Characterization of Simulated Low Earth Orbit Space Environment Effects on Acid-spun Carbon Nanotube Yarns

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Characterization of simulated low earth orbit space environment effects on acid-spun carbon nanotube yarns

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Highlights

- Chlorosulfonic acid spun carbon nanotube fibers were exposed to intense ultraviolet C radiation and atomic oxygen.
- UVC radiation did not significantly affect mechanical strength or conductivity, but enhanced piezoresistive effect.
- Atomic oxygen severely degraded mechanical properties and mildly degraded electrical properties.

Abstract

The purpose of this study is to quantify the detrimental effects of atomic oxygen and ultraviolet (UV) C radiation on the mechanical properties, electrical conductivity, and piezoresistive effect of acid-spun carbon nanotube (CNT) yarns. Monotonic tensile tests with in-situ electrical resistance measurements were performed on pristine and exposed yarns to determine the effects of the atomic oxygen and UVC exposures on the yarn’s material properties. Both type of exposures were performed under vacuum to simulate space environment conditions. The CNT yarns’ mechanical properties did not change significantly after being exposed to UV radiation, but were significantly degraded by the atomic oxygen exposure. The electrical conductivity of the yarn was not significantly affected by either exposure. The piezoresistive effect did not significantly change due to atomic oxygen exposure, but was significantly enhanced as a result of the UV exposure. Scanning electron microscopy revealed significant erosion due to atomic oxygen exposure, but the UV exposure did not significantly change the appearance of the yarn’s external surface. Raman spectroscopy showed that both exposure types induced significant structural disorder in the surface level CNTs. Focused ion beam milling of a UVC exposed yarn revealed that the depth of the induced disorder was very shallow.

1. Introduction

Carbon nanotube (CNT) yarns are made by twisting or braiding multiple CNT fibers or filaments without the use of a binding agent. These yarns may be made large enough to make large gage wires or mechanical tethers. CNT fibers have exceptional strength and electrical conductivity when compared to traditional materials. Fiber synthesis research indicates that CNT fibers may soon be as
ed electrically conductive as copper while exhibiting a high strength-to-density ratio similar to high-strength carbon fiber [1,2]. This ratio is especially important when considering candidate materials for aerospace applications. Replacing metallic wiring and shielding in spacecraft with equally conductive CNT wiring would result in an estimated mass reduction of 85% [1]. Implementing materials that can perform multiple functions simultaneously will result in even greater weight reductions. For example, CNT yarns may be implemented as structural reinforcement while simultaneously transmitting power or data signals [3]. Reducing system weight by replacing electrical and structural components with CNT yarns would reduce the total launch cost or allow aircraft and spacecraft to be equipped with larger sensors or carry additional cargo or fuel at no additional cost.

The material properties of CNT yarns when exposed to a space environment must be fully characterized and quantified in order to safely incorporate them in spacecraft designs. This research specifically focuses on the effects of atomic oxygen (AO) and ultraviolet C (UVC) radiation on the yarns’ material properties and microstructure. These two phenomena are found in abundance in low earth orbit (LEO), which is where most man-made spacecraft and satellites are located. They are both known to have adverse effects on most materials [4]. UVC is being focused on because unlike UVA or UVB, it is filtered by the earth’s atmosphere, so its presence would only be detrimental to space-based applications. UVC can typically penetrate a material by up to 0.3 μm [4], which is roughly 10–1000 times greater than the diameter of a CNT [5].

There have been previous studies on the effects of AO and UVC exposure on CNT yarns. Misak et al. [6] characterized the effects of AO exposure present in LEO and extreme thermal cycling on CNT yarns. Hopkins et al. [7] directly exposed CNT yarns to the LEO environment aboard the International Space Station (ISS) for 2 years. They noticed changes in the yarns’ morphology and argued that AO exposure was the primary cause of yarn surface modification and material property degradation. The current research varies from these previous studies in two significant ways. First, the fabrication method of the current CNT yarns is different than the previous works’ method. Misak et al. and Hopkins et al. studied yarns created by the dry-spinning method, while the current yarns are created using the acid-spinning method. A description of both fabrication methods is available in a study done by Kanakaraj et al. [8]. Second, the CNT composition of the yarns in this study differs from the previous studies. The yarns tested in the previous studies were composed of multi-walled CNTs (MWCNT), while the current yarns are primarily composed of single-walled CNTs (SWCNT) [1]. The dry-spun yarns also contained excess iron catalyst and incorporated proprietary post-processing techniques not used with the current yarns [6,7]. Research on the effects of UVC on CNTs is limited to studies where the effects of UVC on CNT properties were not the focus of the study [9] or non-yarn CNT materials [10]. The continued work of the Rice research group suggests that the acid-spinning method is the most industrially viable process to create the strongest and most electrically conductive CNT yarns [11]. Therefore, it is critical to further the understanding of the effects of the space environment on these yarns.

This work aims to replicate the AO exposure characterization accomplished by Misak et al. [6] with acid-spun SWCNT yarns. The AO exposure will determine whether the acid-spun SWCNT yarns studied in this research are more or less significantly impacted by AO exposure than dry-spun MWCNT yarns. The UVC exposure will elucidate whether UVC alone is detrimental to acid-spun SWCNT yarns. Uniaxial tensile tests were performed post environmental exposure to determine the mechanical properties of the yarns. The electrical conductivity was measured prior to and during tensile testing. The electrical conductivity measurements collected during tensile testing were used to quantify the piezoresistive properties. The yarns were characterized using scanning electron microscopy (SEM) and Raman spectroscopy to observe physical changes or induced disorder in the yarns. The results drawn from this research will allow spacecraft designers to make informed decisions on how these materials can be implemented into satellites and spacecraft.

2. Materials and methodology

2.1. Material

The CNT yarn used in this research were purchased from Dexcel (Houston, TX, USA) in October 2016. The yarn was composed of 21 braided fibers. The fibers were made by the acid-spinning method described by Behabtu et al. [11], and the manufacturer reported that a small amount of chlorosulfonic acid leftover from the spinning process is present. The manufacturer filtered the material to remove any other impurities. The yarns were composed of single- and double-walled CNTs. This was confirmed by the presence of radial breathing modes (RBM) between 100 and 200 cm⁻¹ Raman shift wave numbers in the measured Raman spectral data (Fig. 6) [12]. The constituent CNTs in the yarns are assumed to be of similar lengths as those utilized in the single fibers described in Behabtu et al. [11]. The manufacturer provided a data sheet of the material properties of the yarn, which are reported in Table 1. The cross-sectional area of the yarn was estimated by averaging the diameter, measured in a SEM, of 21 fibers removed from the yarn. The average diameter value was used to calculate the cross-sectional area of a single fiber and then multiplied by 21 to account for all fibers in the yarn. Twenty-one total specimens were prepared for this research. A summary of the different specimen types prepared is presented in Table 2.

2.2. Atomic oxygen exposure

AO exposure was conducted at Montana State University. The exposure was conducted inside of a vacuum chamber, which was pumped down over night before exposure began. The chamber reached an equilibrium pressure that was on the order of 10⁻⁵ Pa prior to exposure. The AO beam was pulsed at 2 Hz for 150,000 pulses. UV light was present in the beam source, which the AO exposure operators estimated to be of the same magnitude of the solar vacuum UV flux in LEO. The total AO flux was equivalent to approximately one year of AO exposure in LEO.

| Diameter (μm) | 113 ± 5 |
| Linear density (tex) | 7.4 |
| Density (g/cm³) | 0.75 |
| Electrical conductivity (MS/m) | 2.81 |
| Tensile strength (GPa) | 0.83 ± 0.040 |

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Quantity prepared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pristine</td>
<td>7</td>
</tr>
<tr>
<td>AO exposed</td>
<td>7</td>
</tr>
<tr>
<td>UVC exposed</td>
<td>7</td>
</tr>
</tbody>
</table>
2.3. Ultraviolet type C exposure

Intense UVC exposure was carried out in-house at the Air Force Institute of Technology. The exposure was conducted inside a vacuum chamber that was pumped down overnight prior to beginning the exposure. The chamber maintained a vacuum pressure on the order of $10^{-5}$ Pa for the duration of the test. The peak intensity of the UVC lamps was 254 nm. The intensity of the UVC at the yarns' location was measured before and after exposure with a UVC light meter. It was assumed that the UVC bulbs' intensity degraded linearly. Using this assumption, the average bulb intensity was determined to be 0.75 mW/cm² over the 1000 hour exposure. The NASA orbital environment design guidance handbook estimates that the intensity of UVC light with wavelengths around 254 nm in LEO is $2.27 \times 10^{-2}$ mW/cm² [13]. Using this intensity as a guideline, the average intensity of the UVC bulbs was estimated to be approximately 33 times the UVC radiation experienced in LEO. Multiplying this intensity ratio by the test duration leads to an approximate 3.77 years of equivalent constant LEO UVC exposure. Taking into account that all spacecraft are not continuously illuminated by the sun due to orbital dynamics, the equivalent exposure time may be much greater.

2.4. Uniaxial tensile testing

Tensile testing was accomplished using an MTS Tytron 250 pneumatic tensile testing machine with a 100 N load cell (see Fig. 1). Each CNT yarn tested was approximately 50 mm long with a
20 mm gage length. The excess material outside of the gage length was anchored with epoxy into a 3D printed plastic yarn holder. The yarn holders incorporated four channels where copper wires were laid to make electrical contact with the CNT yarn and act as the four probes of the electrical conductivity measurement. A schematic of the yarn holder is presented in Fig. 2. Tensile testing was conducted by displacement control at a rate of 0.02 mm/s. Tensile testing data were collected approximately every 0.01 s, and the average tensile test time was approximately 20 s. The applied load and displacement were recorded during testing, and this data were used to calculate the engineering stress and strain.

2.5. Electrical conductivity measurements

The electrical conductivity of two yarns was monitored while exposing the yarns to UVC light. This was done using the four-probe electrical conductivity technique sampled at 2 Hz for the entire exposure [14]. One monitored yarn was directly exposed to the UVC lamps, while the other was shielded and acted as a control specimen. The control specimen was monitored and compared to the exposed specimen to see if any acid diffused from the yarns while they were exposed to ultrahigh vacuum and elevated temperatures caused by the lamps. There were no significant differences between the two yarns for reasons that are discussed in the Electrical characterization subsection. The conductivity, \( \sigma \), was calculated using the equation

\[
\sigma = \frac{L}{R_0 A}
\]  

(1)

where \( L \) is the yarn length, \( A \) is the cross-sectional area, and \( R_0 \) is the initial resistance of the yarn. \( R_0 \) was calculated by averaging thousands of measurements collected by the voltage measurement module prior to tensile testing.

Pristine, AO, and UVC exposed yarns were tensile tested with continuous in-situ four-probe electrical resistance measurements to quantify the electrical conductivity prior to tensile testing and the piezoresistive effect during tensile testing. The test setup with the probe placement is shown in Fig. 2. Small drops of electrically conductive silver paste were used to improve the electrical contact between the wires and yarn and ensured that the contacts were undisturbed during mechanical testing. The in-situ electrical measurements were accomplished by supplying a 100 mA current through the outer wire pair with a lab power supply. The inner wire pair voltage measurements were collected with an NI USB-6009 voltage measurement module and custom LabVIEW program. The voltage was sampled at a rate of 10 kHz.

The voltage values were used to compute the yarn resistance with Ohm’s law. The yarn resistance and tensile strain values collected during the tensile test were used to calculate the gauge factor (GF) of each yarn. The GF is the measure of the piezoresistive effect of a material. The piezoresistive effect is the change of a material’s electrical resistance with the application of mechanical strain. The GF was calculated with the equation

\[
GF = \frac{\Delta R}{R_0 \epsilon}
\]  

(2)

where \( \epsilon \) is the engineering strain of the yarn, \( R_0 \) is the initial resistance of the yarn, and \( \Delta R \) is the change in resistance of the yarn during the tensile test. \( \Delta R \) is defined as

\[
\Delta R = R_f - R_0,
\]  

(3)

where \( R_f \) is the final resistance of the yarn. The GF reached a maximum value prior to yarn failure. The calculated GF values were averaged for all yarns of each exposure type to calculate the average GF.

2.6. Microstructural characterization

Microstructural characterization was carried out by Raman spectroscopy and scanning electron microscopy (SEM). Raman spectroscopy was accomplished with a Renishaw inVia Raman spectrometer with a 514 nm laser. The range of the collected spectra was approximately 50–1850 cm\(^{-1}\). This allowed the for observation of the radial breathing mode (RBM), the D peak found at approximately 1350 cm\(^{-1}\), and the G peak found at approximately 1585 cm\(^{-1}\). Noise was subtracted from the spectral data, and the data was normalized by the intensity of the G peak. The ratio of the heights of the D and G peaks is known as the D/G ratio and is a measure of CNT short- and long-range disorder. Higher D/G ratios indicate a greater amount of disorder [7]. Fifty Raman spectra each were collected at different locations on pristine, AO, and UVC exposed yarns. The D/G ratios were calculated for each spectrum and averaged for each exposure type.

SEM images were collected with a Tescan MAIA3 high-resolution SEM utilizing accelerating voltages between 2 and 15 kV. The sample was secured to a pin mount using silver paste and immersed in a magnetic field to allow for the acquisition of

![Fig. 2. Schematic of a 3D printed plastic yarn holder.](image)
ultrahigh resolution images. Care was taken to ensure that the yarns were secured without excess slack or tautness. A Tescan LYRA3 focused ion beam (FIB) SEM was utilized to cross section a UVC exposed fiber to view the depth of UVC penetration. The FIB utilized a beam energy of 30 keV and a condenser voltage of 25 kV. The beam current was varied between 151 pA and 3 nA.

3. Results

3.1. Mechanical characterization

The pristine, AO and UVC exposed yarns were mechanically loaded to failure by uniaxial tension. Seven yarns from each sample group (21 total) were prepared for testing, while 18 total yarns (five pristine, six AO, and seven UVC) were used to analyze the yarns’ mechanical properties. The tensile strength, strain at failure, and elastic modulus of all samples were calculated from the test data and are reported in Table 3. Comparative plots of the stress-strain diagrams are shown in Figs. 3 and 4. Summarized results in Table 3 include the mean and standard deviation (SD) of each property.

The UVC exposure resulted in a 1% increase in the tensile strength of the yarn and a 17.4% increase in the strain at failure. The small difference in tensile strength warranted the use of formal statistical testing to examine whether the difference was significant. The Kolmogorov-Smirnov (KS) test [15] was used to test whether the pristine and UVC tensile strengths were drawn from the same continuous distribution. The KS test failed to reject the null hypothesis at the 5% significance level. This confirms that the observed increase in tensile strength was not statistically significant.

The AO exposure had a significant deleterious effect and caused a 63.9% decrease in the yarn tensile strength and 56.3% decrease in the strain at failure. The AO exposure results show a more dramatic degradation of the tensile strength than the 25% decrease that Hopkins et al. [7] observed with dry-spun CNT yarns directly exposed to the LEO space environment. The difference may be due to the proprietary post-processing techniques used on the yarns tested in their work or the multi-walled character of the CNTs assembled to create those yarns. The CNT yarns tested by Misak et al. [6] and Hopkins et al. [7] had significantly larger diameters and given that only the surface of the yarn is exposed, the detrimental effects are expected to be less severe in comparison to the much smaller CNT yarns exposed in this research.

The elastic modulus was calculated from the slope of the initial linear region of each stress-strain curve. The average elastic moduli values were 24.69, 17.87, and 20.52 GPa for the unexposed, AO, and UVC exposed samples, respectively. In Figs. 3 and 4, the difference in elastic moduli values is apparent when the two sets of stress-strain curves are compared. The decrease in modulus of the AO yarns was attributed to increased, localized yielding because of the pits observed in SEM images of the yarns (see Fig. 10c). The unexposed and UVC stress-strain curves have very similar maximum stresses, but the lower elastic moduli of the UVC exposed samples may contribute to its greater strain at failure as compared to the unexposed yarns. This difference may be explained by the generation of amorphous carbon on the yarn surface which acts as a lubricant, allowing the fibers in the yarn to more easily slide past one another. This theory is further explored in the Microstructural characterization subsection.

3.2. Electrical characterization

The electrical conductivities of the pristine, AO, and UVC exposed yarns were 2.45 ± 0.12, 1.91 ± 0.07, and 2.45 ± 0.02 MS/m, respectively. AO exposure caused the conductivity to decrease by 22.0%. Microstructural analysis shows that portions of the individual AO exposed fibers have been heavily eroded by the AO flux resulting in a reduced effective cross-sectional area for electron transport. The AO induced decrease in conductivity is very similar to results obtained in the work of Hopkins et al. [7], who recorded conductivity decreases of 28.5% and 26.1% for LEO exposed yarns on two different locations on the ISS. While the equivalent AO exposure time of the yarns in this study is approximately one year on the ISS, Hopkins’ yarns experienced over two years of direct space exposure. This suggests that the AO beam source may be more detrimental than direct space exposure or single-walled CNTs may be more readily eroded by AO flux than multi-walled ones.

UVC exposure did not affect the yarn’s conductivity in a

![Fig. 3. Pristine and AO exposed stress-strain curves.](image)

![Fig. 4. Pristine and UVC exposed stress-strain curves.](image)

Table 3

<table>
<thead>
<tr>
<th>Property</th>
<th>Pristine</th>
<th>Atomic oxygen</th>
<th>Ultraviolet C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength (GPa)</td>
<td>1.00 ± 0.03</td>
<td>0.37 ± 0.04</td>
<td>1.01 ± 0.04</td>
</tr>
<tr>
<td>Strain at failure (%)</td>
<td>2.52 ± 0.29</td>
<td>1.24 ± 0.06</td>
<td>2.96 ± 0.19</td>
</tr>
<tr>
<td>Elastic modulus (GPa)</td>
<td>24.69 ± 1.89</td>
<td>17.87 ± 4.91</td>
<td>20.52 ± 5.59</td>
</tr>
<tr>
<td>Electrical conductivity (MS/m)</td>
<td>2.45 ± 0.12</td>
<td>1.91 ± 0.07</td>
<td>2.45 ± 0.02</td>
</tr>
<tr>
<td>Gage factor</td>
<td>0.97 ± 0.089</td>
<td>1.01 ± 0.18</td>
<td>3.38 ± 0.24</td>
</tr>
<tr>
<td>D/G ratio (× 10^-4)</td>
<td>1.35 ± 0.29</td>
<td>3.34 ± 0.80</td>
<td>3.80 ± 0.79</td>
</tr>
</tbody>
</table>
the UVC exposed yarns because of the diffusion of acid dopants from the fiber. Excess acid dopant from the fiber spinning process is present in the yarns and increases the electrical conductivity of the yarns [11]. The expected drop due to acid diffusion may have occurred, but a competing mechanism may have mitigated this effect. The yarns were held under tension during the duration of the UVC exposure. As the acid diffused, the fibers may have become more densely packed and aligned as the remaining acid left the fibers. Greater fiber alignment and density are positively correlated with electrical conductivity so this may have offset the minor loss of dopant mass. Although the means of both samples’ electrical conductivities remained constant, the standard deviation of the electrical conductivity of the UVC exposed yarns is significantly less than the pristine yarns. This phenomenon may be due to reduced acid dopant content as well as improved packing and alignment of the CNTs in the yarn microstructure. This topic warrants further investigation but is outside the scope of this work.

3.3. Piezoresistance characterization

Fig. 5 shows the piezoresistive behavior of the yarns by plotting curves of \( \frac{\Delta R}{R_0} \) vs. \( \epsilon \). The pristine specimens exhibited linear behavior from initial loading until failure. The AO exposed specimens experienced a small drop in resistance upon initial loading but then exhibited similar magnitude piezoresistive response to the pristine samples until failure. Anike et al. observed similar behavior in low twist yarns produced by the dry-spinning method [16]. They attributed the initial decrease in the curve to a lack of pretension in tests where the phenomenon was observed. The loose network of CNTs in the unstressed yarn were not as tightly packed, which led to an increase in conductivity as stress was applied and the CNTs were brought in closer contact with one another. In this research, the phenomenon was observed in all AO exposed specimens but not in the case of pristine or UVC exposed yarns even though all tensile tests were conducted similarly. The unique surface morphology of the AO exposed specimens, discussed in the Microstructural characterization subsection, may have played a role in this response as the fibers of the yarn moved during initial loading, but it is unclear what exact mechanism led to this behavior. The UVC exposed specimens exhibited similar behavior to the pristine samples upon loading up to a strain of approximately 0.005, but the piezoresistive response dramatically increased above this strain threshold.

The GF of each yarn was calculated to quantify the magnitude of the piezoresistive effect due to the two exposures. These values are reported in Table 3. The pristine and AO exposed yarns exhibited similar GF values which indicates little change occurred to the piezoresistive character of the yarns due to AO exposure. The average GF of the UVC exposed yarns was 3.38, which is a 247% increase over the average pristine yarn GF of 0.98. This dramatic increase is surprising given the minuscule impacts of UVC exposure on the yarns’ tensile strength and electrical conductivity. Mikó et al. also observed that UV radiation had minimal effects on the material properties of CNTs [17]. They observed that even very high intensity UV radiation was not damaging to the constituent CNTs in the yarns they irradiated. The previously discussed mechanisms in the Electrical characterization subsection may have played a role in the dramatic GF increase of the UVC exposed specimens. The piezoresistive response of individual CNTs is dependent on their chirality, but studies on the piezoresistive effect of CNT yarns have led multiple groups to propose that the piezoresistive response is governed by changes to the inter-tube contact resistance [18,16]. Two competing mechanisms affect this response. 1) Applied loading tends to more tightly pack CNTs in the network which tends to increase conductivity and decrease the resistance of the yarn. 2) The weak van der Waals forces between tubes allow the CNTs to slide which leads to stretching and breakage of tube-to-tube electrical contacts and increased resistance with tensile loading. Anike et al. proposed that in more densely packed yarns the latter effect would be more pronounced due to a greater number of electrical connections between CNTs leading to a larger piezoresistive response [16]. Therefore, the proposed dense packing hypothesis of the UVC exposed specimens may explain the much larger GF observed.

3.4. Microstructural characterization

The results of the Raman spectroscopy analysis are summarized in Table 3 and Fig. 6. The representative Raman spectra in Fig. 6 are
those which most closely adhered to the average D/G ratio of each exposure type. The D/G ratio increased for both exposure types with UVC exposed yarns exhibiting the largest increase. Higher D/G ratios indicate a greater degree of CNT molecular disorder. The increased disorder in the AO exposed yarns is a result of oxidation which removed carbon atoms from the walls of the constituent CNTs. The increase in disorder corresponding to the increase in the D/G ratio observed in the UVC exposed yarns is unexpected based on the observations of Chen et al. [9], who did not observe any CNT damage from similar high intensity UVC radiation while under vacuum.

Yarns of each exposure type were imaged by SEM to examine the microstructural effects of the AO and UVC exposures. The pristine (Fig. 7) and UVC exposed (Fig. 8) yarn surfaces were almost indistinguishable apart from some light streaks on the UVC exposed yarn surfaces. These streaks may be thin layers of amorphous carbon that were created after the UVC exposure induced carbon disassociation from the CNT molecules.

The FIB was used to cross-section a CNT fiber within one of the UVC exposed yarns. The cross-sectioned UVC fiber is shown in Fig. 9. The top of the fiber shows a distinct, darkened crust that is not present on the bottom half of the fiber. The top of the fiber was exposed to UVC radiation whereas the bottom was not because it was buried within the bundle of fibers in the yarn. The darkened crust is most likely amorphous carbon induced by the UVC radiation, and the remaining microstructure of the cross-section appears to be unchanged from the exposure. This supports the mechanical and electrical characterization results which showed only small changes due to the UVC radiation. UV light does not deeply penetrate many polymeric materials, so it was expected that the observed microstructural damage would only exist on the surface [4].

Changes in the yarn's physical structure were more evident in the AO exposed samples. The types of structural damage present in the AO exposed yarns include reduced fiber cross sections (Fig. 10a), frayed edges (Fig. 10b), deep pits (Fig. 10c), and increased roughness (Fig. 10d). The damage present in the AO exposed yarn SEM images appears to be much more severe than those presented by Hopkins et al. [7] and Misak et al. [6]. There are three possible explanations for the increased severity of the fiber damage and reduction of tensile strength of these yarns when compared to previously researched yarns. First, multi-walled CNT fibers may be inherently more resistant to AO than single-walled CNTs. Second, the proprietary post-processing techniques used by the previous studies'
manufacturer may have provided additional protection against oxidation. Third, the presence of CSA in this study’s yarns may have aided in the breakdown of the surface CNTs during AO exposure. These microstructural results show that it is necessary to completely protect acid-spun single-walled CNT yarns in LEO orbits. However, at higher orbits where AO is not present, CNTs will not be significantly degraded by UVC radiation and can be used without excess protection.

4. Conclusions

The effects of AO and UVC exposures on acid-spun SWCNT yarns were characterized. AO exposure was found to have significantly degraded the mechanical properties of the exposed CNT yarns by significantly eroding CNTs from the yarn surface, but the electrical conductivity was not as severely impacted. UVC exposure was found to have minimally affected the mechanical and electrical properties of the exposed CNT yarns, but significantly increased the piezoresistance of the yarns. Microstructural examination revealed that UVC exposure only damaged a shallow portion of the fibers within the yarns and left the bulk of the yarn unaltered. These results provide a deeper understanding of the effects of the space environment on CNT materials and will assist spacecraft designers in safely incorporating these promising materials into future spacecraft.

CRediT authorship contribution statement

Ryan A. Kemnitz: Methodology, Formal analysis, Writing - original draft. Gregory R. Cobb: Writing - review & editing. Abhendra K. Singh: Conceptualization, Writing - review & editing. Carl R. Hartfield: Writing - review & editing, Supervision.

Data availability

The data sets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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