Evaluation of the Mechanical Properties of Innovative Spacecraft Materials Under a Low Earth Orbit-Simulated Atomic Oxygen Environment

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Abstract

External spacecraft materials are crucial for protecting satellites from the harsh space environment. This study evaluates the radiation effects of low Earth orbit (LEO) space weather, focusing on high-energy electron and atomic oxygen (AO) exposure, on several modern spacecraft materials. The materials under investigation are "flight duplicates" of samples scheduled for launch as part of the Materials International Space Station Experiment Flight Facility (MISSE-FF) mission in 2025. To observe changes in stress distribution within weathered polymers, the experimental setup based on the photoelasticity technique was developed.

Introduction

During a space mission, spacecraft surface materials are exposed to various damaging environmental factors including high-energy photons, electrons, AO neutrals and ions, micrometeoroids and orbital debris, vacuum, and large temperature fluctuations.[1,2] The resulting change in spacecraft material properties can significantly impact the performance and durability of spacecraft systems. Even though all aspects of the space environment can lead to the deterioration of spacecraft components in LEO, the threat posed by AO is especially severe in terms of structural and optical damage, particularly to exterior spacecraft components that are susceptible to oxidation. A comprehensive understanding of material AO-induced weathering is essential for mission planning in the LEO environment.

In our previous MISSE-16 experiment,[3] we investigated the alterations in the optical properties of various polymers subjected to AO, high-energy electrons, and solar photons in the ram, wake, and zenith directions of the International Space Station (ISS), respectively. One of the conclusions of the MISSE-16 experiment was that AO, especially when combined with vacuum ultraviolet (VUV) irradiation, is the most significant degrading factor in LEO. This research established a foundation for our forthcoming MISSE-22 experiment, scheduled for launch in 2025, which will concentrate on the mechanical properties of novel space-intended polymers predominantly under AO exposure.

Generally, the MISSE projects have focused on post-flight assessment of the various materials exposed to LEO space weather, and only a few experiments have concentrated on examining mechanical properties in orbit. For example, during MISSE-1, a specific test fixture was utilized to subject samples to tensile strain.[4] Upon retrieval, the tensile strength and elongation to failure of the surviving materials were measured. Likewise, during MISSE-7, the test fixture was employed to investigate the effects of flexural stress on samples.[5] To study on-orbit environmentally induced shrinkage or strain, an Active Polymer Strain Experiment (APSE) on MISSE-6 was flown to study strain in several one-end free-standing polymers as a function of time.[6] However, no dynamic changes in material properties under exposure to the complex LEO environment were studied. We aim to characterize the dynamic changes in mechanical properties of novel materials at LEO under AO exposure by integrating an advanced hardware solution based on the photoelasticity technique.

The photoelasticity technique is a commonly used method for measuring stress distribution in transparent or translucent plastic materials.[7] When such materials are subjected to stress, they exhibit birefringence, meaning they split incoming polarized light into two beams traveling at different speeds. This difference in speed, known as optical retardation, causes a pattern of fringes with various colors when viewed through a polarizing filter. These fringe patterns correspond to the stress distribution within the material.

In this study, we present the development of the MISSE-22 hardware prototype and its application in validating the photoelasticity technique for analyzing various polymer materials exposed to AO and irradiated with high-energy electrons. This prototype will be utilized in ground-based experiments to simulate and study the conditions these materials will encounter in space.

Experimental Details

Materials

While the MISSE-22 mission will include twelve different novel AO-resistant polymers from different chemical families, for brevity, we have chosen to focus on representative materials in this study. Polyethylene terephthalate (PET) films are an essential part of multi-layer insulation (MLI). Thermal blankets maintain the thermal properties of a spacecraft, maitaining warm, stable temperatures. In practice, traditional MLI blankets are not perfect and can most likely be improved. With evolving spacecraft technology, soft goods vendors have been challenged to develop newer polymers and thermal shielding that can support small spacecraft (CubeSats) and longer duration exposures, including novel materials, such as those used in MISSE-16 that incorporate plasma charging. We will investigate here one of the novel types of PET, Melinex® 453, intended for improved MLI design and durability. The polyimides (PIs) from the Kapton® family are described as having a unique combination of electrical, thermal, chemical, and mechanical properties that withstand extreme temperature, vibration, and other demanding environments. We included Kapton® CR, a film designed to have improved resistance against coronal partial discharge.

Material Irradiation

High energy electron exposure was performed in the Jumbo space irradiation chamber at the Spacecraft Charging and Instrument Calibration Laboratory (SCICL).[8] Materials were bombarded with high energy (95 keV) electrons produced by a mono-energetic Kimball Physics EG8105-UD electron flood gun. The materials under investigation were exposed to a maximum electron fluence of 8.5 x 10^{13} electrons/cm^2. Details of the electron irradiation procedure are reported elsewhere.[9]

AO exposure was performed using the FAST source at the Physical Sciences Inc., in accordance with ASTM-E2089-15. The effective peak atomic oxygen fluence during the exposure was approximately 3.1 x 10^{20} O/cm^2 and 1.0 x 10^{21} O/cm^2 which corresponds to 6 weeks and 6 months of LEO exposure, respectively. Details of AO-irradiation procedure may be found in.[10]

Setup for Photoelasticity Measurements

To perform the proof-of-concept measurements using the photoelasticity technique, we utilized the large-field SV-2000 Strain Viewer polariscope from Strainviewer, equipped with an LWC-100 compensator and integrated with the Basler daA1600-60uc camera, currently in use at the MISSE-FF. A compensator is a calibrated plate with a scale where retardation varies linearly along its length. When attached to a sample, the displacement of a black line, indicating zero retardation, reveals the stress within the material. Schematic of polariscope setup along with the LW-100 compensator is shown in Fig. 1.

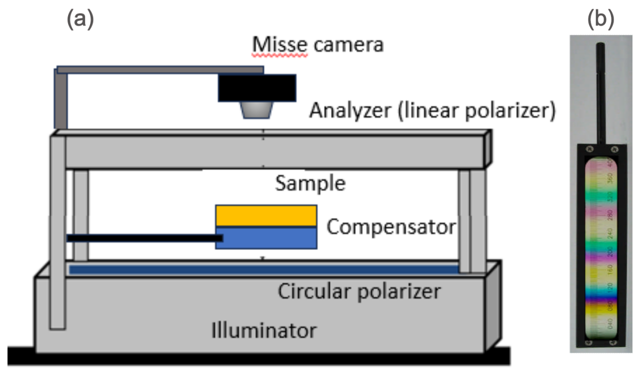

Figure 1: (a) Schematic of polariscope setup, (b) LW-100 compensator

Image Analysis

The scale of LW-100 compensator indicates retardation values along its length. When the compensator is placed in the polariscope, it introduces a controlled amount of retardation to the light passing through the stressed sample. By adjusting the position of the compensator, one can determine the point where the black fringe, indicating zero retardation, aligns with the stress pattern in the sample. Next, if additional color bands appear, they will follow the sequence described in the color sequence table, with the corresponding approximate retardation values indicated.

In order to properly capture these retardation values, we analyzed the images with two separate techniques. Firstly, as the x-axis is primarily where we see fringe information, we averaged over the y-axis, or the rows of the images. From this average, we found the center of the black fringes by finding the minimum-valued position. We then use this minimum to compare between the pristine and aged materials. Secondly, we learn affine transforms[11] between the pristine and aged materials to determine how many pixels the pristine image must be shifted to be similar to the aged sample. Affine transforms are mathematical methods that describe how to scale, rotate, or shift one object (images in this case) to be equivalent to a different object. For this project, only the shift operators are used to determine how the fringe position changes between the pristine and aged materials.

However, it should be noted that this technique only worked for the 5 mil-thick Melinex® 453 aged for 6 weeks as the 3 mil-thick Melinex® aged for 6 months lost the birefringence and contained very little information. Additionally, the affine transform algorithm we use did not converge for any of the Kapton materials. This is most likely due to the tick marks on the compensator, making the images almost identical save for the fringes.

Once we know a black fringe position (r) representing 0 stress and coefficient for recalculation b which is 5.6 nm per division, we can determine retardation (R), and stress (MPa). It can be calculated as follows:

$$R = r \times b \tag{1}$$

$$\text{Stress} = \frac{R}{t \times C_B} \tag{2}$$

where

$$\lambda = \text{Standard wavelength}$$
$$t = \text{Material thickness (mm)}$$
$$C_B = \text{Stress-optic coefficient (B)}$$

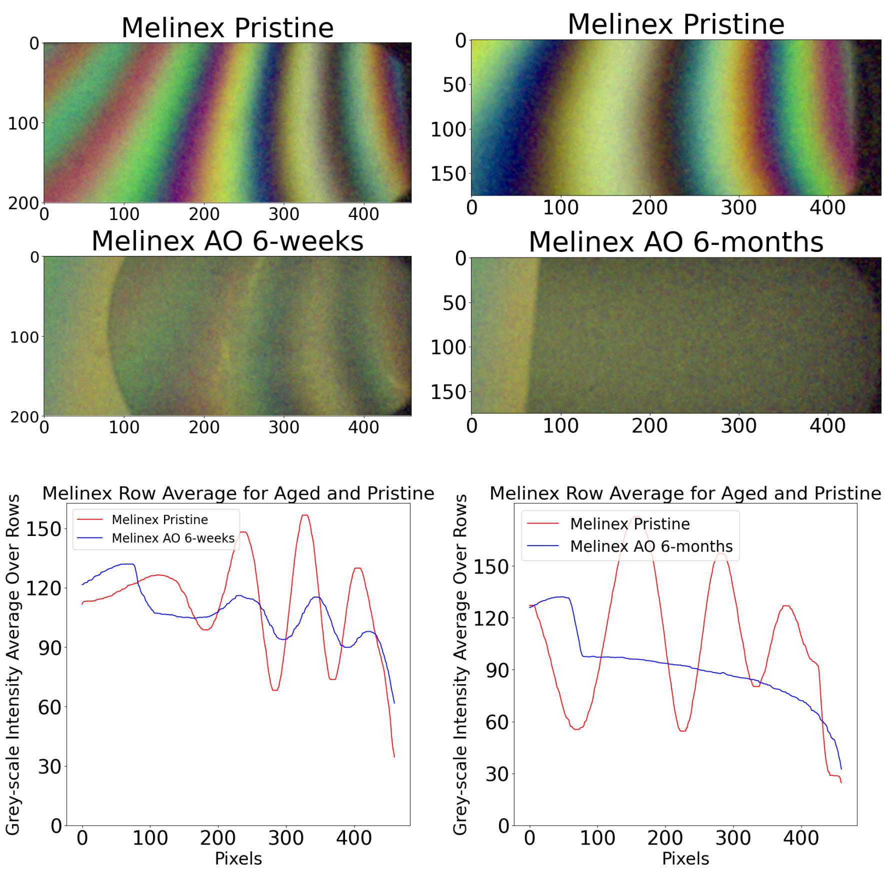

Figure 2: Images taken with polariscope setup and the respective average over the image rows of pristine and AO-exposed Melinex® 453 material with (left column) 5 mil and (right column) 3 mil thickness.

Results

Images of Melinex® 453 taken with the polariscope are displayed in Fig 2 for both pristine materials and those with 6 weeks of LEO-equivalent AO exposure. Row averages over the image show that the position of a black fringe is different for AO-exposed materials. Images of 2 mil thick Kapton® CR using the polariscope setup under three separate states are in Fig 3. The three states are pristine, high-energy electron-irradiated, and AO-exposed irradiation during 6 months of LEO equivalent exposure.

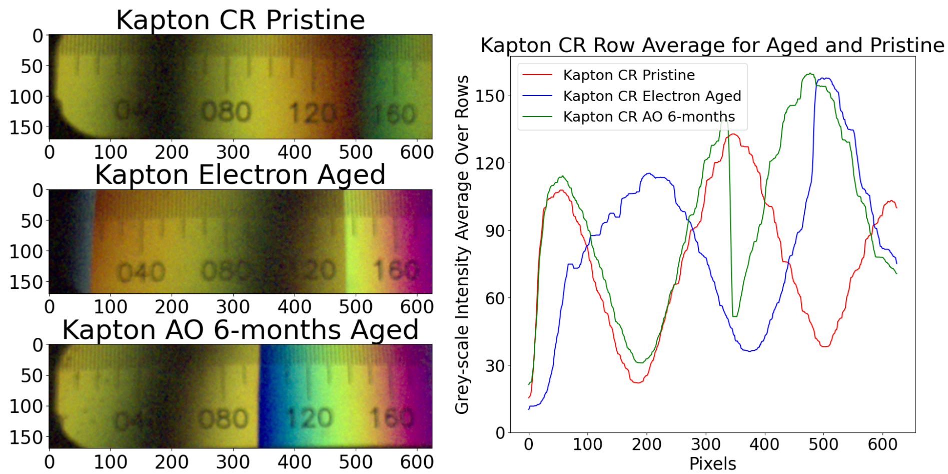

Figure 3: (left) Images of pristine, exposed to high-energy electrons, and AO-irradiated to the 6 months of equivalent LEO exposure 2-mil Kapton® CR taken with polariscope setup; (right) The respective row-average.

Discussion

While the brightness and contrast of color fringes on Melinex® 453 film degrade after 6 weeks of LEO-equivalent exposure, no color patterns are observed on Melinex® 453 material after 6 months of such exposure. Oppositely, Kapton® CR demonstrated nearly unchanged intensities of color patterns after AO and high-energy electrons exposure. This suggests better stability of PI films in general and Kapton® CR in particular, to the degrading effect of space-simulated irradiation.

Retardation in 5 mil thick Melinex® samples calculated from the position of a black fringe is $780 * 5.6$, or 4,368 nm. The stress optics coefficient for Melinex® is 3.4. Then using formula (2), we can estimate the total stress, which is 10.12 MPa. Retardation and stress of pristine, AO exposed and Electron-irradiated samples are shown in Table(1). The difference in retardation of Melinex® pristine and 6 weeks AO exposed is 33 nm and difference in stress is 0.08 MPa. Transparency of the exposed sample is decreased. The brightness and contrast of the exposed images are decreased by a factor of 1.5 and 4, respectively. There are no fringes in the Melinex® with 6-month AO irradiation. The brightness of the image decreased by 1.8 times.

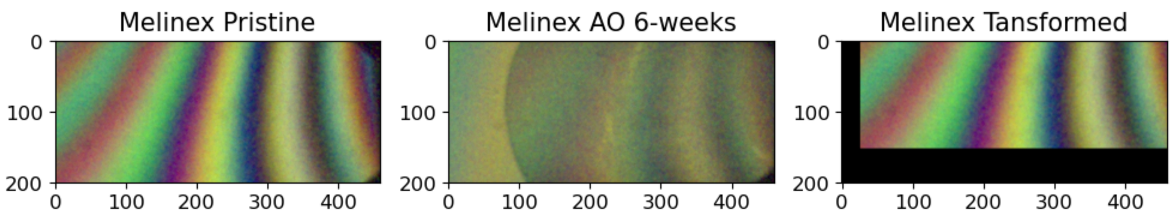

Figure 4: Images of Melinex® 453, comparing the pristine (left) to the 6-week AO-aged material (middle) and the recreated 6-week AO-aged image (right), resulting from applying an affine transform to the pristine image. Using the trained affine transform, the 6-week AO-aged image is observed to be shifted approximately 25 pixels from the pristine image.

Kapton® CR almost did not change after 6 months of LEO-equivalent AO exposure. Retardation is changed by 8 nm (from 276 nm to 284 nm). The stress optics coefficient for Kapton CR is 1.2. Stress changed by 0.13 MPa (from 4.48 MPa to 4.71 MPa). Image brightness decreased by a factor of 1.1 and the image contrast stays approximately the same. The retardation of the electron-irradiated sample a change on 281 nm (4.67 MPa) compared to the pristine material. The brightness and contrast of the electron-irradiated Kapton® CR sample images decreased by a factor of 1.15 and 1.36, respectively. The measured retardation values and estimated stress values for all tested materials are summarized in Table 1

Table 1: Summary of Measured Retardations and Estimated Stresses

Material	Retardation (nm)	Total Stress (MPa)
Melinex® 453 3 mil Pristine	4,032	15.56
Melinex® 453 3 mil 6-months of LEO-equivalent AO exposure	N/A	N/A
Melinex® 453 5 mil Pristine	4,368	10.12
Melinex® 453 5 mil 6-weeks of LEO-equivalent AO exposure	4,335	10.04
Kapton® CR 2 mil Pristine	276	4.48
Kapton® CR 2 mil Electron-irradiated	557	9.25
Kapton® CR 2 mil 6-months of LEO-equivalent AO exposure	284	4.71

Conclusions

In this study, we successfully demonstrated a proof of concept for evaluating stress changes in polymer materials using photoelasticity measurements. We tested two materials from different chemical families, namely polyethylene terephthalate (PET) (Melinex® 453) and polyimide (PI) (Kapton® CR), both potential candidates for the MISSE-22 mission. These materials were subjected to space-simulated LEO conditions. Our findings indicate that Kapton® CR exhibits superior resilience to both electron and AO exposure compared to Melinex® 453. This enhanced durability suggests that Kapton® CR is a more suitable candidate for long-term space missions where exposure to harsh LEO conditions is a critical factor.

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