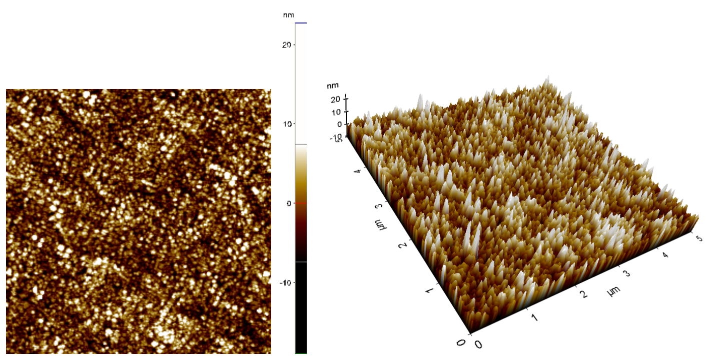


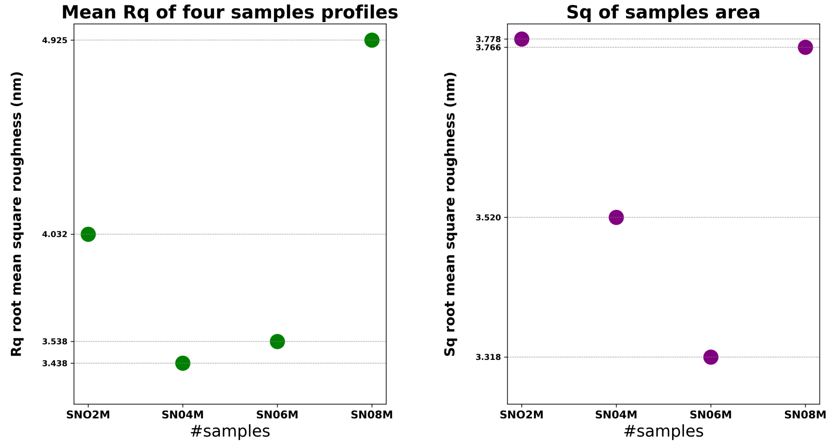
Figure 5. Height map of sample SN06M and its 3D representation.

Roughness measurements are reported in terms of Rq (nm) for the line profiles, with the data representing the average of four profiles taken from each sample. These measurements were conducted using a Park NX10 microscope. Roughness is also reported as Sq to measure the area roughness, with these measurements performed using a Park System XE-Series 70 microscope. Figures 6a and 6b show that the roughness of the samples is in the range 3.3-4.9 nm.

Moreover, Figure 7 presents the roughness parameters of two linear profiles of sample SN04M.

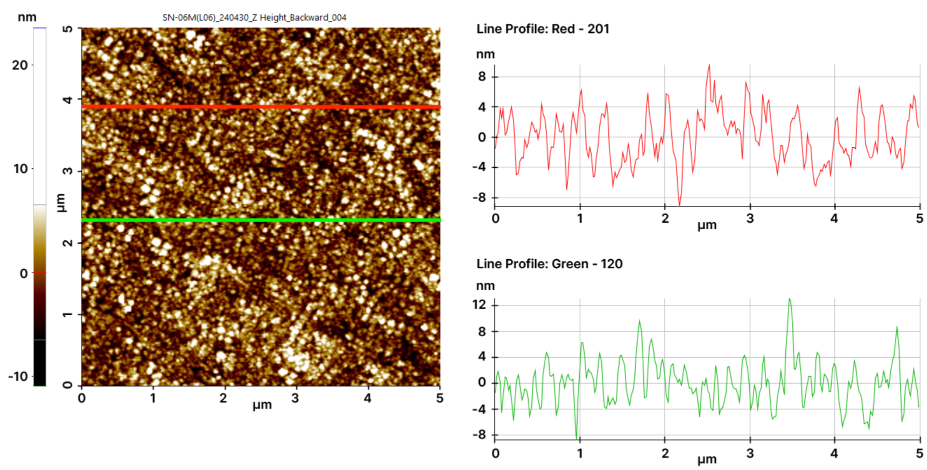
3.3 Reflectance results with FTIR analysis

Reflectance measurements of sample SN1 were provided by CILAS in the waveband 2.5 µm - 22 µm. Figure 8 shows the comparison with reflectance data measured at CNR-IFN for SN1. The difference in the measurement is ±1%.



(a) Rq graph of selected samples. (b) Sq graph of selected samples.

Figure 6. Roughness measurements of four samples.



Statistics

Line	Min(nm)	Max(nm)	Mid(nm)	Mean(nm)	Rpv(nm)	Rq(nm)	Ra(nm)	Rz(nm)	Rsk	Rku
Red	-9.152	9.551	0.200	0.000	18.703	3.313	2.748	13.911	0.093	2.622
Green	-8.802	13.090	2.144	0.000	21.892	3.397	2.584	15.738	0.596	4.232

Figure 7. Linear profiles of sample SN06M.

The measurements of samples SN02M, SN04M, SN06M, and SN08M were conducted for the first time at CNR-IFN and will be taken into account for future comparisons. Figure 9 shows the spectra of the samples in the range 3 µm - 8 µm, which remains above the acceptable limit of 90%.

The drop at around 4.2 µm can be explained by the fact that the FTIR measurements were conducted in an environment that was not completely sealed. Since the band around 4.2 µm corresponds to one of the fundamental vibrational transitions of the CO_2 molecule, this drop in the spectra is due to the absorption of infrared light by the CO_2 present in the atmosphere.

The spectra of sample SN06M exceed the 100% line, likely due to background noise and external interferences affecting the reflectance data. A detailed analysis of these errors is ongoing. It's also planned to improve the configuration by purging the measurement environment with a nitrogen flow.

	3 µm	5 µm	7,8 µm
SN1 Refletance by CILAS	98,416	99,610	99,768
SN1 Reflectance by CNR-IFN	99,210	99,345	99,084

Figure 8. Comparison of reflectance measurements at representative wavelenghts.

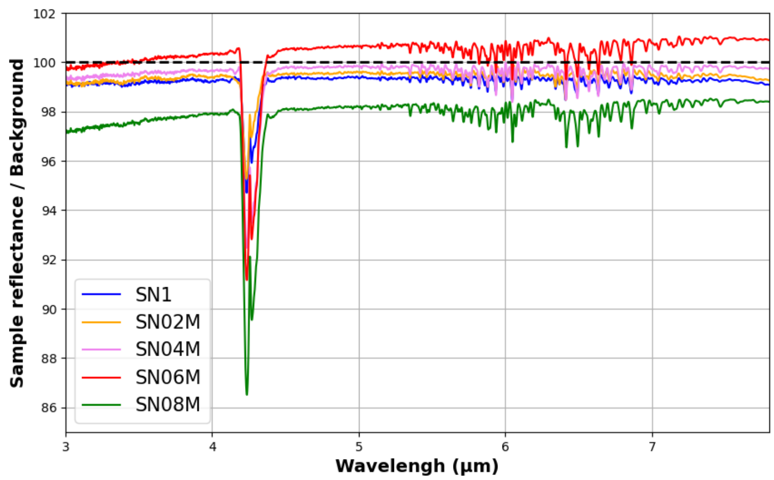


Figure 9. Reflectance of samples in the range 3 µm - 8 µm.

4. CONCLUSIONS

The samples of Al 6061-T651 with a protected silver coating have been subjected to tests to verify qualitative aspects, roughness, and reflectance over time.

There were no signs of degradation observed after the storage period when compared to the initial inspection conducted in April 2022. This observation aligns with the established criteria for acceptable performance. Moreover the surface topology remains qualitatively consistent, with surface roughness still below the required 10 nm RMS. The AFM measurements indicate surface roughness within ± 1 nm of the previous measurements performed at CNR-IFN in April 2022. Finally, all reflectance measurements are within acceptable limits.

In conclusion, the results of the tests showed no significant alteration in the optical performance nor deterioration of the coating. While the ageing effect does not present critical issues at this time, it should be monitored over time to assess any potential future impact.

ACKNOWLEDGMENTS

This activity has been developed under the Implementation Agreement n. 2021-5-HH.0 “Italian Participation to Ariel mission phase B2/C” between the Italian Space Agency (ASI) and the National Institute for Astrophysics (INAF) and under the ASI contracts n. 2021-21-I.0 “ARIEL TA Phase B Industrial Activities” and n. 2023-42-I.0 “ARIEL TA Phase C/D1 Industrial Activities”.

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