Analysis of atomic oxygen and ultraviolet exposure effects on cycloaliphatic epoxy resins reinforced with octa-functional POSS.

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Abstract

In this study, novel nanocomposites were created by incorporation of Silsesquioxane containing eight glycidylether groups (octa-POSS) into a cycloaliphatic epoxy cured by an anhydride. The developed resin system, with different nanoparticle concentrations, was used on the outer layers of an ultra-thin CFRP structure in order to provide better environmental resistance to the environment of low Earth orbit (LEO) which was tested in a ground-simulation facility. The developed resins were subjected to space-like degrading factors and their response to corrosion, radiation and elevated temperatures was monitored by mass loss, together with measuring changes in surface chemistry (ATR-FTIR), functionality development (contact angle measurement and XPS), roughness (scanning laser microscopy) and morphology (SEM). The influence of increasing octa-POSS content on thermo-mechanical properties was measured with DMTA and the strength and modulus of elasticity were determined by flexural test. The addition of octa-POSS in any loading improves the environmental resistance, however, the most significant retention of mass and mechanical and surface properties after space-like exposure was observed in the 20 wt% octa-POSS reinforced cycloaliphatic epoxy. The results presented here may contribute to the development of novel class of nanocomposites which can offer an extended service life in LEO.

Keywords: Atomic oxygen, Cycloaliphatic epoxy resin, POSS, Space materials, UV radiation

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1. Introduction

Many recent developments in space exploration focus on the use of nano-satellites which are lightweight, structurally flexible and more affordable to build and launch than more traditional satellites [1, 2]. For this reason, the use of polymeric materials has significantly grown, especially in the field of space deployable structures which are often epoxy resin based carbon fibre reinforced materials characterized by low thickness and high packaging efficiency [3, 4, 5].

It is well recognized that polymeric materials degrade in space to a much larger extent than metals or ceramics [6, 7]. Based on decades of testing of polymer performance in hostile, LEO environments it is known that the most hazardous factor is atomic oxygen (AO), enhanced by the presence of electromagnetic radiation, temperature extremes, high vacuum and debris impact [8, 9, 10].

Organic materials react with oxygen radicals and form volatile components which results in the loss of structural mass and mechanical properties. Upon exposure to radiation, polymers yellow and embrittle which is caused by absorptions of large amounts of energy that break chemical bonds and consequent crosslinking in order to bridge the dislocated structure. This effect is intensified by thermal cycling that introduces stresses to a material and results in crack propagation. Epoxy resins are strongly affected by the space environment [11, 12, 13, 14] as the high content of oxygen in epoxy resins makes them prone to AO erosion. In addition to this, the types of epoxy with high numbers of benzene rings or other unsaturated bonds in their polymeric backbones exhibit strong UV absorption.

Various properties of polymers can be improved by the addition of nanoparticles. In the space industry, a nano-reinforcement was reported as a successful methodology to increase environmental resistance of Kapton [15, 16] and other polymeric matrices [17, 18, 19, 14]. In combating etching effects of AO, silicon nanoparticles are of significant utility. As has been observed both in ground-simulation facilities [20, 21, 22, 23, 24, 25, 26] and during in-space materials testing [27, 28], the strong chemical affinity between bombarding oxygen and embedded silicon results in formation of silicon dioxide, rather than carbon-oxygen recombination into volatile components. This property of silicon has resulted in much lower erosion yields of siliconized materials in comparison with their untreated counterparts. POSS is a particular type of nanoparticle that forms cage-like structures, with a functional group at each vertex. This means that various type of POSS exist that might bear any number between zero and eight reactive, functional groups, which makes it an excellent

candidate to blend with polymeric materials. In the present work the POSS is highly functionalised with eight glycidylether (epoxy) groups (octa-POSS).

The aim of this study was to manufacture an ultra-thin epoxy resin based CFRP structure using materials and methods developed for long deployable CFRP masts [29, 30], such as those used in CubeSail [31], InflateSail [32] or REMOVEDebris missions [33, 34], but with advanced adaptations to LEO. To achieve that, outer layers of the composite were replaced with octa-functional POSS reinforced cycloaliphatic epoxy resin which shows much better dispersion in epoxy matrix than mono-functional POSS [35]. This novel resin blend offers enhanced UV stability due to the lower UV absorption of cycloaliphatic epoxies and the UV-blocking effects of POSS nanoparticles, together with the protection against AO and thermal extremes that octa-POSS also offers.

2. Experimental method

Materials. The cycloaliphatic epoxy resin used in this study (bis-(epoxycyclohexyl)-methylcarboxylate) was obtained from Huntsman Advanced Materials (Netherlands) and is recognised under the trade name CY 179. The anhydride hardener from the same supplier of type Aradur 917 CH was used to cure the resin in the presence of an accelerator (1-methylimidazole, DY070) for 45 min at 90°C, followed by 2h at 180°C.

The selected type of nanoadditive was a glycidyl POSS bearing eight reactive epoxide groups of type EP0409, denoted further as octa-POSS, purchased from Hybrid Plastics (Hattiesburg, USA). Samples with a POSS content of 5,10,15, and 20 wt% were manufactured. The chemical structures are presented in Figure 1.

Figure 1: Chemical structure of materials used in this study, cycloaliphatic epoxy resin cured with anhydride in the presence of an accelerator (left) and octa-functional POSS (right).

Figure 2: Schematic of the ultra-thin CFRP structure. Layup A presents the structure manufactured with aromatic epoxy resin only, whereas Layup B presents the structure with outer layers replaced by octa-POSS reinforced cycloaliphatic epoxy resin for improved environmental stability in LEO.

The octa-POSS reinforced cycloaliphatic epoxy resin system was applied to form the outer surfaces of a 0.3 mm thick CFRP structure. For reference, the same kind of structure was manufactured using aromatic epoxy resin supplied by Huntsman recognised under a trade name XB 6469 cured with cycloaliphatic polyamine Aradur 2954. Figure 2 presents the layup of both structures, where Layup A will be further denoted as Aromatic and Layup B as Cycloaliphatic.

Manufacturing. The driving application for this work is a type of thin CFRP tape spring, which may or may not be bistable [36], which can be used to form the basis of support structures for a number of long duration missions, including drag-deorbiting sails and deployable flexible solar arrays. The manufacturing methodology for the ultra-thin epoxy resin based CFRP masts described in [37] was altered in order to provide a structure with better environmental resistance.

Figure 3 presents the main manufacturing steps. Firstly the core of the structure is constructed from two plies of carbon fibre braid (Figure 3a) and a central UD ply, which are all impregnated with an aromatic epoxy resin film (Figure 3b and 3c). Following this, an octa-POSS reinforced cycloaliphatic epoxy resin blend was applied to the outer surfaces (Figure 3d) and the structure was cured on either a cylindrical mandrel (Figure 3e) or on a metallic plate when samples with specific rectangular shape were required for DMTA and bending tests. The final boom (Figure 3f) was cut into specimens of approximately 2×2 cm for AO and UV analysis.

Testing facility. In order to simulate atomic oxygen etching, materials were exposed to the plasma environment created by a radio-frequency (RF) generator. Plasma was generated in a glass tube of

Figure 3: Manufacturing stages of the ultra-thin CFRP masts. Including CF braid draping (a), impregnating the core of the structure (b and c), impregnating the surface layers (d) and finally thermo-forming (e).

7 cm in diameter and the samples were placed in the plasma afterglow, approximately 1 cm from the tube end. The pressure in the main chamber was 1.65×10^{-4} Torr while a gas mixture of oxygen and argon was pumped into the chamber at 5 sccm (1.5 sccm oxygen and 4 sccm argon). The total exposure time was 24h at 50W RF power. Based on the mass loss of a reference Kapton sample, AO fluence was calculated to be 3×10^{20} atoms/cm².

The effects of UV radiation were approximated by using a deuterium lamp (Heraeus, model D200VUV) which generates photons primarily in the UVC range (100-280 nm). In the UV range of 200-280 nm the photon energy is between 6.2 eV and 4.5 eV, which is energetic enough to break most carbon functional groups such as C-C and C-O [7]. This portion of radiation is by far the most damaging to polymeric materials. The flux produced by the deuterium lamp in the range of 100-200 nm is $10 \times$ the flux of the sun in this region, therefore the observed changes in materials are accelerated when compared to solar radiation. In order to measure the lamp's intensity, an AXUV100 EUV-UV photodiode was mounted inside the chamber. The total flux measured at the

location of the specimen stage was $110 \mu\text{W}/\text{cm}^2$. For comparison, the UV flux incident on the
85 samples and the ASTM E-490-00 solar spectrum flux [38] in the UVC range is presented in Table
1.

Table 1: UV-C Lamp Irradiance vs Solar ASTM E-490-00 Irradiance.

Wavelength Range (nm)	Lamp Power ($\mu\text{W}/\text{cm}^2$)	Solar Power ($\mu\text{W}/\text{cm}^2$)
115-120	11	0
120-130	21	0.7
130-150	23	0.1
150-170	35	0.5
170-200	8	8.5
200-240	7	142
240-280	3	516.5

Samples were placed on a specimen stage in a vacuum chamber, approximately 40 cm from the
lamp for 24h. The specimen stage was covered with a silicon heating mat in order to simulate
heat which in orbit acts simultaneously with radiation. A thermocouple attached to the specimen
90 stage was connected to the temperature meter via a vacuum feedthrough and indicated $80\text{-}85^\circ\text{C}$
throughout the experiment.

3. Characterization

Mass loss measurements. Measurements of mass loss were performed on samples outgassed in a
vacuum chamber for at least 24h in order to make sure that any mass loss is associated with the
95 effects of degradation. Prior to testing samples were stored in a desiccator. After the exposures,
mass was measured within maximum of 10 minutes from samples removal from the chamber using
a four digits precision lab balance.

Surface chemistry. XPS analyses were performed on a ThermoFisher Scientific Instruments K-
Alpha+ spectrometer, using a monochromated Al $K\alpha$ X-ray source ($h\nu = 1486.6 \text{ eV}$) on an X-
100 ray spot of $\approx 400 \mu\text{m}$ radius. Survey spectra were acquired employing a Pass Energy of 200 eV.
High resolution, core level spectra for all elements were acquired with a Pass Energy of 50 eV.

All spectra were charge referenced against the C1s peak at 285 eV to correct for charging effects during acquisition. Quantitative surface chemical analyses were calculated from the high resolution, core level spectra following the removal of a non-linear (Shirley) background. The manufacturer's
105 Advantage software was used to analyse the data.

Contact angle measurement was performed on a basis of the sessile drop method using a KRÜSS Easydrop-DSA1 apparatus and a DSA1 dedicated Drop Shape Analysis software.

Surface spectroscopy before and after UV radiation was measured using the Fourier transform Infrared (FTIR) spectroscopy in the Attenuated Total Reflectance (ATR) mode, using an Agilent
110 Cary600 spectrometer, 32 scans per sample, at the resolution of 4 cm^{-1} in absorbance mode. Spectra were acquired in the region $800\text{--}3800\text{ cm}^{-1}$ at room temperature.

Thermo-mechanical properties. Dynamic mechanical thermal analysis (DMTA) was performed using the DMA Q800 V7.5 Build 127 apparatus, using $30\text{ mm} \times 15\text{ mm} \times 0.3\text{ mm}$ rectangular specimens in a single cantilever bending mode. $\tan\delta$ was calculated as a function of temperature from 25°C
115 to 230°C , using 5 K/min heating rate at 0.1% strain and 1 Hz frequency.

Flexural tests were carried out using an Instron bending machine in a simply supported mode, with a 10 mm distance between the supports. The sample dimensions were 10 mm wide, 0.3 mm thick.

Surface roughness and morphology. Surface topography was analysed using a laser scanning confocal microscope Zeiss, LSM 700, and a dedicated ConfoMap Surface Imaging and Analysis Software
120 for ZEISS microscopes. 3D images were produced from the scanned area of approximately $3 \times 3\text{ mm}^2$, using a $10\times$ objective. The average surface roughness was calculated from a minimum of 5 scans.

4. Results and discussion

125 4.1. Mass loss measurements due to AO exposure

Mass measurements were performed before and after AO etching in order to evaluate the effectiveness of octa-POSS. The results are presented in Table 2. It was observed that increasing octa-POSS content decreases the total mass loss in comparison to the reference material. This is due to the shielding effect of silicon inorganic nanoparticles that do not form volatile components

130 with oxygen, but rather a silicon dioxide layer which protects the underlying organic part of the structure. This effect of silicon self-passivation is in agreement with previous studies and is also confirmed by contact angle measurements and XPS analysis (Section 4.2).

Table 2: Total mass loss [TML] due to AO of cycloaliphatic/anhydride epoxy resin system reinforced with varied amount of octa-POSS (*) versus unmodified, aromatic epoxy used as reference (**).

	0%**	5%*	10%*	15%*	20%*
TML [%]	4.19	3.57	2.87	2.80	2.66
% of reference	-	85	69	67	64

4.2. Surface chemistry

AO etching has a profound effect on surface chemistry of epoxy resins. This may be observed
 135 by measuring water contact angles on the treated surfaces as presented in Figure 4. The contact angle analysis reveals that all surfaces undergo a transition from hydrophobic ($\alpha \approx 90 - 100^\circ$) to hydrophilic ($\alpha \approx 35 - 15^\circ$). Glass surfaces exhibit perfect wettability ($\alpha = 0^\circ$), therefore decreasing contact angle can be taken as an indication of an emerging silica-like layer on the surface. However, in case of the aromatic epoxy which does not contain any silicon, the water contact angle also
 140 decreases which is associated with high surface energy due to creation of carbon-oxygen functional groups. In order to confirm the silica formation on the surfaces of octa-POSS containing epoxy resins due to AO etching, a complementary XPS study was performed which shows a significant reduction in carbon content and an increase in oxygen in all tested samples (Table 3). A slightly higher carbon and lower oxygen content measurement in the 10wt% octa-POSS reinforced sample
 145 is most likely the result of scanning a low resin and carbon fibre rich area.

AO etching causes a decrease in carbon and oxygen surface content of aromatic epoxy by 13% and 30% respectively, which is an indication of surface oxidation and development of an oxygen functionalized surface. In the case of octa-POSS reinforced cycloaliphatic epoxy resins, both oxygen and silicon content increase. To confirm that the POSS cages undergo opening and recombination
 150 with atomic oxygen an analysis of Si2p peak shift was performed. The shift in Si2p binding energy, which is in the range of 103.2-104.5 eV for SiO₂ and 101.8-102.4 eV for siloxanes is presented in Figure 5 which confirms that the POSS cages undergo opening and react with atomic oxygen in formation of silica protective layer.

Figure 4: Water contact angle measurements on cycloaliphatic/anhydride epoxy resin system reinforced with varied amount of octa-POSS versus unmodified, aromatic epoxy before and after etching by AO.

Table 3: Changes in surface elemental composition[%] due to AO of cycloaliphatic/anhydride epoxy resin system reinforced with varied amount of octa-POSS (*) versus unmodified, aromatic epoxy used as reference (**).

	C1s	O1s	N1s	Si2p	Others
Aromatic**- raw	77.42	14.62	4.43	-	3.53
Aromatic**- AO	66.99	19.44	3.9	-	9.67
5wt%* -raw	69.26	13.66	2.66	2.55	11.87
5wt%* -AO	63.52	25.71	3.28	4.55	2.94
10wt%* -raw	82.18	7.69	2.27	1.06	6.8
10wt%* -AO	70.37	21.28	2.81	3.36	2.18
15wt%* -raw	75.01	14.22	3.05	2.16	5.11
15wt%* -AO	45.05	35.92	2.05	12.74	4.24
20wt%* -raw	81.37	11.31	1.7	1.8	3.82
20wt%* -AO	26.69	46.28	1.07	20.63	5.33

4.3. Thermo-mechanical properties

155 DMTA analysis was only performed on the aromatic and 5wt% octa-POSS reinforced cycloaliphatic epoxy, before and after AO etching (Figure 6). In a purely aromatic material, AO exposure

Figure 5: Si2p measured by XPS. Before the AO exposure the Si peak indicates presence of siloxanes (black line) and after the AO exposure the Si peak shift indicates creation of silica on the surface (red line).

causes a slight increase in storage modulus, which indicates that the material undergoes further crosslinking initiated by the plasma temperature. The glass transition (T_g) is shifted by 27° towards higher temperatures and the decrease in $\tan\delta$ peak illustrates that the polymer undergoes ageing. In the case of the structure modified with octa-POSS reinforced cycloaliphatic epoxy resin, there is a slight decrease of storage modulus in the glassy region, which indicates material softening. This material exhibits two distinctive T_g , one associated with the cycloaliphatic surface epoxy and one with the underlying aromatic epoxy, which both increase due to AO exposure. Such behaviour might be a consequence of both crosslinking and surface reorganisation into an ordered and tighter silica-like network. The broad $\tan\delta$ peak indicates that the range of the polymer chain lengths is much wider than in case of aromatic epoxy due to the incorporation of octa-POSS which increases the resin's complexity.

Figure 6: Changes in storage modulus and glass transition (maximum of $\tan\delta$) due to AO etching. Cycloaliphatic/anhydride epoxy resin system reinforced with 5wt% of octa-POSS used on outer layers of the structure (b) versus purely aromatic epoxy structure used as reference (b).

4.4. Surface roughness

Smooth surfaces exhibit lower environmental degradation, because the surface area is smaller and consequently the probability of reaction with atomic oxygen radicals or energetic photons is lower. Both aromatic and octa-POSS reinforced cycloaliphatic epoxy resins are expected to be etched by AO, because in both cases organic and volatile phases are present on the surface. Oxygen radicals show strong chemical affinity towards carbon and silicon, forming volatile components with the former and SiO_2 layer with the latter, as discussed in Section 4.2. The epoxy component in all samples undergo a certain degree of erosion, which was confirmed by the mass loss studies presented in Section 4.1.

Table 4: Changes in surface roughness due to AO etching of cycloaliphatic/anhydride epoxy resin system reinforced with varied amount of octa-POSS (*) versus unmodified, aromatic epoxy used as reference (**).

	S_a Unexposed [μm]	S_a AO exposed [μm]
Aromatic epoxy**	7.94	10.49
5wt%*	8.43	6.21
10wt%*	6.89	5.16
15wt%*	10.05	2.78
20wt%*	10.42	5.94

Surface roughness (S_a) was measured by scanning the surface in several places and the averaged results are presented in Table 4. In case of the aromatic epoxy, an increase in the S_a parameter is observed which confirms that portions of matter are removed and realised as volatiles, which is validated by the highest mass loss from all studied samples. In all cases of the octa-POSS reinforced cycloaliphatic epoxy resins, it was observed that the S_a decreases. In industry, plasma tends to be used to remove contamination and impurities from surfaces and most probably several nanometres of material were removed during etching, which evened out the surface, however this was not observed in the untreated aromatic epoxy samples. Therefore, it may be concluded that during etching, a SiO_2 layer builds up on the surface, creating an ash residue that shields the organic part of the surface and retards the erosion rate, consequently making the surface smoother.

5. Morphology

Surface degradation, due to AO exposure, can also be assessed visually by examining changes in the morphology using SEM (Figure 7). It is apparent that all materials exposed to AO undergo surface etching and a transition from a very smooth surface (Figure 7a) to an etched surface, which is most severe in the case of the purely aromatic epoxy (Figure 7b). This material experienced creation of craters reaching 20 μm in size and the highest mass loss, as presented in Section 4.1. In the case of structures covered with the octa-POSS reinforced cycloaliphatic epoxy resin, the surfaces are degraded to a much lesser extent and it can be observed that samples modified with higher octa-POSS content (Figure 7d) experience lower erosion rates than those with lower octa-POSS content (Figure 7c).

6. Mechanical properties

The analysis of unexposed samples shows that the addition of octa-POSS up to approximately 15wt% produces an increase in both flexural strength and modulus, as can be observed in Figure 8. In general, AO exposure tends to soften the CFRP plates which results in lower modulus of elasticity, however, a slight increase in modulus can be observed for the 20wt% sample which might be associated with the creation of a brittle silica layer which would increase the modulus of the material. Nevertheless, the magnitude of this increase is within the range of measurement error expected for this form of characterisation. A slight increase in strength is observed in aromatic and

(a) Virgin material.

(b) Aromatic epoxy.

(c) 10wt% octa-POSS reinforced cycloaliphatic epoxy

(d) 15wt% octa-POSS reinforced cycloaliphatic epoxy

Figure 7: Changes in surface morphology due to AO etching of cycloaliphatic/anhydride epoxy resin system reinforced with 10wt% (c) and 15wt% (d) octa-POSS versus unexposed (a). Aromatic epoxy used as reference (b).

205 5wt% octa-POSS reinforced cycloaliphatic epoxy, which might be due to progressing crosslinking upon AO exposure, as described in Section 4.3.

In the case of AO exposed samples, interestingly the decrease in strength is lower in 15wt% than in 10wt% modified samples and is not observed at all in the case of a sample with 20wt% POSS loading. It was concluded that this behaviour is related to the fact that if the loading of nanoparticles is low (5wt%), then the epoxy structure is not significantly disturbed, however, the increasing nanoadditive content causes a significant drop in strength and modulus, which is probably associated with the disturbed polymer's network and consequently the uncured portions of a

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polymer are more easily removed during a thermo-oxidative AO exposure. Additionally, with the increasing POSS content, the silicon concentration on the surface is higher and a silica protective layer is formed as discussed in the Section 4.2. It is believed that this silica-like protective layer partially absorbs the acting loads which contributes to retention of mechanical parameters.

Based on the analysed data, it can be stated that the samples with 5 and 20wt% octa-POSS show a highly satisfactory maintenance of mechanical properties after AO exposure. Although nanoparticles can be very effective in combating the environmental degradation, they might also hinder the crosslinking density and consequently decrease mechanical properties.

Figure 8: Changes in flexural strength (left) and flexural modulus (right) due to AO etching of cycloaliphatic/anhydride epoxy resin system reinforced with increasing amount of octa-POSS versus unmodified, aromatic epoxy used as reference.

7. Resins degradation due to UV radiation

UV irradiation tests in the UV-C region were conducted in order to evaluate the efficacy of octa-POSS/cycloaliphatic epoxy blends on combating UV-induced degradation.

7.1. Mass loss due to UV radiation and outgassing

225 The effectiveness of using cycloaliphatic epoxy/octa-POSS blends in combating UV-induced
chain scissioning and the consequent mass loss is presented in Figure 9. A dramatic reduction
in mass loss for all cycloaliphatic epoxy/octa-POSS is observed in comparison with the purely
aromatic epoxy. The differences in mass loss observed in the octa-POSS loaded samples (in the
order of 0.05%) are probably associated with impurities or lack of sample homogeneity, such as
230 slight differences in level of cure, or exposure to humidity. Samples were subjected to outgassing
prior to UV testing in order to ensure that any mass loss was caused by the radiation. It has
been found that cycloaliphatic epoxy/octa-POSS blends also show much lower mass loss due to
outgassing in high vacuum.

Figure 9: Mass loss in % of the octa-POSS reinforced cycloaliphatic epoxy resins subjected to 24h of UV-C radiation versus an unmodified, purely aromatic epoxy resin.

7.2. Surface chemistry

Surface chemistry spectra obtained by ATR-FTIR spectroscopy presented in Figure 10 show that UV-C radiation considerably changes the chemistry of purely aromatic epoxy resins (Figure 10a) while no measurable changes in octa-POSS/cycloaliphatic epoxy were observed (Figure 10b). Some of the most distinctive signs of aromatic epoxy degradation are: the decrease in hydroxyl group at 3396 cm^{-1} , the decrease at $1000\text{--}1300\text{ cm}^{-1}$ which is assigned to -C-O and -C-H groups indicating chain scission in this region and the creation of a carbonyl band at 1725 cm^{-1} . The hydroxyl groups are the weakest and most probable cleavage site in the aromatic epoxy and the recorded FTIR scans support the statement that the epoxy monomer is indeed broken in this place, which causes the appearance of the carbonyl band and decrease in both -C-O and -OH regions.

Figure 10: Changes in surface chemistry measured by ATR-FTIR due to UV radiation of cycloaliphatic/anhydride epoxy resin system reinforced with 5wt% (b) versus unmodified, aromatic epoxy used as reference (a).

8. Conclusions

Resistance of CFRP structures to environmental degradation might be improved by using a modified epoxy resin system. The proposed octa-POSS reinforced cycloaliphatic epoxy resin is a promising approach to retard the atomic oxygen and thermo-radiative induced degradation.

It has been shown that with an increasing octa-POSS content, mass loss due to AO etching decreases, which is associated with high inorganic content on the surface hence a retarded erosion rate. The water contact angle decreases with increasing octa-POSS content which together with a complementarity XPS analysis illustrates a transition from a hydrophobic to a hydrophilic surface

and the creation of a silicon dioxide protective layer. Exposure to AO causes all polymers to undergo further crosslinking and an increase in T_g .

255 The morphology of the structure and surface roughness are lower in the case of octa-POSS reinforced cycloaliphatic epoxies. The addition of octa-POSS prevents large craters formation on the surface and results in lower roughness when compared to the unmodified, aromatic epoxy.

The highest retention in mechanical parameters was observed for samples with either low (5wt%) or high (20wt%) octa-POSS content. In the former it is most likely associated with the undisturbed epoxy resin structure and in the latter the formation of a silica layer that partially carries the acting
260 load.

Octa-POSS reinforced cycloaliphatic epoxy resins are also more resistant to UVC radiation and outgassing, which was confirmed by lower mass loss and little changes in surface chemistry, as opposed to the aromatic epoxy which was strongly affected.

The findings of this study will contribute to the development of ultra-thin CFRP deployable
265 structures in order to make them a truly feasible option for use in long duration missions and better adapted to the hazardous space environment.

Acknowledgements

Financial support from the EPSRC and RolaTube Technology Ltd in the form of a research studentship (Industrial CASE EP/L505675/1) for Agnieszka Suliga is gratefully acknowledged.
270 The authors should like to thank Huntsman for generous donations of material. Details of the data presented here and how to request access are available from University of Surrey publications repository: (<http://epubs.surrey.ac.uk>).

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