JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 43, No. 2, March–April 2006

Surface Modification of Conductive and Nonconductive Paints for Space Durability Enhancement

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A program was initiated to further improve the space durability of nonconductive polymer-based paints and of conductive thermal control paints presently under development. The results of surface modification of both types of paints, including the ground-based testing and performance evaluation, are presented. Functional properties and performance characteristics, such as thermal optical properties and surface resistivity characteristics of pristine and treated materials, were verified. Tests results revealed that the successfully treated materials did not exhibit any mass loss or surface morphology change, thus, indicating good protection from the severe oxidative environment. It was demonstrated that the developed surface modification treatment can be applied successfully to charge dissipative paints.

Introduction

ATOMIC oxygen (AO) in low Earth orbit (LEO) has been shown to cause severe damage to organic-based spacecraft materials, producing changes in optical, mechanical, electrical, and chemical properties.[1–8] The erosion effect of AO that in many cases can be predicted quantitatively[7] is a major limitation for using unprotected polymer-based materials in long-term space LEO missions. Because of the importance for materials to maintain their durability and performance in LEO missions, a program was initiated to further develop and evaluate the patented surface modification technology Photosil™[9] and its application to a variety of space-related polymer thin films and thermal control coatings and to assess its impact on the materials' durability, functional properties, and stability in LEO environment.

Photosil surface modification technology has been developed to provide an advantageous alternative to protective coatings in reducing AO erosion of organic materials and composites.[9–12] Photosil is a surface modification process that chemically incorporates silicon-containing functional groups from a silylation solution into the subsurface layer, that is, up to 1 μm in depth, of the polymer structure, creating an organosilicon surface layer derived from the original material. This surface treatment was employed, for instance, recently to protect painted external components of NASA's Canadarm systems[12] and has been used to treat painted external components of the special purpose dexterous manipulator (SPDM), a sophisticated evolution of the Canadarm to be installed onboard the International Space Station.[12]

For many high-performance space-bound polymers and polymer-based materials, Photosil technology has shown to provide average erosion yields of less than $\sim 10^{-26}$ g/atom under ground-based fast AO exposure, that is, at least two orders of magnitude lower than most pristine polymer materials.[11,12] The process practically does not affect the thermal optical and other material properties of thin polymer films and some paint materials[11,12] that are critically important for thermal control space applications. Surface conductivity is another important functional characteristic for many external space coatings and paints used for prevention or alleviation of spacecraft charging. For such coatings/paints, the evaluation of space environmental stability and electrical performance should be done together.[13–16]

This paper describes the most recent results of an ongoing program of space durability enhancement of a number of recently developed conductive polymer-based paints and a few nonconductive polymer-based paints.

Experiment

A number of paints have been surface modified using the original or modified Photosil process and tested in ground-based testing facilities imitating the LEO conditions. All paints were characterized before and after ground-based testing, and their performance evaluated. The treated paints included the U.S. commercially available polyurethane-based nonconductive white, black, and gray Aeroglaze paints, to which Photosil technology had already been applied[11,12] and Russian acrylic copolymer-based dissipative and conducting white, black, and silver–gray thermal control EKOM paints, not previously treated by Photosil surface treatment. Space-grade aluminum alloy was used as the substrate material for all paints. The painting of the coupons was performed following all necessary painting specifications. Table 1 provides a brief description of the thermal control paints used in this program. The compositions of the chosen paints differ in binder and pigments (Table 1); however, both binders are, like other hydrocarbon polymers,[1–7] sensitive to AO erosion.

Surface Modification of Thermal Control Coatings

A Photosil process optimization for surface modification of Aeroglaze paints that started earliear[11,12] was continued in this work.

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Table 1 Thermal control coating (TCC) paints, selected for surface modification

TCC	Class	Chemical composition: Binder	Chemical composition: Pigments	Visual appearance	Volume resistivity ρ_v, $\Omega \cdot$ m
A276	Reflector	Polyurethane	TiO_2	White (gloss)	N/A
Z302	Absorber	Polyurethane	Carbon	Black (gloss)	N/A
Z306	Absorber	Polyurethane	Carbon	Black (flat)	N/A
A276:Z306	Other	Polyurethane	TiO_2 + Carbon	Gray	N/A
EKOM-1[a]	Reflector	Acrylic copolymer	Ga-doped ZnO	White	$1–5 \times 10^5$
EKOM-1P	Reflector	Acrylic copolymer	Ga-doped ZnO + Al paste	Silver–gray	$\leq 10^2$
EKOM-2	Absorber	Acrylic copolymer	Carbonyl nickel + carbon black + mixtures of Fe, Mn, Ni, and Cu oxides	Black	$\leq 7 \times 10^3$

[a] EKOM-1 samples have been exposed on Mir Space Station for 3 years.[20]

In addition, the Photosil process was applied to the EKOM coatings. For process optimization, the parameters of the process in all three stages, that is, the surface activation, silylation, and stabilization, were analyzed and varied. Some of the variable treatment parameters were, for the activation stage, type and energy of surface pretreatment, and UV or oxygen plasma treatment conditions and duration; for the silylation stage, silylating solution formulation, type and concentration of solvent and silylating agent, and temperature and duration of the process; and for the stabilization stage, type and energy of surface posttreatment for stabilization, UV or oxygen plasma, and treatment condition and duration.

X-ray photoelectron spectroscopy (XPS) showed that the presence of Si on successfully treated surfaces of otherwise silicon-free materials had increased up to 20–25 at.% (Refs. 11 and 12). The treated materials showed a significant increase in erosion resistance, when exposed to different sources of AO.[11,12] Based on the obtained results, the oxygen plasma testing and XPS were chosen as the major screening test and characterization tools, respectively, for evaluation of the treated paint samples and identification of the most successful surface treatment version and conditions.

Testing of Treated Coatings/Paints

Samples of all thermal control paints listed in Table 1 were treated by selected versions of Photosil technology and tested together with their pristine counterparts in a number of different ground-based AO and AO/Vacuum UV (VUV) sources. An oxygen plasma asher and a recently upgraded University of Toronto Institute for, Aerospace studies/Integrity Testing Laboratory, Inc. (UTIAS/ITL), fast AO (FAO) beam facility were used to test the Aeroglaze samples before and after Photosil treatment, to evaluate the effectiveness of the AO protection. Plasma testing provides, in a comparatively easy way, the ability to create high AO effective fluence exposure but with thermal energy AO and other oxygen plasma species and uncontrolled VUV radiation.[17] FAO beam testing closely resembles FAO exposure, one of the major real LEO environmental conditions. It has been often shown in ground-based studies that oxygen plasma asher testing seems to be too harsh an environment for testing advanced "self-protecting" or surface modified polymer-based materials.[12,18] Therefore, FAO beam testing, combined with well-defined VUV radiation, is specifically required to simulate the real LEO environment more closely.

Oxygen plasma exposure tests were conducted in a low-temperature, inductively coupled radio frequency plasma asher. The test samples and a witness Kapton® 500HN sample were placed in a holder and positioned in the middle of the 8-liter asher reactor. The minimum average equivalent fluence of atomic oxygen in a 5-h exposure, as evaluated from the mass loss of the Kapton witness sample, was $\sim 1.9 \times 10^{20}$ atoms/cm^2. All samples were preconditioned in the plasma facility under vacuum for 24–48 h for outgassing. Mass change of the samples under plasma exposure was measured with an electronic microbalance.

FAO beam exposure was conducted in the recently upgraded UTIAS/ITL Space Simulator.[11,12] Each sample was exposed to FAO with an average energy ~2.6 eV at an average fluence of up to $\sim 1–2 \times 10^{20}$ atoms/cm^2 for a minimum period of 5–6 h at a constant temperature. A control set of samples was placed in the same chamber out of the FAO beam path for the duration of the test. The mass change of each of these samples was subtracted from the mass loss of the matching FAO-exposed specimen, all measured by a microbalance, to account for mass loss due to outgassing and to find the mass loss (mass change) due to FAO exposure.

In addition, selected samples of pristine and surface modified Z306, A276:Z306, EKOM-1, EKOM-1P, and EKOM-2 thermal control coatings were tested in NASA Marshall Space Flight Center (MSFC) Atomic Oxygen Beam Facility (AOBF).[19] Note that this was the first independent testing of the Photosil-treated paints under 5-eV AO beam with a 5–10 times higher fluence and in a combined FAO+VUV environment. The original EKOM-1 white paint was tested in-flight for 3 years in an outside exposure experiment on Mir space station.[20] MSFC AOBF is a radio frequency-driven lower hybrid plasma system, capable of supplying 5-eV neutral AO atoms in a pulsed fashion. During the AO exposure, VUV radiation was produced in the AOBF, primarily at 130 nm, the AO resonant peak in the VUV region. The samples were exposed to FAO fluence and VUV radiation that ranged from 5.2×10^{20} atoms/cm^2 and ~780 equivalent sun hours (ESH) of VUV radiation to 10.1×10^{20} atoms/cm^2 and 865 ESH of VUV. In all cases, the AO path was normal to the sample surface.

Characterization of Treated Coatings/Paints

A number of characterization methods have been used to evaluate the changes in surface composition and the morphology, as well as the major functional properties of the evaluated materials. In addition to XPS, scanning electron microscopy/energy dispersive spectroscopy (SEM/EDS) studies and thermal optical properties and surface resistivity measurements have been used for pristine and surface-modified materials erosion, performance, and durability evaluation. SEM coupled with EDS was mostly used to study the surface morphology and elemental composition of the investigated samples. The surfaces of nonconductive samples were coated with a thin layer of carbon to prevent charging.

The thermal optical properties, solar absorptance α and thermal emittance ε of the untreated, surface-treated, and treated/tested materials were evaluated, based on appropriate American Society for Testing and Materials standards.[21–23]

Solar absorptance and infrared emittance of pristine and treated/tested coatings/paints were measured at MSFC using an AZ Technology Laboratory Portable Spectroreflectometer and TEMP 2000 Infrared Reflectometer, respectively, before and subsequent to testing. These results have been found to be in a reasonable agreement with the same characteristics of pristine materials provided by the manufacturers, and pristine, surface modified, and treated/FAO materials tested at ITL, Inc., and are presented in Tables 2 and 3.

Surface resistivity of the charge dissipative or conductive paints was investigated with an electrometric voltmeter coupled with a bi-electrode cell.[23] Resistance measurements were made at an applied voltage less than 10 V. Aluminum foil electrodes 5.0 ± 0.1 mm wide were set apart at a distance $L_0 = 20.0 \pm 0.1$ mm. The physical

Table 2 Test results of polyurethane-based nonconductive Aeroglaze paints exposure to FAO+VUV at MSFC

Treatment	AO fluence, atoms/cm^2	Mass change, μg/cm^2	Solar absorptance			Infrared emittance		
			Pretest	Posttest	$\Delta\alpha$	Pretest	Posttest	$\Delta\varepsilon$
			A276:Z306					
Control (untreated)	5.53×10^{20}	−572	0.855	0.594	−0.261	0.87	0.90	+0.03
Photosil	5.25×10^{20}	+6	0.864	0.859	−0.005	0.87	0.86	−0.01
			Z306					
Control (untreated)	5.25×10^{20}	−387	0.953	0.975	+0.022	0.90	0.92	+0.02
Photosil	5.53×10^{20}	+1	0.974	0.952	−0.022	0.90	0.89	−0.01

Table 3 Test results of acrylic-based antistatic or conductive EKOM coatings after exposure to FAO+VUV at MSFC

Specimen	AO fluence, atoms/cm^2	Mass change, μg/cm^2	Solar absorptance			Infrared emittance		
			Pretest	Posttest	$\Delta\alpha$	Pretest	Posttest	$\Delta\varepsilon$
EKOM-1								
Control (untreated)	7.22×10^{20}	−178	0.302	0.289	−0.013	0.88	0.90	+0.02
Photosil	8.07×10^{20}	−52	0.303	0.299	−0.004	0.88	0.91	+0.03
EKOM-1P								
Control (untreated)	9.96×10^{20}	−130	0.229	0.206	−0.023	0.23	0.24	+0.01
Photosil	10.1×10^{20}	−37	0.232	0.213	−0.019	0.24	0.26	+0.02
EKOM-2								
Control (untreated)	7.61×10^{20}	−301	0.950	0.942	−0.008	0.87	0.89	+0.02
Photosil	8.51×10^{20}	−58	0.955	0.943	−0.012	0.87	0.89	+0.02

Table 4 Surface resistivity of pristine, tested, and surface-modified/tested EKOM paints

Material	Surface resistivity, ρ_s, Ω/□		
	Pristine	Tested	Surface modified/tested[a]
EKOM1 (white)	3.25×10^6	3.5×10^7	2.5×10^7
EKOM1P (silver–gray)	3.8×10^3	5.85×10^3	3.08×10^5
EKOM2 (black)	4.1×10^5	1.18×10^6	4.5×10^6

[a] Tested at AOBF at MSFC.

contact of the electrodes with the sample was accomplished by affixing the electrodes to the surfaces of the samples with a strip of tape. Surface resistivity ρ_s was calculated using the expression

$$\rho_s = R(\tau) \times B/L_0 \qquad (1)$$

where $R(\tau)$ is measured resistance at time $\tau = 1$ min, B is electrode width, and L_0 is distance between electrodes. The results are presented in Table 4.

Results and Discussion

Nonconductive Aeroglaze Paints

The degradation effects of ground-based simulation and in-flight (LEO) exposure on white and black Aeroglaze paints have been published elsewhere.[1–6] The results of this study agree well with the published data and confirm the past results of extensive oxygen plasma and FAO beam testing of pristine and Photosil-treated polyurethane-based Aeroglaze paints.[11,12] The obtained information was used for further technology optimization and comparison with the new test results obtained at higher 5-eV FAO fluence and simultaneous VUV exposure in the AOBF at MSFC.

In general, the untreated and unprotected polyurethane-based paints exhibited considerable surface erosion following FAO exposure and even stronger erosion effects after oxygen plasma asher testing, whereas the Photosil-treated samples did not show any significant signs of erosion. Mass loss and visual inspection using optical and SEM analyses were used for evaluation of the erosion. Both the untreated gray (A276:Z306) and white (A276) paints attained a white powdery appearance, and the unprotected black paints (Z306 and Z302) developed a powdery dark-gray surface.

All paints modified by the most recent version of the Photosil process have shown, in comparison with pristine samples, at least one to two orders of magnitude lower mass loss in plasma asher testing and practically no measurable mass loss in the UTIAS/ITL FAO beam testing facility, within the precision of the measuring microbalance. These data were used for comparison with the results of testing at MSFC.

Note that, in general, some small mass loss or even mass gain, that is, mass changes, may occur under AO exposure, not only by erosion of the surface-modified samples (if any), but also due to additional surface conversion, with competitive processes of volatiles release and oxygen uptake and Si oxide-based protective structures formation. The mass loss is nonlinear, and the calculated average erosion yields given in such cases are just semiquantitative indications of the improved durability in an AO environment and require complementary SEM and elemental surface analysis studies for final conclusions.

Mass change data and the change in thermal optical properties for Aeroglaze paints tested at MSFC AOBF are given in Table 2. The untreated samples exhibited significant mass loss, as expected, due to the reactive nature of the polyurethane and the carbon pigment to AO. The changes in the appearance of the untreated samples were also visible to the naked eye. The untreated gray (A276:Z306) paint faded to a lighter gray, and the unprotected black (Z306) paint developed a velvety texture, typical of AO erosion of black paint. On the other hand, the protected samples showed very slight color change and, for the first time in the testing program, some small mass gain instead of mass loss. This might be indicative of the formation of a fully stabilized, protective surface layer through oxygen uptake in the course of some additional surface conversion and stabilization of the modified surface in the reactive oxidizing AO environment.[24,25]

Thermal optical characteristics of pristine, Photosil-treated, and Photosil/FAO-tested Aeroglaze paints had shown that, similar to polymer films and paints,[11,12] the Aeroglaze paints maintained their original thermal optical properties after the surface treatment, as well as after treatment/FAO exposure up to 1–2 × 10^2 atoms/cm^2. Both solar absorptance and thermal emittance values remained essentially unchanged within the experimental uncertainty, $\alpha = \pm 0.02$ and $\varepsilon = \pm 0.01$.

All tested samples exhibited only slight changes in optical properties as a result of a high-fluence MSFC AOBF exposure, except for the untreated A276:Z306 sample that exhibited a substantial change in solar absorptance. The solar absorptance of the untreated A276:Z306 decreased by about 0.26, and its thermal emittance increased by about 0.03. The Photosil-treated A276:Z306 sample was more stable, exhibiting only a slight decrease in both solar absorptance and emittance (about 0.005 and 0.01, respectively). These independent results reconfirmed the protective effectiveness of the Photosil process in terms of mass change and optical stability at higher FAO fluences, in combination with VUV exposure.

The surface morphology changes of the paints after testing were also evaluated using SEM surface analysis, with the results for testing at AOBF at MSFC presented in Figs. 1 and 2. SEM images of the untreated paints show highly eroded surfaces, with the pigments exposed (Figs. 1a and 2a). As one can see in Table 2, the thermal emittance of the untreated samples increased after AO exposure. This is due to roughening of the surface through a nonuniform erosion of the paint constituents. On the other hand, all Photosil-treated samples that exhibited no mass loss exhibited no surface morphology changes on a microscopic level (Figs. 1b and 2b). SEM examination of the surfaces of the treated and tested samples clearly demonstrated that the Photosil treatment and the assumed surface conversion process during AO do not alter the surface morphology of the materials and provide a fully stabilized surface after FAO or FAO/VUV exposure.

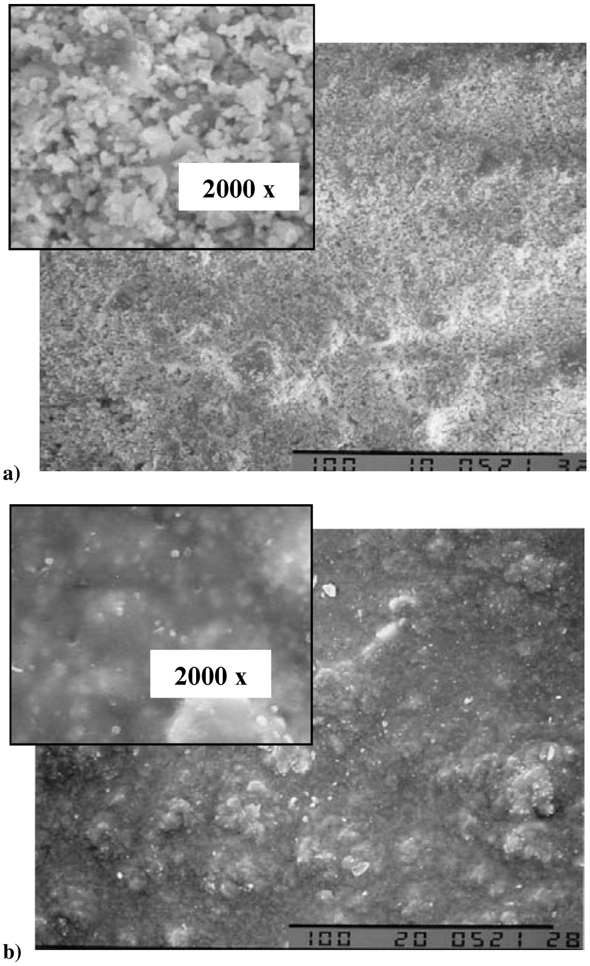


Fig. 1 SEM micrographs (magnification 500×, magnification of insert 2000×) of A276:Z306 paint after FAO+VUV exposure at AOBF MSFC at FAO fluence ∼5 × 10^{20} atoms/cm^2: a) pristine (untreated) and b) Photosil treated.

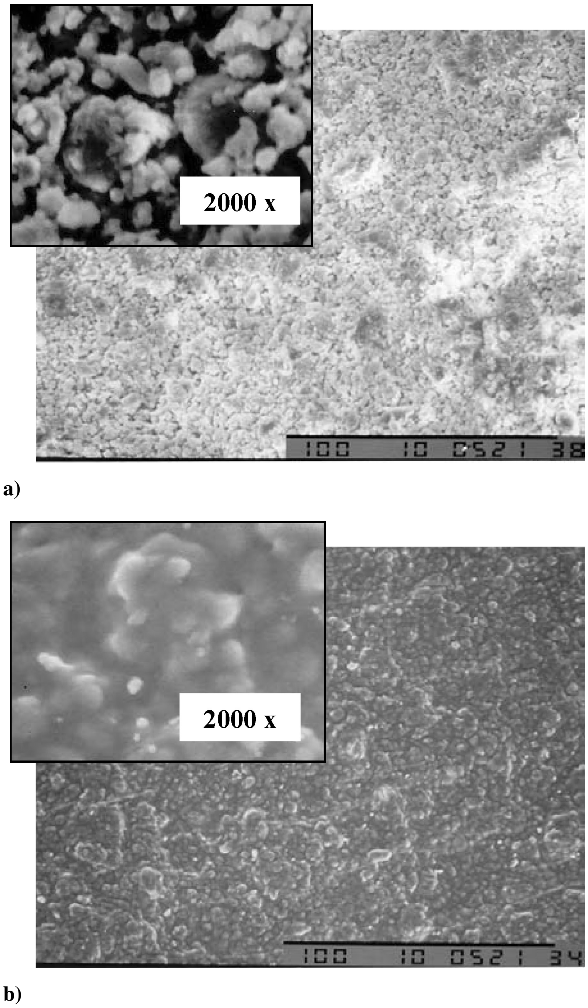
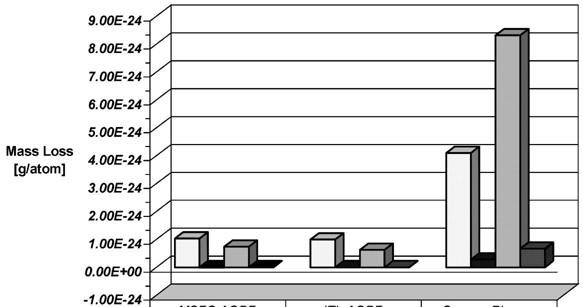


Fig. 2 SEM micrographs (magnification 500 ×, magnification of insert 2000 ×) of Z306 paint after FAO+VUV exposure at AOBF of MSFC at FAO fluence ∼5 × 10^{20} atoms/cm^2: a) pristine (untreated) and b) Photosil treated.

The measured averaged mass loss yields for untreated and Photosil-treated A276:Z306 and Z306 samples, following ground-based accelerated testing in three different AO facilities, are presented in Fig. 3. The displayed data are used only for comparison of the AO stability between pristine and surface-treated paints. Averaged mass loss yields are higher in oxygen plasma tests, as expected. This is attributed to the plasma asher system that also subjects the materials to UV/VUV radiation, excited state neutrals, and energetic ions, all of which can affect the material erosion rate. Practically no measurable mass loss has been shown for the Photosil-treated samples after FAO beam testing that may be attributed to high-quality surface stabilization and protection by the optimized Photosil treatment. As mentioned earlier, the results of testing at AOBF of MSFC indicated that the surface-modified paints had demonstrated a very low mass gain that may be attributed to additional oxygen uptake by the surface conversion and final stabilization[23,24] processes under higher FAO fluence. In conclusion, all three AO facilities used in this study confirmed the protective capability of the Photosil treatment to provide full protection and long-term stability for polyurethane-based Aeroglaze paints.

Conductive EKOM Coatings

The conductive acrylic-based EKOM paint samples, both untreated and treated by a few versions of the Photosil process, were initially screened in an oxygen plasma system (effective fluence



	MSFC AOBF	ITL AOBF	Oxygen Plasma
□ *Pristine Gray Paint*	1.03E-24	1.00E-24	4.10E-24
■ *Photosil™-treated Gray Paint*	-1.15E-26	0.00E+00	2.82E-25
▨ *Pristine Black Paint*	7.38E-25	6.24E-25	8.32E-24
▩ *Photosil™-treated Black Paint*	-2.05E-27	0.00E+00	6.69E-25

Fig. 3 Mass change yields of pristine and surface-modified polyurethane-based Aeroglaze coatings, averaged by the testing time; comparison of the results in different AO testing facilities.

$\sim 2.45 \times 10^{20}$ atoms/cm^2). Both mass change data and SEM images indicated that Photosil-treated samples were more stable than the untreated ones. The effectiveness of the protection varied among EKOM-1, EKOM-1P, and EKOM-2 coatings. The surfaces of the unprotected EKOM paints strongly eroded, acquiring a powdery appearance, with the phenomenon being strong for the EKOM-1 (white) and even stronger for the EKOM-2 (black). Visual inspection of Photosil-treated paints revealed no significant change in color or appearance. Clearly, the surface-modified layer provided very good protection against AO erosion. To the contrary, the acrylic matrix of the untreated specimen was severely etched, thereby exposing the pigment particles. A similar, but less noticeable, erosion was observed for the binder in the untreated EKOM-1 and EKOM-1P samples that, most probably, is because these coatings have a smaller amount of acrylic binder than in EKOM-2 (EKOM-2 = 65% pigment, EKOM-1 = 80% pigment, and EKOM-1P = 86% pigment, by volume). Also note that although lower erosion of EKOM-1 and EKOM-1P was achieved after Photosil treatment in oxygen plasma, full protection was not evident.

In addition to the plasma asher exposure, selected Photosil-treated EKOM samples were tested at MSFC AOBF. These treated samples, along with their untreated counterparts, were exposed to 5-eV AO at the fluence approximately 7–10 $\times 10^{20}$ atoms/cm^2, together with $\sim$865 ESH of VUV radiation, with the AO path also normal to the sample surface. MSFC AOBF ground-based testing results are presented in Table 3. From the mass loss data in Table 3, it is evident that complete protection was not achieved yet. All specimens, both untreated and Photosil-treated, showed some mass loss. However, the resistance to FAO erosion of EKOM-1, EKOM-1P, and EKOM-2, as evaluated from mass loss tests, was improved in the first surface treatment trials at least 4–6 times. Also note that some EKOM coatings are still in various stages of development and full optimization of the Photosil process, as applied to EKOM paints, is planned.

During SEM/EDS analysis, it was possible to obtain clear SEM images from the surfaces of all EKOM paints without deposition of any conductive thin film to avoid charging the surface with electrons. This behavior of the samples in the SEM provided a qualitative indication that the conductive nature of those paints has not been drastically changed either by the surface modification treatment, or by testing in AOBF or by both treatment/testing.

The results of an EDS analysis of pristine, pristine/tested, surface modified, and modified/tested EKOM paints that were tested at MSFC are presented in Figs. 4 and 5. Figure 4 shows EDS spectra of the pristine (Fig. 4a) and Photosil-treated (Fig. 4b) EKOM-1 samples subjected to AOBF testing. The peak at 1.74 keV, associated with Si, is indicative of its presence in the surface layer of the modified sample. The EDS spectra collected from EKOM-1P and EKOM-2 samples after surface modification also contained a silicon peak. To the contrary, Si was absent in the EDS spectra collected from the pristine (Fig. 5a) and pristine/AO-tested (Fig. 5b) EKOM-2 samples, a fact that confirmed the absence of Si in the

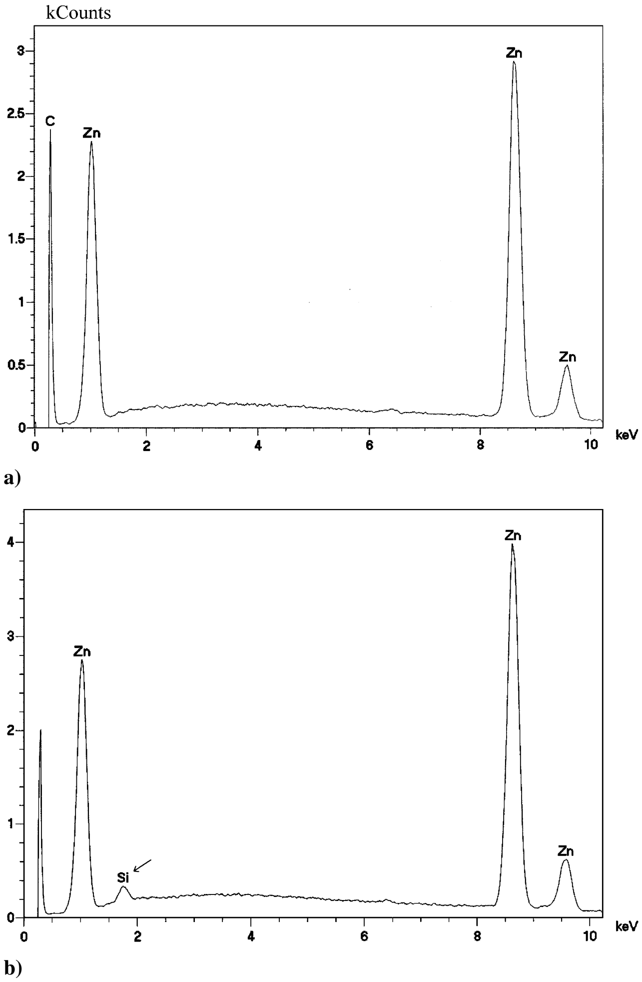
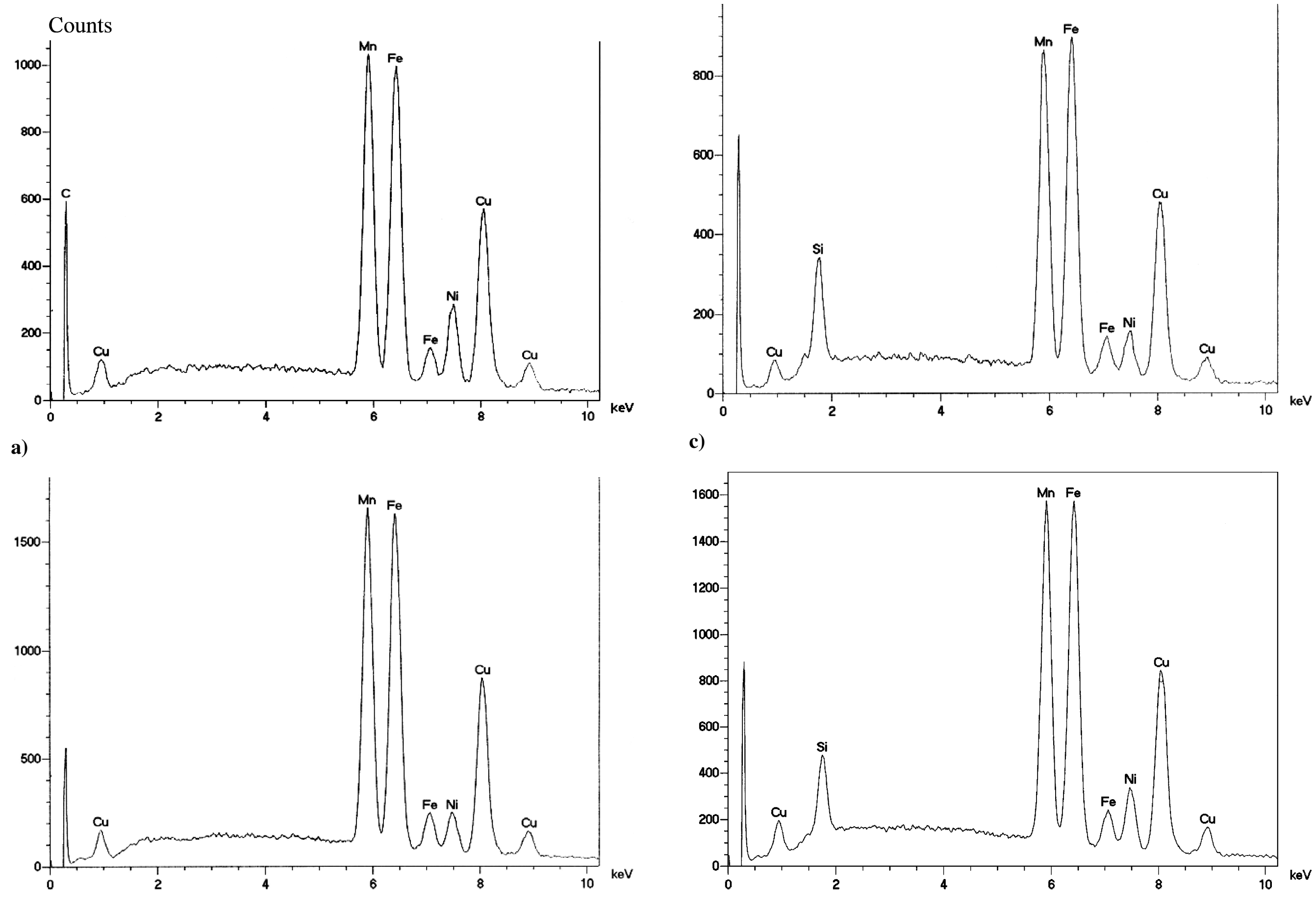


Fig. 4 EDS spectra after AOBF testing, indicating the presence of Si on the treated samples after testing: a) pristine EKOM-1 and b) Photosil treated EKOM-1.

original materials or as a contaminant in the testing system. The EDS analysis results of the Photosil-treated unexposed surface of the EKOM- 2 sample shown in Fig. 5c suggest also that silicon was incorporated into the surface layers and remained on the surface, to a significant extent, after FAO testing (Fig. 5d). All of these results are in a good agreement with the demonstrated enhanced resistance to FAO exposure of the treated samples. Moreover, Si remained on the surfaces even after the high-fluence AOBF testing, which further supports the enhanced long-term durability and FAO + VUV resistance of the modified layer.

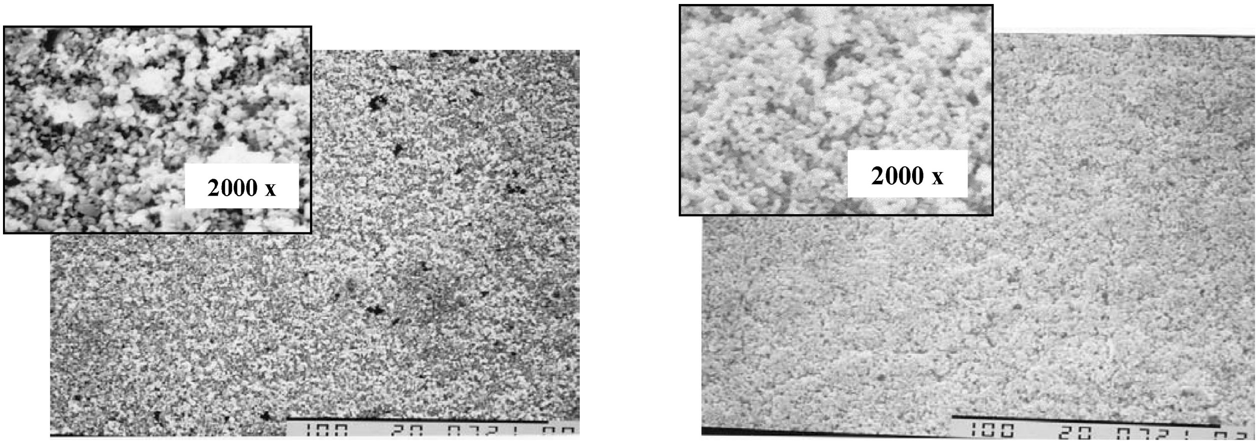
Additional support data on the effectiveness of the Photosil-surface modification treatment came from the results of the surface morphology studies. A significantly higher erosion of the surfaces, exhibiting the exposed pigments and highly developed surface morphology, was clearly visible for the pristine EKOM-1 paint after the FAO testing (Fig. 6a), whereas the surface of the Photosil-treated and FAO-tested sample remained practically unchanged (Fig. 6b). Comparison of the pristine-untested material (Fig. 7a) and the tested sample (Fig. 7b) shows a developed surface morphology on the pristine-tested sample. A comparison of surface morphology of the EKOM-2 Photosil-treated (Fig. 7c) sample with the Photosil-treated and FAO-tested (Fig. 7d) sample and with the FAO-tested pristine sample (Fig. 7b) indicates that the surface-modification treatment had a limited protective effect for the EKOM-2 paint.

Thermal optical characteristics of the EKOM coatings were evaluated before and after Photosil treatment and AOBF testing (Table 3). The solar absorptance of all test specimens slightly decreased after exposure to AO. Thus, the solar absorptance values of pristine EKOM-1 and EKOM-1P decreased by about 0.013 and 0.023, respectively. The Photosil-treated counterparts were slightly more



a) b) c) d)

Fig. 5 EDS spectra of EKOM-2 at FAO fluence ~10 × 10^{20} atoms/cm^2: a) pristine, unexposed at AOBF (under the holder); b) pristine, exposed at AOBF; c) Photosil-treated EKOM-2, not exposed at AOBF (under the holder); and d) Photosil-treated, exposed at AOBF.



a) b)

Fig. 6 SEM micrographs (magnification 500 ×, magnification of insert 2000 ×) of EKOM-1 paint after FAO+VUV exposure at AOBF of MSFC, at FAO fluence ~10 × 10^{20} atoms/cm^2: a) pristine (untreated) and b) Photosil treated.

stable, with solar absorptance decreasing by about 0.004 for EKOM-1 and 0.019 for EKOM-1P. All test samples, including the untreated and treated ones, showed a small increase of about 0.02 in thermal emittance. In summary, the thermal optical properties of both untreated and treated EKOM coatings after AO exposure did not change significantly.

In Fig. 8, the averaged mass loss yields are shown for untreated and Photosil-treated EKOM coatings following ground-based accelerated AO exposure in a plasma asher and in AOBF at MSFC. Once again, the obtained values are used only for comparison purposes between the pristine and the surface-modified materials. These results confirm the severity of the environment generated in the oxygen plasma asher system, resulting in approximately an order of magnitude higher degradation than in the FAO beam facility, and illustrate the distinguishable durability enhancement by the surface modification treatment.

Besides optical stability, the maintenance of electrophysical characteristics is another major functional requirement of this type of conductive coating. Surface conductivity must remain without significant changes after treatment and after in-flight or imitation LEO

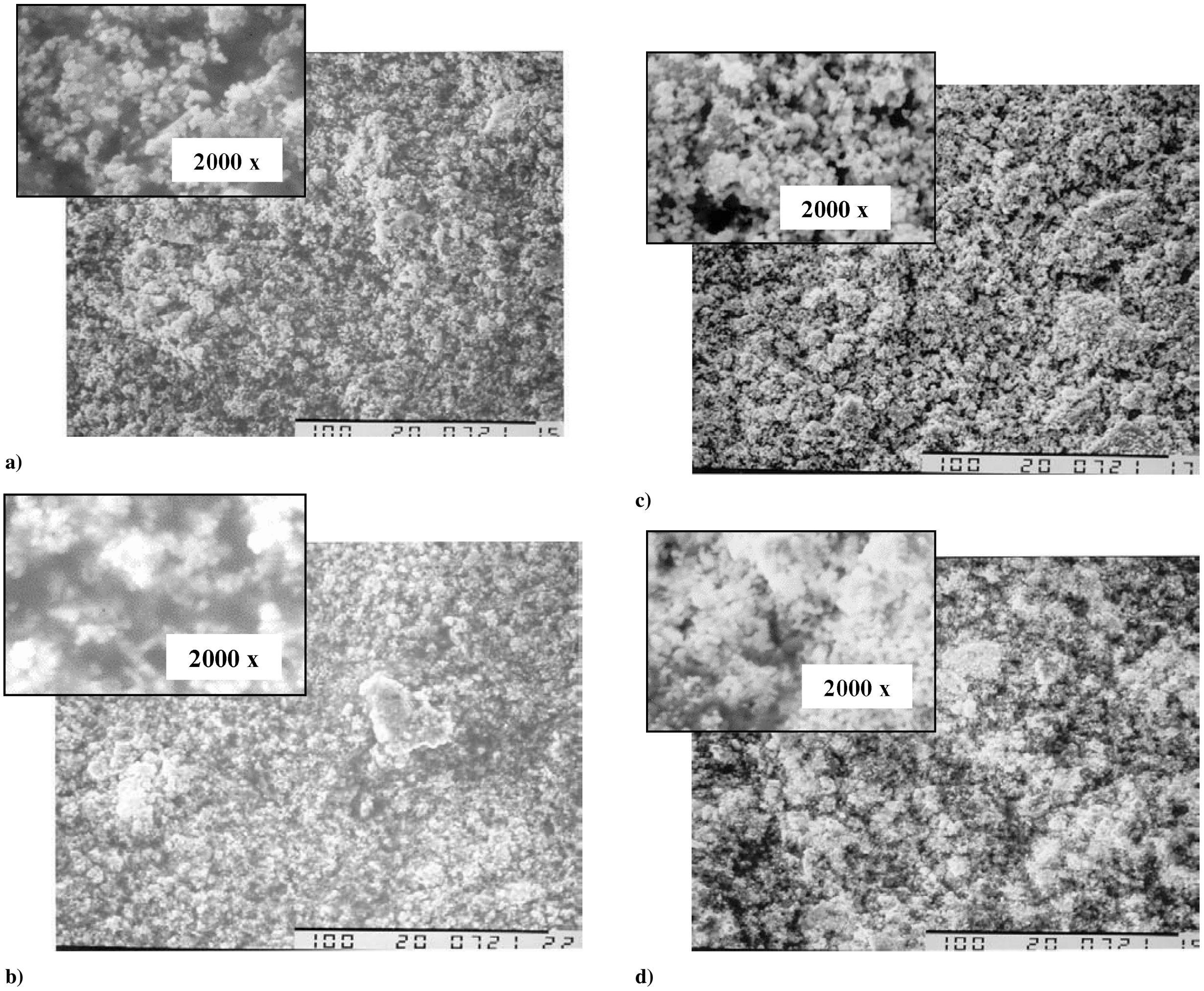
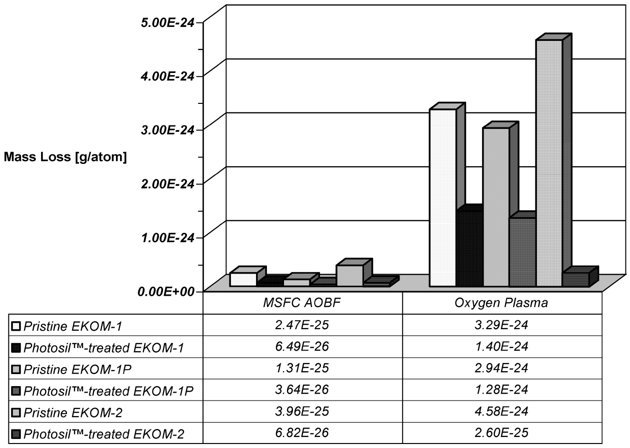


Fig. 7 SEM micrographs (magnification 500 ×, magnification of insert 2000 ×) of EKOM-2 paint after FAO+VUV exposure at AOBF of MSFC, at FAO fluence ∼10 × 10^{20} atoms/cm^2: a) pristine unexposed (under the holder), b) pristine FAO exposed, c) Photosil treated, unexposed (under the holder), and d) Photosil-treated, exposed.



	MSFC AOBF	Oxygen Plasma
□ Pristine EKOM-1	2.47E-25	3.29E-24
■ Photosil™-treated EKOM-1	6.49E-26	1.40E-24
▨ Pristine EKOM-1P	1.31E-25	2.94E-24
▨ Photosil™-treated EKOM-1P	3.64E-26	1.28E-24
▨ Pristine EKOM-2	3.96E-25	4.58E-24
■ Photosil™-treated EKOM-2	6.82E-26	2.60E-25

Fig. 8 Mass loss yields of EKOM paints, averaged by the testing time; comparison of the results in different AO testing facilities.

environment exposure. It was shown recently that there was practically no change of the surface resistivity of highly insulating space-related polymers by Photosil treatment. No results regarding the surface resistivity, however, have been available for other classes of materials.

Surface resistivity measurements were conducted in this study for pristine, AOBF-tested, and surface-modified/AO-tested EKOM paints, and the results are presented in Table 4. Analysis of the data suggests that for EKOM-1 and EKOM-2 that were designed as charge dissipative, neither AO testing nor surface treatment/AO testing increased the surface resistivity by more than an order of magnitude. The observed behavior of the surface resistivity for these paints suggests that Photosil treatment/AO testing did not change the class of materials with regard to surface resistivity. These results provide the first indication that Photosil surface modification technology can be used for surface treatment of charge dissipative space coatings to enhance the erosion-related space durability, without affecting significantly the electrophysical characteristics. The conductive EKOM-1P paint was the only paint sample for which the surface resistivity was altered, increasing almost two orders of magnitude after Photosil treatment/AO testing and, thus, shifting this paint from the conductive class of materials to charge dissipative coatings. At the same time, AO testing of the pristine EKOM-1P paint sample provided an insignificant, less than two times, increase in surface resistivity.

Conclusions

Conductive and nonconductive polymer-based space-related paints were treated and evaluated using a recently developed surface modification process Photosil^{TM}. A number of different ground-based AO and AO+VUV facilities were used for testing the paints. It was demonstrated that the surface modification treatment significantly improves the paints resistance to AO and AO+VUV erosion, while leaving their optical and electrical properties almost unchanged.

All properly treated polyurethane-based paint samples, such as A276:Z306 and Z306 paints, demonstrated the development of a surface layer fully resistant to AO and VUV exposures. These findings were confirmed by both mass loss/gain and SEM studies after in-house FAO and AO+VUV testing and in an independent high-fluence ground-based accelerated (5-eV) FAO + VUV testing in MSFC AOBF.

The stability of the acrylic-based conductive EKOM coatings to FAO + VUV exposure was improved after initial surface treatment trials using Photosil technology. The treated charge dissipative paints still maintained the surface resistivity within an order of magnitude, which is critically important for the required space applications. Full protection, however, was not achieved in these trials.

Future work with these class of paints will include the full optimization of the Photosil process for the EKOM coatings and other conductive organic-based paints with the main goal to attain complete FAO + VUV erosion resistance and space durability enhancement.

Although the results from all test systems for all samples demonstrated the same trends, the quantitative results were found to be sensitive to the environment parameters produced in each of the testing facilities, with plasma asher producing the most severe environment.

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