

ANALYSIS OF HYPERVELOCITY-IMPACTED THIN FILMS FOR SPACE APPLICATIONS

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ABSTRACT

Exposure to the harsh space environment and hypervelocity impacts from micrometeoroids and small orbital debris can affect space operations through long-term degradation of spacecraft materials, surfaces, or systems. Multi-layer insulation (MLI) and coated, polyimide films are spacecraft materials commonly found on the external surfaces of spacecraft for thermal control and protection. Characterizing the damage to these exposed materials with in situ and laboratory measurements can better inform spacecraft designers and operators in understanding and mitigating surface or system degradation. In this paper, we examine flown Hubble Space Telescope (HST) Equipment Bay 5 MLI and coated, polyimide ground test articles to characterize hypervelocity impact damage. Impact feature cavities are inspected to identify damage, which can validate long-term degradation models, improve thermal management systems, or improve accuracy of damage predictions. An overview of the impact characterization using optical microscopy, narrow-band spectroscopy, and Scanning Electron Microscopy/Energy Dispersive X-ray (SEM/EDX) of the two materials is presented. Observations of robustness in the space environment, as well as a detailed assessment of cratering and penetration statistics for the space-exposed sample, also are discussed.

Keywords: orbital debris; MLI; hypervelocity impact phenomenology; thin film; impact residue

1. INTRODUCTION

Thin films used in space-based systems can provide protection from the space environment, including micrometeoroid and orbital debris (MMOD) hypervelocity impacts (HVI). Multi-layer insulation (MLI) and coated-polyimide thin films are examples of commonly used films that cover external space-based surfaces, with the typical purpose of thermal regulation and/or to provide the first layer of protection from MMOD impacts. Previously flown MLI/thin films can serve as passive *in situ* sensors of the space environment. For example, the Hubble Space Telescope's (HST) Equipment

Bay 5 MLI was on orbit for 19 years. The observed impacts previously were used by the NASA Orbital Debris Program Office (ODPO) to validate the Orbital Debris Engineering Model (ORDEM) 3.1 [1]. To better interpret the impactors causing damage on spacecraft and systems, it is necessary to conduct research such as ground testing, optical characterization, and Scanning Electron Microscopy/Energy Dispersive X-ray (SEM/EDX) analysis. Understanding projectile parameters (*i.e.*, density, velocity, projectile size, impact angle) that contribute to the impact damage to thin films will better define MMOD populations in the space environment by improving the interpretation of impact features on returned surfaces, leading to better protection of space systems. This paper describes different thin film characterization methods and summarizes the HVI damage of previously flown and ground-tested MLI and Indium Tin Oxide (ITO)/Vapor Deposited Aluminum (VDA) coated-polyimide thin films. Microscopy is used to characterize the HVI features in the MLI and ITO/VDA-coated-polyimide samples. The VDA-coated-polyimide samples are additionally characterized with polarized light, spectroscopy, and SEM methods.

2. MLI

2.1. Microscopy

The Keyence VHX-7000 digital microscope is used by the ODPO to characterize material properties through non-destructive evaluation. The thin film evaluation process includes taking images, measuring, and recording all features and their diameters with the outer through-hole as the representative best fit position for measuring diameter in thin films [1]. The outer through-hole is the largest diameter of the inside of a through-hole which may display a ragged penetration hole. The first thin film inspected was the HST Equipment Bay 5 MLI. HST MLI is useful for providing on-orbit data and enables comparison with similar ground tested samples that have known parameters. HST Bay 5 MLI is composed of 17 layers, where the outermost layer is aluminized polytetrafluoroethylene (PTFE) fluorinated ethylene-propylene

(FEP). Each layer is 0.126 mm thick, and inner layers are made of embossed, aluminized polyimide that is 0.0108 mm thick [2]. Four random samples of approximately 200 × 200 mm in size were chosen for analysis in 2019 [1]. On the four samples a total of 623 features (craters and penetrations) ranging from 0.009 mm to 3.724 mm in diameter were recorded. The locations of these samples and their craters/penetrations are identified in Fig. 1.

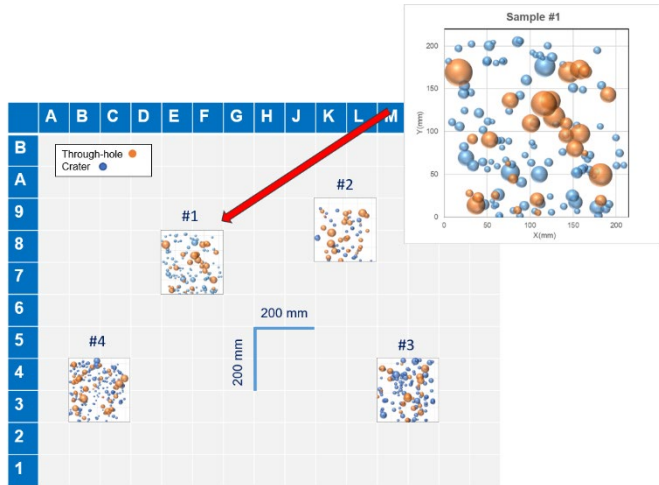


FIGURE 1: LOCATIONS OF PENETRATIONS (ORANGE) AND CRATERS (BLUE) ON THE FOUR SAMPLES EXCISED FROM THE BAY 5 MLI [1]. THE SIZE OF THE BUBBLE, AS DEPICTED IN THE INSET, IS PROPORTIONAL TO THE SIZE OF THE FEATURE.

No impact features were found to make it through all 17 layers. The maximum number of layers penetrated through the MLI layers was determined to be eight, and labeled from L1 through L8, as shown in Table 1. For purposes of this paper, the samples from the HST Bay 5 MLI with impact penetrations will be termed ‘flown’ HST MLI. A summary of features found, and the number of layers penetrated are listed in Table 1.

TABLE 1: STATISTICS FOR THE FOUR SAMPLES OF FLOWN HST MLI.

Layer	Feature Count	Size range (mm)
L1	550	0.009 - 0.853
L2	33	0.04 - 3.724
L3	21	0.043 - 3.541
L4	10	0.07 - 2.014
L5	3	0.552 - 1.082
L6	3	0.510 - 1.894
L7	2	1.068 - 2.282
L8	1	0.451
Total Features	623	

Parameters such as velocity, projectile size, angle of impact, or density of projectile that created these impact holes are not known for the flown HST MLI, so HVI testing was conducted in an attempt to replicate these features.

In 2010, HVI shots were conducted by the NASA JSC Hypervelocity Impact Technology group (HVIT) in the Remote Hypervelocity Test Laboratory (RHTL) at the NASA Johnson

Space Center’s (JSC) White Sands Test Facility (WSTF), located near Las Cruces, New Mexico [3]. Testing was completed on single-layer MLI similar to the flown HST MLI outer layer. The 2010 samples are referred to as ‘MLI’ in Table 2.

In 2019, blank (unimpacted) flown HST MLI samples were excised from the Bay 5 MLI blanket for further testing. These samples are referred to as ‘exposed’ HST MLI to differentiate between flown HST MLI samples that were impacted from MMOD in the space environment. Replica (‘pristine’) MLI samples were assembled as well to represent the flown HST MLI (17 layers) to the greatest fidelity possible. The two outermost layers of the pristine MLI were PTFE FEP (0.126 mm thickness) and the 15 inner layers were polyethylene terephthalate film (0.010 mm thickness). Twenty-one total HVI shots were conducted on the MLI, exposed MLI, and pristine MLI using varied impact parameters. These test parameters are shown in Table 2. As a note, some impact shots were tested using only the first layer and are called ‘single’-layer configuration versus the ‘multi’-layer configuration of 17 layers. Projectile materials included glass, nickel, aluminum (Al), stainless steel (SS), and polymethyl methacrylate (PMMA).

TABLE 2: TEST RUNS WITH PARAMETERS AND CONFIGURATIONS USED IN HVI TESTING OF MLI SAMPLES.

ID	Projectile Material	Projectile Size (mm)	Velocity (km/s)	Angle (deg)	Type	Configuration
20022	Glass	0.02	7.0	0	Exposed HST	Multi
10334	Nickel	0.10	5.1	45	MLI	Single
20014	Al	0.10	5.0	0	Exposed HST	Multi
20023	Glass	0.10	4.9	45	Pristine MLI	Multi
20009	SS	0.20	5.0	0	Exposed HST	Multi
20010	SS	0.20	7.0	0	Exposed HST	Multi
20013	Al	0.20	7.0	0	Exposed HST	Multi
10328	Glass	0.25	4.2	0	MLI	Single
10329	Glass	0.25	3.7	45	MLI	Single
10330	Glass	0.25	4.3	70	MLI	Single
20008	SS	0.30	7.0	0	Exposed HST	Multi
20012	Al	0.30	7.0	0	Exposed HST	Multi
20011	SS	0.36	8.2	0	Exposed HST	Single
20017	PMMA	0.36	8.1	0	Exposed HST	Multi
20020	Glass	0.36	8.3	0	Exposed HST	Single
20021	PMMA	0.36	8.0	0	Exposed HST	Single
20024	PMMA	0.36	8.3	0	Pristine MLI	Multi
10331	Al	0.40	4.9	45	MLI	Single
20006	SS	0.40	7.0	0	Pristine MLI	Single
20007	SS	0.40	7.0	0	Pristine MLI	Multi
10332	Al	0.60	4.6	45	MLI	Single

The resultant impact holes and their diameter measurements are presented (Fig. 2) in a scatter plot to represent hole diameter as a function of projectile diameter.

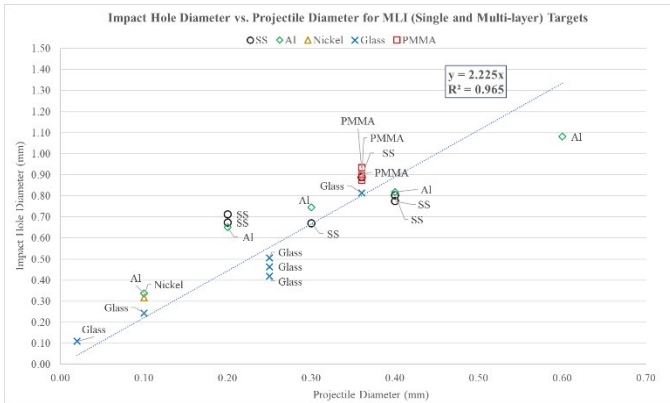


FIGURE 2: REPRESENTATION OF THE IMPACT HOLE DIAMETER AS A FUNCTION OF PROJECTILE DIAMETER FOR HST AND HST EQUIVALENT MLI TARGETS.

There is a relationship between the projectile diameter size (and accompanying parameters) and the hole it creates. The association between projectile size and resulting hole diameter is 2.225 (*i.e.*, a projectile will create a hole of approximately 2.2 times the size of the projectile in HST MLI-type film). Some of the spread along the trendline can be attributed to parameters being varied. For example, the material/density varied with the 0.36 mm and the 0.10 mm projectile shots. Another example is the 0.2 mm-sized projectiles, where the velocity was changed. In the 0.25 mm projectile size grouping, the angle parameter was varied. The target configuration (a single-layer versus multi-layered sample) also can be a factor in the spread of data. Further research is in work to answer target configuration questions specifically, in addition to what parameter or subset of parameters is connected to resultant impact hole diameter.

Common impact signatures occurring on all samples included ray patterns, melt, spallation, delamination, radial cracking, and blown-away coating. Radial cracking was found only on the flown HST MLI; which could be from thermal cycling along with electron and proton radiation from the space environment [4]. All other impact signatures were found on both flown HST MLI and ground-tested MLI. A classification system for the common impact signatures on thin films is being developed. Examples of some common impact signatures are shown in Fig. 3.

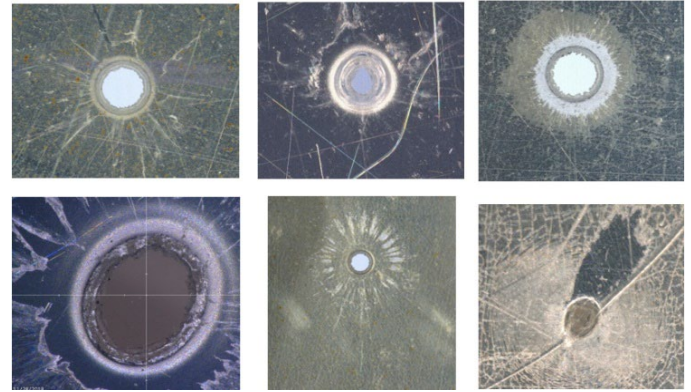


FIGURE 3: COMMON IMPACT SIGNATURES ON THE MLI SAMPLES. FROM LEFT TO RIGHT, TOP ROW TO BOTTOM ROW (X: MAGNIFICATION): 50X INSTANCE OF RAY PATTERN, 100X INSTANCE OF MELT, 50X INSTANCE OF SPALLATION, 150X INSTANCE OF DELAMINATION, 20X INSTANCE OF BLOWN AWAY COATING, AND 100X INSTANCE OF RADIAL CRACKING.

3. ITO/VDA COATED POLYIMIDE FILM

3.1. Microscopy

Using the Keyence VHX-7000 digital microscope, 51 samples of ITO-coated-polyimide (0.0125 mm polyimide thickness, 10 nm coating) and 13 samples of the VDA-coated-polyimide (0.0125 mm polyimide thickness, 100 nm coating) were evaluated. These samples were all HVI tested, with further testing in progress. Due to large-scale tearing of the film or melted material preventing accurate diameter measurement, 15 impact features are removed from analysis. Projectile materials included Glass, Al, SS, PMMA, and Copper (Cu). Projectile sizes ranged from 0.25 mm to 1.7 mm, velocities were approximately 7 km/s, and impact angles were 0° and 15°. The resultant impact hole diameter measurements are presented in Fig. 4 as a scatter plot representing hole diameter as a function of projectile size (diameter).

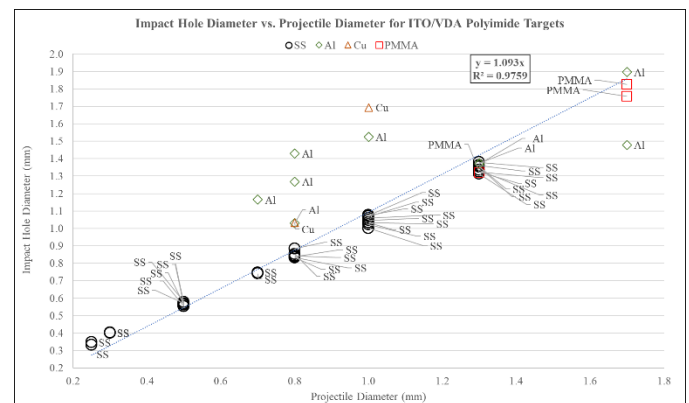


FIGURE 4: REPRESENTATION OF THE IMPACT HOLE DIAMETER AS A FUNCTION OF PROJECTILE DIAMETER FOR ITO/VDA-COATED-POLYIMIDE TARGETS.

Principal outliers on the plot are Al and Cu projectiles, which may be due to the breakup of the projectile material on the film. The ratio of impact hole diameter to projectile diameter (1.093) is about half of the ratio found in the MLI samples, which may indicate a dependence on the thickness of the film or the material type (polyimide versus PTFE). More investigation is in progress to quantitatively determine the dependence of impact hole to the film thickness and film material type.

The ITO/VDA film's impact signatures included ray patterns and blown away coating, similar to MLI impact signatures. Figure 5 shows examples of ITO and VDA impact holes after impact with a SS projectile.

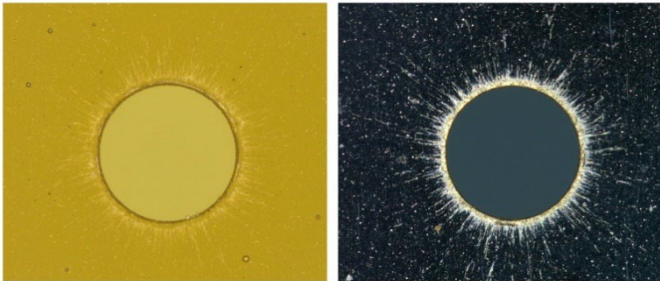


FIGURE 5: LEFT: ITO-COATED-POLYIMIDE IMPACT HOLE WITH RAY PATTERN. RIGHT: VDA-COATED-POLYIMIDE WITH IMPACT HOLE RAY PATTERN AND BLOWN-AWAY COATING (GOLD AREA). MAGNIFICATION: 100X, PROJECTILE SS.

Although the ITO/VDA-coated-polyimide films have different coatings and coating thicknesses, when compared to each other, their impact signatures are very similar. An example resultant impact hole for both ITO and VDA film shot with an Al 1.7 mm projectile (same velocity and angle) is shown in Fig. 6. Note the material fragmented or melted in a lace pattern.

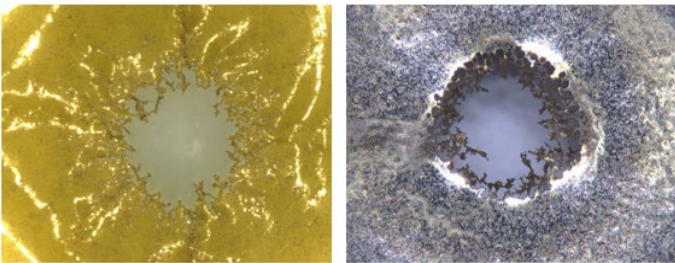


FIGURE 6: THE RESULTANT IMPACT HOLE IN BOTH AN ITO (LEFT) AND VDA (RIGHT) SAMPLE. MAGNIFICATION: 20X, PROJECTILE AL.

3.2. Spectroscopy

To better characterize the optical signature response of thin films, specifically those being assessed for flight projects, the following provides an overview of the reflectance spectroscopy measurements on uncoated, unimpacted ITO-coated, impacted ITO-coated, and unimpacted VDA-coated-polyimide films. The motivation for this analysis was to determine if specific coatings on polyimide film led to cracking/fragmenting or delamination as a result of HVI. The measurements were acquired using a field spectrometer with a range from 350 nm

to 2500 nm, a quartz lamp illumination source, and a white reference calibration, as seen in Fig. 7.

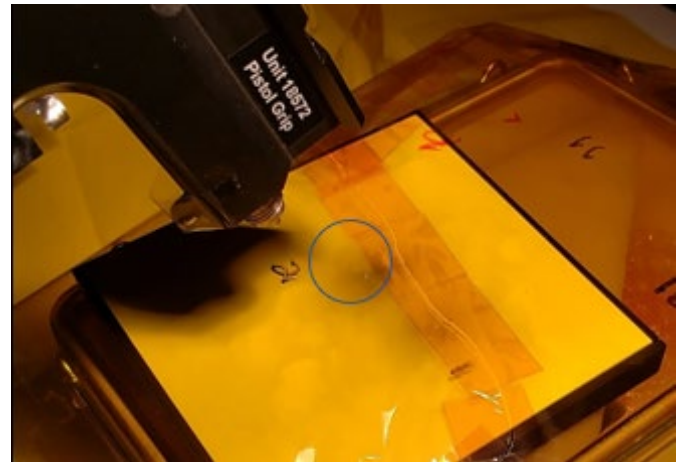


FIGURE 7: IMAGE OF PISTOL GRIP OPTICAL FEED FROM SPECTROMETER BEING USED ON IMPACTED ITO-COATED-POLYIMIDE. NOTE POSSIBLE REFLECTANCE VARIATION DUE TO HVI TEST GUNPOWDER SOOT (BLUE CIRCLE).

The spectral response of the four material classes is presented in Fig. 8. Measurements greater than 1.0 absolute reflectance indicated a detector saturation as the measurements are calibrated against a white reference (absolute reflectance ~ 1 across all wavelengths).

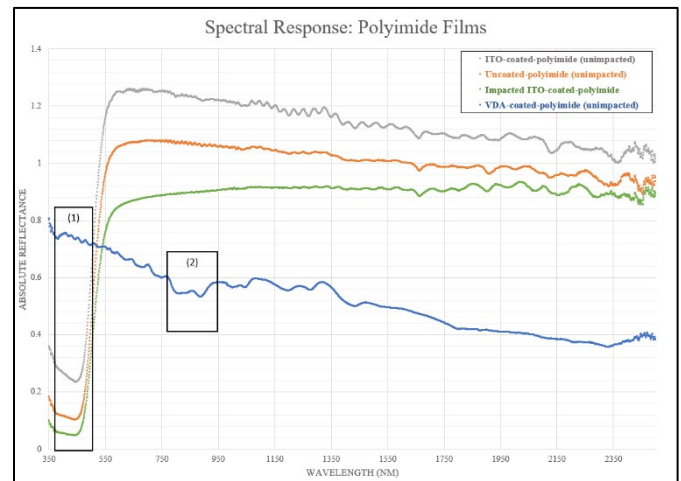


FIGURE 8: SPECTRAL RESPONSE OF POLYIMIDE MATERIALS INVESTIGATED. NOTE, THE UNCOATED POLYIMIDE AND ITO-COATED-POLYIMIDE SAMPLES SATURATED THE DETECTOR (ABSOLUTE REFLECTANCE > 1).

The data presented provides a mean of multiple samples and data collects for the material classification. Twenty areas of uncoated polyimide (unimpacted), three areas of unimpacted ITO-coated-polyimide, seven areas of the impacted ITO-coated-polyimide, and three areas of the VDA-coated-polyimide were used to acquire mean statistics on the total reflectance spectra. The measurements from a minimum of three sample areas are used to determine if the reflectance varies due to surface structure, contamination, or other noise that could interfere with the signal. The first spectral response

region of interest is indicated in Fig. 8 (1) that clearly distinguishes the uncoated- and ITO-coated-polyimide films from the VDA between 400 nm and 500 nm. Due to the thicker VDA coating, the typical absorption feature in polyimide is not present. The second feature (2) noted is a doublet between 800 nm and 900 nm, an absorption feature common with Al materials, but not typically presented as a doublet. Several organic features (dips in the curves) are present near 1650 nm and 2300 nm in all three non-VDA-coated-polyimide samples, and a weak H₂O feature near 1400 nm and 1900 nm is present in all four samples, but the organic features are more difficult to isolate in all of the materials. Additionally, in all measurements of the thin films, there appear to be significant oscillations due to the incident light interacting with the films. It is also possible that the measured samples were not in a perfectly pristine state and minor biases could have been introduced by accidental contamination.

In summary, the impacted ITO-coated-polyimide film appeared to have an overall decreased reflectance attributed to the gunpowder soot but was optically flat, which is consistent with the uncoated and unimpacted ITO-coated samples. The VDA-coated sample appears to have the lowest reflectance, decreasing slowly into the infrared regime. Without further inspection, it is not evident that the ITO coating fractured or cracked, as the reflectance did not return to baseline (ITO-coated-polyimide) and consequently, reflectance spectroscopy is limited when additional materials/contamination are present on thin films.

3.3. Polarized Light Measurements

The Keyence VHX-7000, when used in bright field/coaxial lighting mode, has the capability to collect linear, polarized-light imagery at all angles between the polarizer and analyzer. The hypothesis that HVI may create morphological features that would be evident in polarized light but not otherwise apparent in normal microscopic studies of the penetration features motivated this work. Examples of such features include “ray and ring” structures, “frozen in” stress features, or other evidence of impact-induced changes to physical properties, stress, or thickness. To evaluate this hypothesis, pristine and impacted samples were collected from ITO-coated-polyimide films. Possible morphological features were examined by imaging penetration holes in both standard dark field/ring light illumination modes and in polarized light, as compared in Fig. 9.

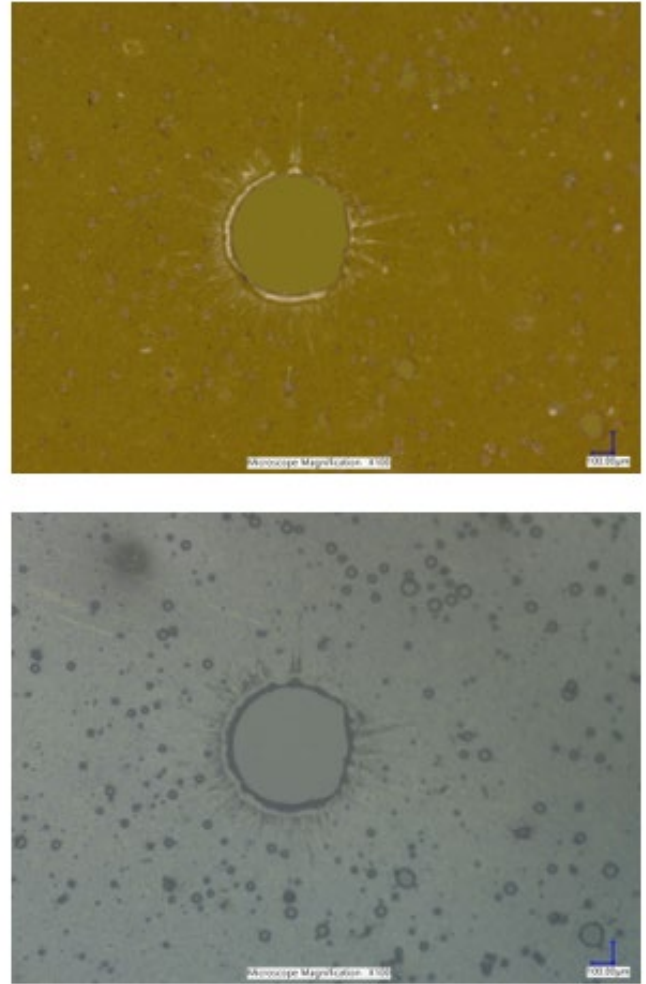


FIGURE 9: A COMPARISON OF A PENETRATION HOLE IN BROADBAND VISIBLE LIGHT (TOP) AND POLARIZED LIGHT (BOTTOM). THIS SAMPLE PENETRATION WAS IMAGED AT 100X. PENETRATIONS OF SECONDARY DEBRIS FROM THE SHOCKED PROJECTILE ARE CLEARLY VISIBLE.

While ray structures were evident in the polarized light imaging, no other large scale, pronounced features attributable to the penetration appear present; note that the rays were evident in the broadband image, and are similar to those present in Fig. 5. Rays appear to be present on the first surface penetrated (front) but not on the rear surface. The same penetration feature was observed at 20X and is compared (broadband visible light and polarized light) in Fig. 10.

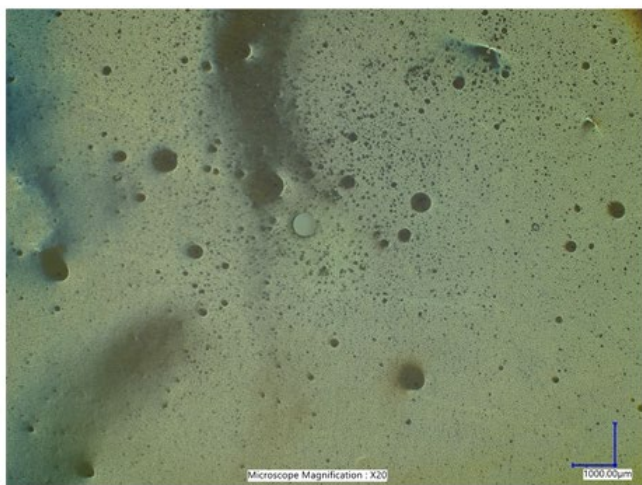
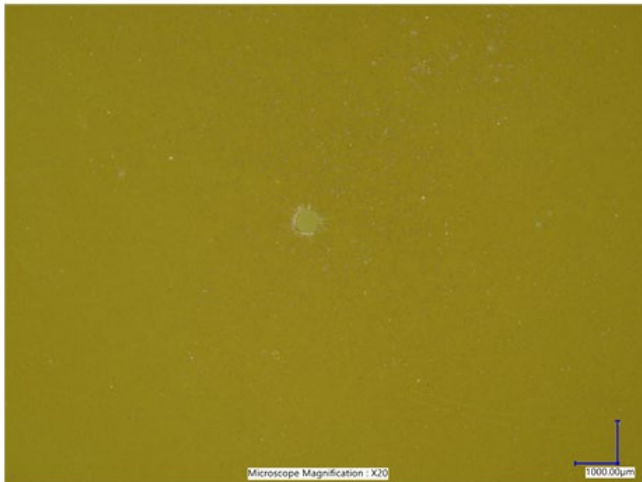


FIGURE 10: FIGURE 9'S IMPACT FEATURE IMAGED AT 20X MAGNIFICATION. ANGLE BETWEEN ANALYZER AND POLARIZER APPROXIMATELY 26°. BOTTOM: LARGE IRREGULAR DARK FEATURES ARE DUE TO SAMPLE FLEXURE.

In this instance, large features with no apparent broadband analogue feature are evident, manifesting as the dark, generally circular features in the vicinity of the penetration (other, more linear features are either scratches due to manufacture or handling, are attributable to sample flexure, or remain to be investigated). Attribution to the event is demonstrated by the frequency of occurrence decreasing with radial distance from the projectile penetration hole and their absence on the pristine control sample. While some features, perhaps internal to the layer, appear and disappear as the analyzer is rotated over (0°, 90°) these circular features were constant. As some "soot" was also evident in the vicinity of the penetration, both sides of the sample were wiped with isopropyl alcohol, using a clean glass slide placed over the penetration to protect one half of the imaged area from cleaning for visual reference, as depicted in Fig. 11.

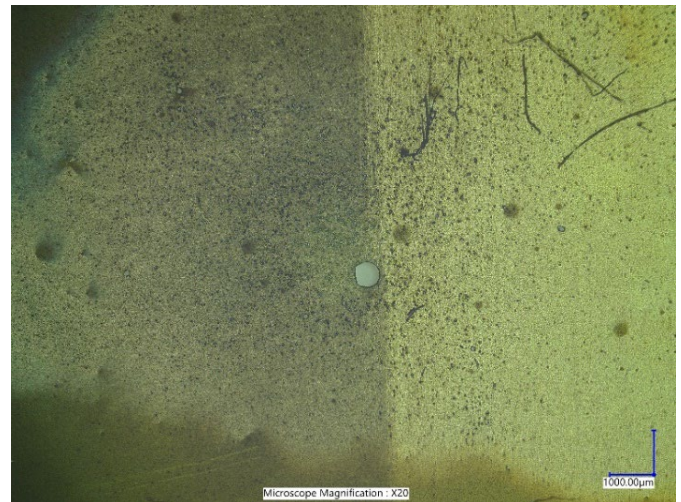


FIGURE 11: RIGHT: THE IMPACT LOCATION CLEANED WITH ISOPROPYL ALCOHOL WIPES. THE LEFT PORTION WAS PROTECTED DURING CLEANING TO PROVIDE A VISUAL REFERENCE. THE PROTECTED LEFT SIDE IN THIS TRANSMISSION IMAGE DEMONSTRATES THE PRESENCE OF SOOT AS NOTED IN SECTION 3.2 SPECTROSCOPY ANALYSIS.

These dark features remain, indicating they are not soot or other HVI range products, but indelible features. Higher magnification imagery indicated that many of the dark circular features had one, very small penetration located within its boundary, however, indicating a possible association with HVI by-products of spall or ejecta.

In summary, HVI penetration of the thin film produced rays that emanated from the penetration hole's front surface but does not, at this time, indicate any other large-scale morphological phenomena around the penetration. Significant work remains to be done to better characterize these phenomena and gauge the extent of the results presented herein, but polarized light imaging offers an intriguing option for understanding HVI damage to thin films.

3.4. SEM/EDX

SEM/EDX has proven effective in identifying HVI-related residue constituents [5] and was applied to the investigation of polyimide impact phenomenology. The Astromaterials Research and Exploration Science (ARES) Basic and Applied Research Department (BARD) at NASA JSC used a field emission SEM, equipped with energy-dispersive, X-ray spectroscopy to characterize the polyimide samples, seeking to determine the distribution of projectile residue, to assess the state of the ITO coating after HVI, and to detect any HVI-related material on the front face of the film. Samples were mounted on Al-SEM mounts and coated with about 15 nm of sputtered carbon. One blank ITO-coated-polyimide film, and five impacted ITO-coated-polyimide films were analyzed and are briefly described in Table 3. The blank provided a means of developing handling and analysis procedures and a reference or baseline for further comparative measurements and studies.

TABLE 3: SUMMARY OF SAMPLES PROVIDED FOR SEM/EDX ANALYSIS.

Sample ID	Sample Serial Number	Impactor
A	Blank	none
B	1-19	Al
C	1-50	Al ₂ O ₃
D	2-35	SS
E	3-59	Cu
F	3-71	PMMA

Samples had projectile residue identified; however, for the last sample (PMMA impactor), the SEM/EDX was unable to differentiate projectile residue from the polyimide film due to similar chemistries. When the projectile and matrix are intermingled due to melting, it is difficult to conclusively identify or separate one from the other.

All samples, excepting sample D (SS), had ITO coating detached or removed from the polyimide film in the immediate vicinity of the impact, as shown in Figs. 12 and 13. The VDA-coated sample was not analyzed but is unlikely to experience damage similar to the ceramic ITO; however, this awaits confirmation.

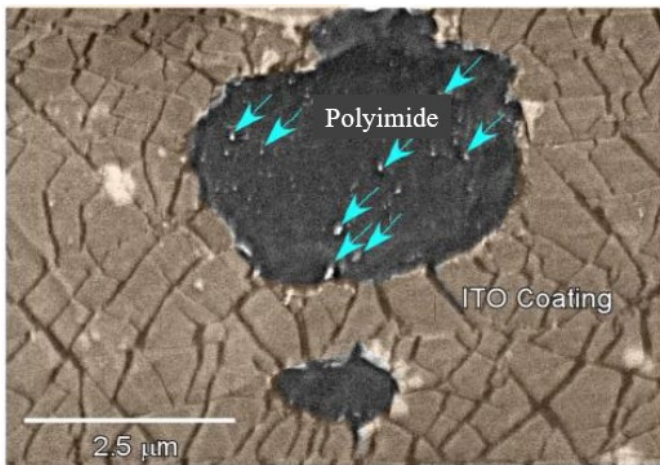


FIGURE 12: LOW ANGLE BACKSCATTER ELECTRON IMAGES OF THE ITO COATING SHOWING SOME REGIONS HAVE BEEN REMOVED FROM THE UNDERLYING POLYIMIDE. THE COATING DISPLAYS A CHARACTERISTIC MOSAIC PATTERN. CYAN ARROWS IN THE TOP VIEW HIGHLIGHT CONTAMINANT PARTICLES, MOST OF WHICH ARE CALCIUM-BEARING.

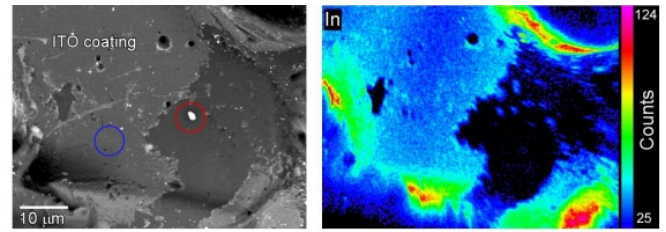


FIGURE 13: LEFT: POLYIMIDE SURFACE LOCATED NEAR THE CENTER IMPACT HOLE OF SAMPLE B RETAINED SOME ITO COATING (SMOOTH, DARK REGIONS ARE RELATIVELY FREE OF COATING). RIGHT: ELEMENT MAP OF THE REGION AT LEFT SHOWING THE DISTRIBUTION OF INDIUM FROM THE ITO COATING.

Select samples displayed the effects of spallation. Figure 14 depicts such damage for sample B. Damage from up-range spallation and down-range ejecta, in fact, appears a common effect for these samples.

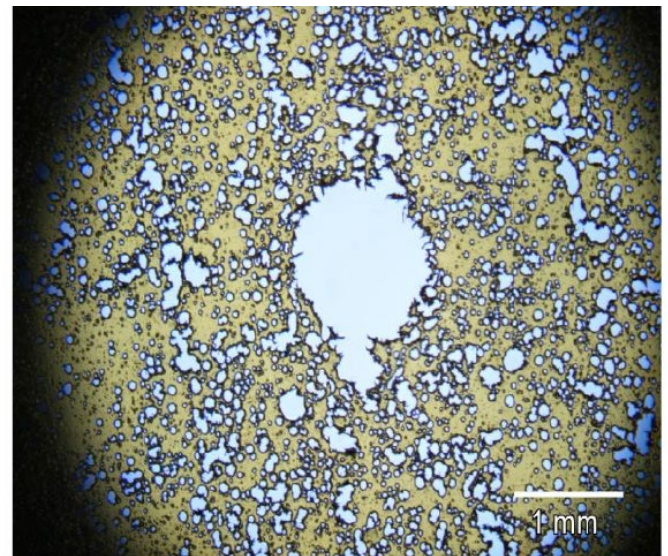


FIGURE 14: TRANSMITTED LIGHT IMAGE OF SAMPLE B. HOLES AND PITS/CRATERING NEAR THE CENTRAL PENETRATION ARE LARGER IN SIZE AND BECOME PROGRESSIVELY SMALLER WITH INCREASING DISTANCE FROM THE PRIMARY PENETRATION HOLE.

4. CONCLUSIONS

Characterizing material changes on thin films is key to understanding the longevity of these thin films after HVI and lends to quantifying the long-term degradation of these proposed films after exposure to the MMOD environment. Flown HST Equipment Bay 5 MLI and coated-polyimide thin film ground-test articles were examined to characterize HVI damage. Characterization methods included microscopy, spectroscopy, polarized light measurements, and SEM/EDX. Using microscopy, statistics for four samples of flown HST MLI were produced. To recreate HVI features, hypervelocity testing was completed on unimpacted HST MLI and replica HST MLI test articles to compare with flown HST MLI impact features. Common impact signatures between flown HST MLI and the ground-tested samples were ray patterns, melt,

spallation, delamination, radial cracking, and blown-away coating. Additionally, HVI testing was completed on ITO/VDA-coated-polyimide films and resulted in similar impact signatures such as blown-away coating and ray formation. More testing and evaluation on these polyimide films is in progress, along with a classification of HVI in thin films. The projectile size and impact hole diameter was recorded for both MLI and polyimide films. The HST MLI and polyimide film's projectile size to impact hole diameter seems to have a dependence on film thickness, material type, or the effect between multi-layered and single-layered articles, which is currently being examined.

The optical signature responses of impacted polyimide film, uncoated polyimide film, and unimpacted polyimide films were compared by spectroscopy to determine if specific coatings on polyimide led to cracking/fragmenting or delamination as a result of HVI. The impacted ITO-coated film appeared to have an overall decreased reflectance attributed to gunpowder soot and spectral response similar to the other samples. The VDA-coated sample appears to have the lowest reflectance and was more difficult to analyze due to its coating. Further inspection is needed to determine if the ITO coating fractured or cracked after an impact.

Polarized light imaging was completed on impacted ITO-coated-polyimide film. Emanating rays from the penetration hole's first surface were easily identifiable, but relatively high-resolution imagery did not indicate any extensive morphological phenomena around the penetration. This appeared consistent with results of the SEM/EDX analysis.

During SEM/EDX analysis, HVI projectiles were successfully identified on samples of coated polyimides. Additionally, SEM/EDX analysis has demonstrated that HVI may damage and dislodge coatings, such as charge-dissipating ceramic ITO, on thin films.

The characterizations and methods described in this paper will help to better understand projectile parameters (density, velocity, projectile size, and impact angle) that contribute to HVI damage to thin films, the robustness of the coated films, and better define MMOD populations in the space environment, leading to better protection of space systems.

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