



European non-reflective thin polymer films for space sails

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Received 5 May 2026; Received in final form 10 May 2013; Accepted 13 May 2013;

Available online 15 May 2013

Abstract

In low Earth orbit (LEO), ATOX is highly reactive and erodes spacecraft materials over time. ATOX-resistant materials for drag sails, flexible solar arrays, thermal insulation and other structures exposed directly to the space environment, and especially in ram direction, are essential to ensure durability and long lifetime of satellites in LEO. Furthermore, the growing number of satellites creates bright streaks in telescope images, disrupting optical and infrared astronomy, and could cause confusion and sometimes fear among those unfamiliar with the phenomenon. This increases the necessity to consider “dark and quiet skies” in the design process of satellites.

A German-Austrian consortium develops new ATOX-resistant thin film products, considering the needs to ensure dark and quiet skies, and especially meeting the needs of the European market. The development is conducted under the ESA funded General Support Technology Programme (GSTP) Project ProFilm (4000145511/24/NL/KK/mdu; however, the views expressed herein can in no way be taken to reflect the official opinion of ESA). With modified polyimides two polymer films, a black and transparent one, are produced with different thicknesses. The thin films are further processed depending on the applications, for example applying coatings, perforations, or adhesives.

With the first prototype materials that have been produced, initial tests were carried out to determine mechanical and thermo-optical properties. Those parameters were determined before and after thermal cycling. For the future production of the thin films an upscaling of the production facilities is currently being implemented. The initial test results as well as the planned qualification test campaign, which includes thermal cycling, UV-testing, and ATOX-testing are presented.

This paper introduces thin films for space, made in Europe, boosting LEO endurance while enabling dark skies with next-gen space sails, solar arrays, and thermal insulation.

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Keywords: materials; thin films; qualification testing; space environment; dark skies; drag sails

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Abbreviations

ADEO	Drag Augmentation Deorbiting System
Al	Aluminium
AO/ATOX	Atomic Oxygen
Au	Gold
CAD	Computer-Aided Design
CIF	Complex Irradiation Facility
CTC	Charge-Transfer Complex
DLR	German Aerospace Center
DSC	Differential Scanning Calorimetry
EDX	Energy Dispersive X-ray Spectroscopy
ESA	European Space Agency
ESD	Electrostatic Discharge
ESH	Equivalent Sun Hours
ESTEC	European Space Research and Technology Centre
FEP	Fluorinated Ethylene Propylene
FTIR	Fourier-Transform Infrared Spectroscopy
GEO	Geostationary Orbit
GSTP	General Support Technology Programme
ITO	Indium Tin Oxide
LEO	Low Earth Orbit
LEOX	Low Earth Orbit Oxidation facility
MLI	Multi-Layer Insulation
PAA	Poly(amic acid)
PET	Polyethylene Terephthalate
SLI	Single Layer Insulation
UV	Ultraviolet
VLEO	Very Low Earth Orbit
VUV	Vacuum Ultraviolet

1. Introduction

The advancement of thin film technologies has significantly contributed to the development of high-performance materials for space applications, where extreme environmental conditions demand materials that can withstand the harsh space environment. In-space materials must withstand thermal cycling, intense ultraviolet (UV) radiation, atomic oxygen erosion, and micrometeoroid impacts. Coated thin films, due to their lightweight nature and tuneable properties, are a proven design solution in various spacecraft systems, including thermal control surfaces, optical elements, solar cells, and protective layers.

A fundamental consideration in the development of thin-film systems is the choice of the polymer substrate, which strongly influences the adhesion, mechanical integrity, and overall performance of the coating. Besides the above-mentioned durability requirements, space applications also require low outgassing rates to avoid contamination of other functional surfaces and components. Commonly used polymer substrates are polyimides (e.g., Kapton®), valued for their excellent thermal

resistance and mechanical stability; polyethylene terephthalate (PET), which offers good mechanical strength and optical clarity; and fluorinated ethylene propylene (FEP), often used for its low surface energy and ATOX resistance.

Traditionally, materials such as aluminium (Al), gold (Au), silver (Ag), silicon dioxide (SiO₂), and indium tin oxide (ITO) have been widely employed in thin-film coatings for space due to their favourable optical, electrical, and thermal characteristics. These materials are often deposited via sputter techniques.

In recent years, more and more satellites were launched into Low Earth Orbits (LEO) and even their application in Very Low Earth Orbits (VLEO), below 200 km altitude, is considered ever more frequently Union of Concerned Scientists (2024); Fasoulas et al. (2025). This has significantly increased the need for ATOX resistant substrates. Furthermore, the massive increase in launches also raises questions about how to preserve dark and quiet skies as pointed out by the European Southern Observatory (ESO). This is of particular importance for drag sails which are used to quickly de-orbit satellites at the end-of-life.

The availability of such materials in Europe is very limited, and they are often sourced from suppliers outside Europe. With supply chain disruptions in recent years, an independent European supply of these materials has become increasingly relevant. Within the ESA ProFilm project, fluorinated polyimide thin films manufactured in Europe are developed to address this need. A detailed disclosure of all process parameters is beyond the scope of this paper; certain synthesis and processing details are proprietary and are therefore not reported here. The description provided is intended to convey the overall approach and the resulting material properties rather than a complete manufacturing recipe.

The following sections describe the initial stages of the project, in which laboratory-scale developments are advanced toward the manufacturing of functional products for space applications. Section 2 gives an overview of the products to be developed. Sections 3 and 4 provide an overview of the manufacturing processes and Section 5 describes the testing already carried out and planned to characterize and qualify the materials for space applications.

2. ProFilm products

ProFilm aims to establish a product line that provides thin films for various space applications, including

- thermal insulation,
- sun shields,
- flexible solar arrays, and
- drag sails.

These usually transparent thin films will be tailored and further processed into different semi-finished products as shown in Fig. 1. This results in

- black non-transparent films by adding certain additives,

- specific thermo-optical properties (α/ε) by applying coatings,
- incorporating electrical conductivity either through coatings (e.g. ITO) or conductive additives (prevent electrostatic discharge (ESD) events),
- include perforations (venting), and
- sheets with applied pressure sensitive adhesives that allow for bonding the sheets to each other or to other components.



Fig. 1: Semi-finished products of ProFilm thin films. On the left an aluminized polymer film, in the middle a transparent film, and on the right a black non-transparent film.

In general, the ProFilm products can substitute FEP and standard polyimides (e.g. Kapton®) thin films that are currently being used for different space applications. In comparison, the here presented products would provide superior atomic oxygen resistance and mechanical properties. From these semi-finished films, specific products are derived for the application fields outlined above; those products are

- second surface mirrors for thermal insulation (for single or multilayer insulation),
- radiators (for single or multilayer insulation),
- sun shields, e.g. for antennas or other payloads,
- non-reflective drag sails membranes, see HPS GmbH (2025) for ADEO products – Deployable Drag Sails for Deorbit, and
- substrates for flexible deployable solar arrays such as those developed by DLR, see Sprowitz et al. (2023).

In order to fulfill the space specific high-quality standards for low production volumes, all products are manufactured as single sheets with a size of $1\text{ m} \times 0.5\text{ m}$. This is in contrast to mass manufacturing roll-to-roll approaches that are not flexible enough for small production volumes of a variety of products. Single sheets can be bonded together, e.g. with acrylic transfer

adhesive 3M™966, to create larger areas, which covers the size requirements of drag sails currently manufactured. An illustration of the currently implemented manufacturing apparatus is shown in Fig. 2, some details about the manufacturing process are given in the next section.

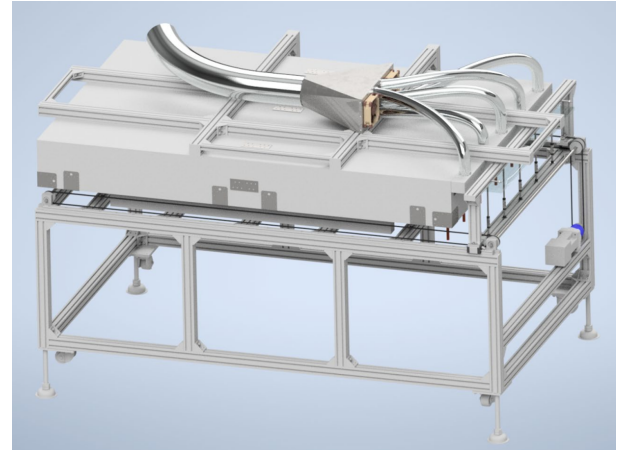


Fig. 2: CAD illustration of the thin film manufacturing apparatus. The apparatus is sized so that single sheets with a size of $0.5\text{ m} \times 1\text{ m}$ can be manufactured.

3. Thin film manufacturing

ProFilm products are based on novel fluorinated polyimide thin films, both transparent and black, synthesized and tailored for the space environment. The process development emphasizes not only mechanical and environmental resilience but also the scaling of the manufacturing process from laboratory-scale film preparation to a dedicated facility capable of reproducibly producing thin-film sheets of approximately $1\text{ m} \times 0.5\text{ m}$ with consistent material properties, while supporting the availability of these materials within Europe.

3.1. Polymer substrate

The selection of the polymer substrate is a critical factor in the development of high-performance thin films for space applications, particularly in LEO, where materials are exposed to high fluences of atomic oxygen (ATOX), UV radiation, and thermal cycling. Fluorinated polyimides were chosen as the base material due to their proven performance in harsh environments and their unique combination of optical, thermal, and mechanical properties.

Fluorinated polyimides exhibit enhanced durability under atomic oxygen (ATOX) exposure compared to conventional polyimides and other common space polymers. This improved resistance is primarily attributed to the high bond energy of carbon–fluorine (C–F) bonds ($\approx 7\text{ eV}$). In the LEO environment, atomic oxygen possesses both high chemical reactivity and kinetic energies of $\approx 5\text{ eV}$ (Banks et al. (2004)). These energetic and reactive oxygen atoms can break weaker bonds in conventional polymers, such as C–C and C–H ($\approx 3.5\text{--}5.0\text{ eV}$), leading to surface oxidation and erosion. In contrast, the stronger C–F

bonds provide enhanced resistance against this combined energetic and chemical attack. The incorporation of fluorine atoms into the polymer backbone therefore offers a chemically robust solution, making fluorinated polyimides excellent candidates for LEO applications, particularly as outer-layer films in drag sails and thermal insulation systems. This behaviour is also discussed in the literature Atkins & de Paula (2014) and Mahmoud et al. (2021).

Beyond ATOX resistance, Liu et al. (2022) describe how fluorination also contributes significantly to the optical clarity of polyimide films. The introduction of trifluoromethyl ($-\text{CF}_3$) groups into the polymer structure exerts strong electron-withdrawing effects and steric hindrance. These structural changes disrupt the regular packing of polymer chains, increase inter-chain distances, and reduce charge-transfer complex (CTC) formation, resulting in greater transparency and lower intrinsic colour. This property is especially critical for applications that require minimal stray light reflection or absorption, such as in flexible solar arrays or optical instruments on board satellites. According to literature, perfluorinated polyimides, where both the diamine and dianhydride monomers are fluorinated, show significantly better optical performance compared to semi-fluorinated analogues.

The performance and longevity of thin film systems in LEO environments are fundamentally tied to the choice and processing of the polymer substrate. Polyimide films are traditionally synthesized through the imidization of poly(amic acid) (PAA), a process that converts precursor chains into the highly stable imide structure characteristic of polyimide. The imidization step is pivotal in determining the final film's performance, influencing factors such as residual stress, optical clarity, and thermal stability. Here, residual stress refers to microscopic stresses generated during solvent evaporation and thermal curing. During imidization, solvent removal, polymer chain rearrangement, and thermal gradients across the film thickness may introduce internal stresses within the polymer network, which can influence film flatness and mechanical stability. Within the scope of manufacturing upscaling, three principal imidization approaches were investigated: one-step thermal imidization, two-step thermal imidization, and chemical imidization.

The one-step thermal imidization, also known as the direct or "one-pot" method, combines polymerization and imidization in a single high-temperature step, typically in the presence of catalysts and high-boiling solvents. While this approach simplifies processing by avoiding intermediate PAA handling, it is mainly suitable for specific polyimide chemistries involving aliphatic or weakly reactive monomers. Its application in high-performance polyimide film manufacturing remains limited due to lower molecular weight control, potential formation of insoluble intermediates, and a lack of tunability in film casting.

The two-step thermal imidization method is most robust and a widely established approach. It allows precise control over film casting and imidization by separating the synthesis of PAA and its conversion to polyimide. Following casting onto a substrate, thermal curing above 300°C is employed to achieve complete imidization. This process is cost-effective and avoids the need for expensive catalysts, making it attractive for industrial

scale-up. It produces films with excellent mechanical and thermal properties, critical for applications such as drag sails and thermal insulation layers. However, the high imidization temperature introduces challenges including energy demands, potential yellowing, and oxidation effects, particularly where optical transparency is required.

In contrast, chemical imidization enables processing at significantly lower temperatures ($25\text{--}150^\circ\text{C}$), offering advantages for optical applications and reducing thermal stress on sensitive substrates. By incorporating dehydrating agents and catalysts, chemical imidization can yield polyimides with improved optical transmittance and lower surface energy, simplifying release from casting substrates. This method also mitigates high-temperature degradation effects, a known concern in optical applications where colour stability is vital. However, its suitability for large-scale production is limited by higher raw material costs, a more complex processing chain, and frequent need for post-curing at elevated temperatures to achieve full imidization and mechanical stability (see also Liu et al. (2022)).

A trade-off analysis was conducted to assess all three methods against criteria such as scalability of the manufacturing process from laboratory samples toward larger sheet production, cost, film quality, and process robustness. While each presents distinct advantages, the two-step thermal imidization process was confirmed as the most appropriate baseline method for the project and the manufacturing upscaling pathway. Its ability to deliver mechanically strong and thermally stable films with fewer processing steps and proven repeatability makes it a sound choice for European manufacturing of thin film substrates for next-generation space applications.

3.2. Manufacturing Process

The manufacturing of the thin films, both transparent and black, was developed through a scalable laboratory process, aiming to fulfil the stringent performance criteria for LEO applications. Earlier laboratory work was conducted using A4-sized films and separate processing equipment for casting, drying, and imidization. Within the ProFilm project these steps have been integrated into a dedicated facility, enabling the reproducible production of larger sheets (approximately $1\text{ m} \times 0.5\text{ m}$) and providing a pathway toward future industrial-scale manufacturing. The selected process is based, as mentioned above, on two-step thermal imidization, which enables the fabrication of robust, high-quality polyimide films with well-defined thermal, mechanical, and optical properties.

The process is illustrated in Fig. 3. The precursor of polyimide, PAA, is synthesized under nitrogen atmosphere at room temperature, ensuring high molecular weight and uniform solution quality. For the black variant, selected functional pigments and fillers are homogeneously dispersed into the PAA matrix before casting. The resulting solution is then cast onto glass substrates using a doctor blade, with blade gaps ranging from $200\text{ }\mu\text{m}$ to $1000\text{ }\mu\text{m}$ to achieve final film thicknesses from approximately $25\text{ }\mu\text{m}$ up to $100\text{ }\mu\text{m}$ after imidization.

After casting, the wet films undergo a stepwise drying and imidization sequence in nitrogen atmosphere, from ambient

temperature in different steps to over 300 °C for full imidization. The films are then cooled gradually to room temperature, in order to minimize mechanical stress and cracking. The final cast-off step, in which the film is detached from the substrate, is carried out in boiling water, which enhances the diffusion of moisture to the interface between glass substrate and polyimide thin film, aiding release especially for thicker films where conventional room temperature or cold water baths proved insufficient.

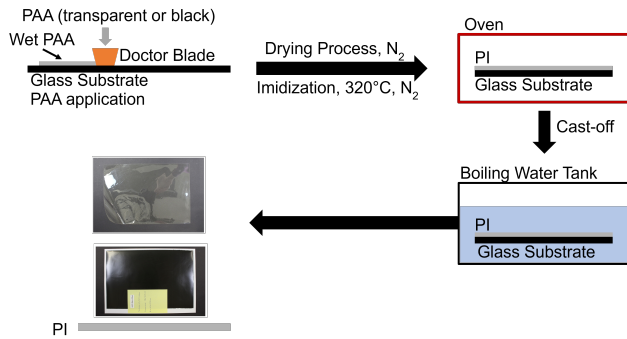


Fig. 3: Schematic representation of the transparent and black polyimide film production via two-step thermal imidization.

Throughout the manufacturing process, key parameters such as the viscosity and concentration of the PAA solution are carefully monitored prior to casting to ensure consistent film quality and reproducibility. After thermal imidization, the film thickness is measured across multiple points to confirm uniformity and adherence to target specifications. Visual inspection is performed systematically to detect surface defects such as bubbles, inhomogeneities, or irregularities that could impact mechanical or optical performance. For quality assurance from the chemical point of view, selected film samples undergo detailed material characterization. Energy Dispersive X-ray Spectroscopy (EDX) is used to determine elemental composition and verify the reproducibility of the thin films via the two-step thermal imidization process. Differential Scanning Calorimetry (DSC) is applied to determine the glass transition temperature (T_g), a key indicator and unique feature of the polymers. According to DSC measurements the T_g of the ProFilm polyimide is ranged between 160–168 °C, which serves as a distinguishing material property and benchmark for batch consistency. Fourier-Transform Infrared Spectroscopy (FTIR) is a useful tool in order to confirm the chemical structure, the reproducibility of the process and finally verify the completeness of the imidization process.

FTIR spectra of polyimide samples from different production batches are presented to show the consistent appearance and intensity of characteristic imide absorption peaks, for example symmetric and asymmetric C=O stretching, C–N stretch (see Fig. 4). In FTIR spectroscopy, the characteristic absorption peaks of polyimides correspond to vibrational modes of specific chemical bonds. The symmetric and asymmetric C=O stretching bands originate from the imide carbonyl groups, while the C–N stretching band corresponds to vibrations of the imide linkage within the polymer backbone. The presence of these

peaks confirms successful imidization of the polymer structure. These combined control and validation steps are essential to ensure each production batch meets the stringent performance requirements for LEO applications and remains consistent with the project’s scalability goals.

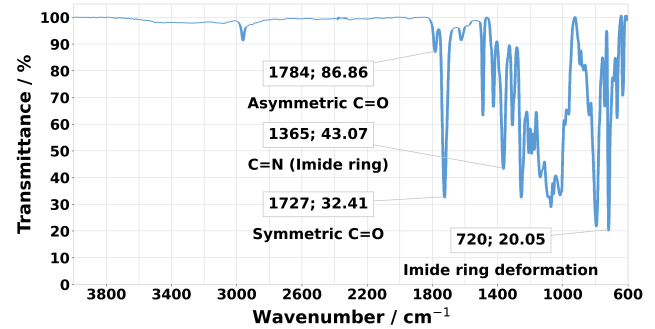


Fig. 4: Representative FTIR transmittance spectrum of the ProFilm polyimide thin film, showing the characteristic imide absorption bands (asymmetric and symmetric C=O stretching, C–N stretching of the imide ring, and imide ring deformation).

4. Thin film processing

Further processing of the thin films is necessary to enable their use for different space applications, such as drag sails and thermal insulation. The main postprocessing steps are the application of coatings, adhesive and perforations as described in the following sections.

4.1. Coatings

The coatings are usually applied through a sputter process. In our case all considered suppliers use magnetron sputter processes. Since we are developing processes that can manufacture single sheets, we also selected the coating processes accordingly so that single sheets can be coated (in contrast to roll-to-roll processes). Building an own sputter coater for our needs would require a total investment of about 1.2 M€ (which is equivalent to the complete project budget). Furthermore, the coating system alone would occupy a footprint of at least about 3 m × 1.5 m, and operating it as a dedicated facility requires at least one technical employee for maintenance and operation. Consequently, we decided to establish relationships to three different suppliers for the coating of our thin films.

The single sheets will be mounted on a frame and in two steps each side can be coated. For quality assurance each batch will be tested by tape lift-off to ensure sufficient adhesion between coating and substrate, thermo-optical properties will be measured and for the ITO also the conductance will be measured.

4.2. Adhesive application

For the manufacturing of e.g. drag sail membrane, but also for single layers of thermal insulation, several foils need to be joined, or the thin films need to be bonded to some kind of surface. For this purpose, adhesive is applied to the thin films.

With our experience in drag sail design and manufacturing, specifically the ADEO products for end-of-life deorbiting, we established a process to apply pressure sensitive adhesives. While it is possible to apply different pressure sensitive adhesives, one standard adhesive that we use and that is a common choice in the space sector is the 3MTM966.

The process is compliant to ASTM D3330 and uses a pressure roller to apply a defined load along the contact line between tape and the thin film. During the application a vacuum table holds the thin film in place while a rail system guides the roll of adhesive and the pressure roller along the sheet. An overview of the design is shown in Fig. 5.

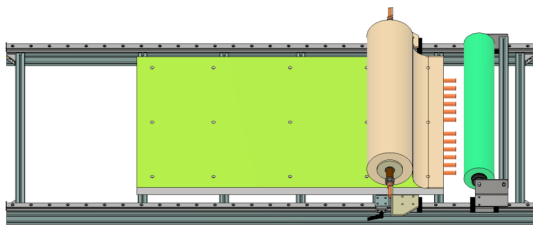


Fig. 5: CAD illustration of the adhesive tool, designed to apply transfer adhesive onto the 1 m × 0.5 m thin film sheets (the complete tool with the support frame is slightly larger). On the very right side the green pressure roller is shown and right beside it is the roll with the adhesive. Both are guided on rails and move along the thin film sheet mounted on the table in-between the rails.

For verification of the application process, tests were carried out in accordance with ASTM D1876. Several small samples of standard Kapton material, MLI foils with perforation as well as MLI without perforation, and initial samples of transparent and black thin-film sheets with different thicknesses, were examined. The resulting values for the peel resistance of these samples are listed in the following Table 1. The results show that the peel resistance of the thin-film samples is in the same range as for standard materials and are comparable to the Kapton samples. The peel-off force for products using 3MTM966 is often stated with 2.2 N/cm (under 90°) on stainless steel. This means that the peel resistance of the ProFilm products is in the same order of magnitude.

4.3. Perforation

For some application such as multi-layer insulation (MLI) blankets, perforation of the thin films is required to enable venting of trapped air inbetween the different layers. For this purpose, several tools and processes have been tested in first experiments and a tool for the automated application of thin films was designed.

While no formal requirements on the perforation quality could be found, initial tests were carried out to identify a suitable approach for the development of a dedicated perforation tool that can create clean cutouts. For initial tests of a mechanical perforation, conical hollow punches with hole diameters of 0.5 mm, 1.0 mm, 1.5 mm, and 2.0 mm as well as straight hollow punches with a diameter of 2.0 mm were used. The wording “conical” and “straight” refers to the geometry of the standard tools used. The first tests were performed on a cutting mat, which was too soft. As a result, the foils were not cut but

Table 1: Results of peel resistance test.

Sample	Film thickness [μm]	Coating 1 type [nm]	Coating 2 type [nm]	Peel resist. [N/cm]
Kapton 1	25	-	-	4.03
Kapton 2	25	-	-	4.70
ProFilm MLI w/o perf.	25	Al 100	Al 100	1.47
ProFilm MLI with perf.	25	Al 100	Al 100	1.66
ProFilm Transp.	25	ITO 50	ITO 50	3.34
ProFilm Transp.	100	Al 100	ITO 10	3.62
ProFilm Black	25	-	-	2.76
ProFilm Black	100	Al 100	-	4.44

pressed into the cutting mat during punching. The results also depend on the hardness of the underlying pad; perforation on a polystyrene plate worked well and is therefore considered for use in the dedicated perforation tool.

The results with conical hollow punches with a diameter of 0.5 mm and 1.0 mm led to holes in which the conical geometry of the punching tool was strongly imprinted. With diameters of 1.5 mm and 2.0 mm of the conical hollow punches, the quality of the holes is better. Perforation by straight hollow punches show very good quality. Due to the straight cutting edge of the tool, there is no conical imprint of the tools geometry.

Furthermore, a second perforation approach with the laser engraving machine USB570E1 from OMTech with a max. power of 100 W has been tested. It uses a CO2 laser with a max. speed of 600 mm/s and an accuracy of 0.01 mm. There are many parameters, like laser power, speed and frequency that vary the results. The results also strongly depend whether the substrate is transparent or black and of course with the thicknesses of the material. However, no parameter could be determined for which a high quality of the holes was achieved. One problem is that edges of the holes often still hold partly burned material. Another problematic aspect is that the material is not completely evaporated but some ash is left behind. This would have required extensive cleaning of the thin films after the perforation process which is considered impractical.

For the perforation of the thin film, a three axis linear drive system for automation was designed. The system enables customized movement of the perforation unit over the entire thin film sheets (1 m × 0.5 m). A vacuum table is used as base and fixation for the samples. The mechanical perforation is realized by moving the vertical actuator. An impact-like movement – as

previously tested using different tools and a force gauge – will be carried out by the machine. A drill chuck is used to mount the punching tool. This allows for an easy tool exchange. Fig. 6 shows an illustration of the tool that is currently assembled.

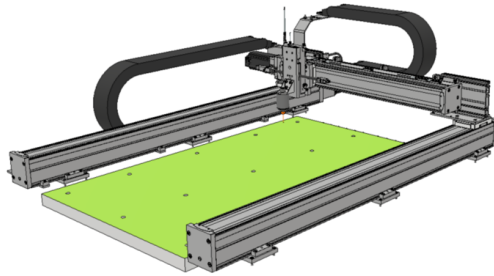


Fig. 6: CAD illustration of the perforation tool showing the three-axis system in-between which the thin film sheets are mounted on a vacuum table.

5. Qualification testing

When testing materials for space application one usually looks at the mission design and its reference scenarios. Here we are trying to qualify not only one product but a whole series of products for various space applications without a specific reference scenario. We are therefore trying to implement a generic test approach, that should demonstrate the general suitability of the products for a wide range of applications.

In a preliminary testing campaign prototype samples (see Fig. 7) have been tested for integrity of the coating during thermal cycling, which will be elaborated in the following section, afterwards a test plan draft for the final products will be presented.



Fig. 7: Samples for preliminary testing (25 mm x 80 mm strips).

5.1. Preliminary Testing

Preliminary testing encompassed in a first step the persistence of various coatings on the polymer films during thermal cycling. The coatings were applied by three different coating suppliers. The test in a climate chamber at DLR is shown in Fig. 8. The tests included 100 cycles between -60°C and 170°C. It

was the widest temperature range possible using the available climate chamber. The samples have been investigated via microscopy and measurements of thermo-optical properties before and after thermal cycling and peel testing. Investigated coatings have been ITO and aluminium. Apart from one sample



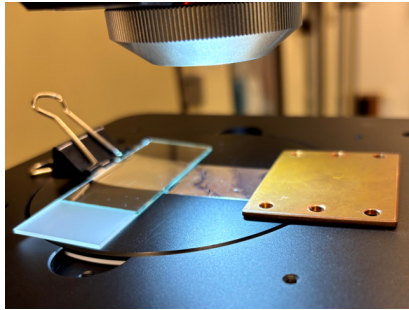
Fig. 8: Preliminary thermal cycling test in a climate chamber at DLR's Institute of Space Systems.

all coatings passed the peel test. It is believed, that the failed sample was contaminated, possibly with silicones, before the coating process. Silicones are omnipresent particles that can go airborne and condense on surfaces, e.g. in this case the film. This highlights the importance of a controlled production process that is currently implemented within the project.

It has been found, that due to the production technique the two sides of the polymer films vary in their properties. The side in contact with the casting plate is very smooth, while the opposite (top) side is rather rough. E.g. the two samples in Fig. 8 are smooth. By applying e.g. the aluminium coating to one side or the other, the specular reflectance can be adjusted to be either high (>0.8) or low (0.3). Total reflectance of aluminium coating is in both cases around 0.8 which is slightly lower than expected for bulk aluminium (≈ 0.92). An image of a measurement is shown in Fig. 9b.

All thermo-optical properties have been found to be unaffected by thermal cycling (from -60 to +170°C for 100 cycles) and peel tests, indicating that the coating was still intact. Due to the limited availability of prototype thin films, peel tests had to be adapted from ASTM D1876-01 (2001). Sample sizes were smaller. The 3M Scotch Magic Tape 810 was used. This tape is used in the relevant ECSS standards and frequently used for optical coatings to test the adhesion. Overall coatings did not show any unexpected behaviour.

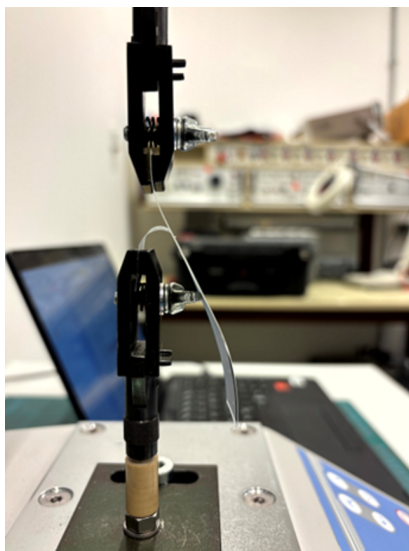
Since all coating suppliers provided a decent coating quality, it will be attempted to qualify all suppliers within the ProFilm activity.



(a) Microscope measurements (with Keyence VHX 7000). Weights have been used to keep the film from bulging.



(b) Reflectance measurements with Surface Optics 410Solar / ET100. On top of the reflectometer is a light trap in order to absorb transmitted light e.g. for transparent drag sails.



(c) Peel-off test in starting position before driving the upper clamp upwards and peeling the tape.

Fig. 9: Investigations of samples before and after thermal cycling.

5.2. Qualification test plan

The test plan is supposed to cover as many application scenarios as possible. Considered environments are LEO, especially for drag sail materials, and additionally the Geostationary Orbit (GEO) for thermal insulation and solar array materials. Testing will be conducted according to ECSS-Q-ST-70-17C (2018).

Environmental factors of relevance are UV irradiation and thermal cycling (including thermal vacuum), proton radiation for GEO and atomic oxygen for LEO. The test campaign also considers humidity testing as a first step of the test campaign.

Taking the experiences from the preliminary tests, the inspection points will include thermo-optical properties but also measurements of the surface conductivity and tensile tests will be included.

UV testing will encompass 4000 ESH, which approximately equals 1.6 years in LEO following estimations of the ECSS-Q-ST-70-06C (2008). The standard assumes for a LEO ISS orbit 2500 ESH on Ram and less on the other sides. Using the Complex Irradiation Facility (CIF) presented by Renger et al. (2014) and its Argon Vacuum-UV source, which generates VUV with an acceleration factor of ≈ 26.3 , requires about 153 hours radiation time for that test. When calculating the laboratory irradiation time, the total irradiance in laboratory and the relevant environment are compared. The laboratory irradiation time is that which generates the same energy deposition inside the investigated samples. Hence, if the laboratory source has an irradiance 26.3 times higher than the actual in the relevant environment, the irradiation time is 26.3 times shorter to reach the same overall fluence.

For thermal cycling a reference scenario encompassing all possible temperatures had to be found. Considering front and rear absorptivity and emissivity as well as SLI versus drag sail scenarios, the lowest and hottest temperatures are likely encountered by the black drag sail configuration, e.g. experiencing 104°C in its hot case and -89°C in the cold case. The temperatures have been derived assuming an LEO Orbit for the hot case, because of increased Earth albedo and IR radiation, and GEO orbit for the cold case. As for the hot case, the sun shines perpendicular onto the surface, whereas a hypothetical sail is assumed to be in Earth shadow for the cold case. In accordance to ECSS-Q-ST-70-17C (2018), at least the first 5 cycles will be tested under vacuum.

For protons, an 18-year reference scenario in GEO has been established. The fluence will be split into low ($<10\text{ keV}$) and high ($>10\text{ keV}$) energetic radiation, because especially coatings are susceptible to low energetic particle radiation.

In a last step the products are to be tested for atomic oxygen erosion using the LEOX facility at ESA/ESTEC. Here the emphasis is mainly on finding the erosion yields for substrates and coatings. The erosion yield against ATOX is defined as volume loss per atomic oxygen atom, given in cm^3 / AO . Then the total loss in volume, or if the exposed area is known, as a thickness loss, can be determined simply by multiplying with the ATOX fluence of a given mission scenario. Then a statement on whether, e.g. a coating, will last until end-of-life or not can be made.

Table 2: Preliminary ProFilm products characteristics. Thinner thickness are still being evaluated indicated by the $< 25 \mu\text{m}$.

Product	Substrate	Thickness	Coating side 1	Coating side 2	α	ε	R
Second surface mirror	transparent	25 μm	100 nm Al	10 nm ITO	0.2	0.7	0.8
Second surface mirror	transparent	100 μm	100 nm Al	10 nm ITO	0.2	0.8	0.8
Black radiator	black	100 μm	100 nm Al	none	>0.9	0.9	<0.1
Black radiator	black	25 μm	none	none	>0.9	0.9	<0.1
Transparent sail	transparent	$< 25 \mu\text{m}$	50 nm ITO	50 nm ITO	-	-	0.2
Black sail	black, semi-transparent	$< 25 \mu\text{m}$	none	none	-	-	0.06

6. Conclusion

We have successfully pre-tested our new products and have evaluated preliminary material parameters. Up-scaling of the manufacturing processes is ongoing and we are preparing an extensive qualification testing campaign for the ProFilm material. Preliminary material parameter are given in Table 2. Here, α is the solar absorptance, ε is the thermal emittance and R is the total hemispherical reflectance. The surface resistance of the 10 nm ITO coating is about 5 k Ω , in principle it is adjustable between 1 k Ω to 10 k Ω . The atomic oxygen erosion yield of the substrates is $7.8 \cdot 10^{-26} \text{ cm}^3/\text{AO}$. This is a significant advantage compared to an erosion yield of Kapton which is about $3 \cdot 10^{-24} \text{ cm}^3/\text{AO}$.

With respect to dark and quiet skies and our work on “dark sails”, the semi-transparent black material has a very low reflectance (see Fig. 10). This will likely be considered for future ADEO drag sails.

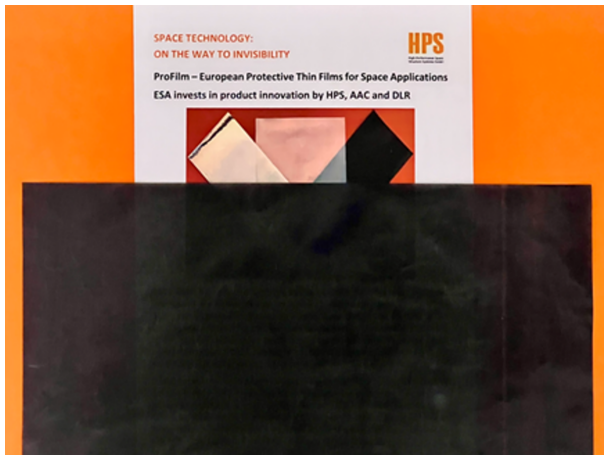


Fig. 10: Semi-transparent black sail material for “dark sails” (for illustration purposes on top of our ProFilm flyer). Reflectance $R=0.06$.

Acknowledgments

This project is carried out with ESA co-funding under ESA Contract 4000145511/24/NL/KK/mdu. We are grateful for the support within ESA’s new GSTP sub-programme “Product Initiative” that supports European companies in establishing products for space. The views expressed herein can in no way be taken to reflect the official opinion of the European Space

Agency (ESA) and are not intended to endorse particular technologies, companies, or products.

We further thank Dr. Yahya Motemani and his Materials & Coating Technology group at the Sekurit R&D Center Germany (Saint-Gobain Sekurit Deutschland GmbH) for their support with the coating of the thin polymer films.

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