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ScienceDirect

Advances in Space Research xxx (2016) xxx–xxx

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Characterization of carbon nanotube yarn after exposure to hyperthermal atomic oxygen and thermal fatigue ☆

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Received 11 January 2016; received in revised form 3 August 2016; accepted 16 August 2016

Abstract

Carbon nanotube (CNT)-yarn was evaluated for the survivability under hazardous space environmental conditions which were thermal fatigue, atomic oxygen and additive effect of these two exposures. Its tensile strength, tenacity, stiffness, strain to failure and electrical conductivity were characterized at the two extreme space temperatures of −150 and 120 °C before and after exposure to these environmental conditions. Tensile strength, stiffness and electrical conductivity of unexposed CNT yarn increased at the cryogenic temperature relative to at the elevated temperature. There was no change in the tensile properties after exposure to the space environmental conditions when measured at the elevated and cryogenic temperatures. Electrical conductivity decreased after exposure to three hazardous environments involving thermal fatigue, but it had no or small decrease when exposed to atomic oxygen only. No additive effect of thermal fatigue followed by atomic oxygen or by atomic oxygen followed by thermal fatigue environments on the CNTs' tensile properties and electrical conductivity was observed. Considering the low density 0.59 g/cc and good resistant to the extreme hazardous space environment, CNT-yarns have potential for applications in spacecraft and satellites.
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Keywords: Carbon nanotube yarns; Atomic oxygen; Thermal fatigue; Tensile strength; Electrical conductivity

1. Introduction

Materials are constantly exposed to harmful radiation, thermal excursions and space debris in space. This leads to deterioration, and/or chemical modification of the material. Selecting materials that would survive in low earth orbits (LEOs) vehicles, satellites, space stations, and space devices has been a challenge. There are difficulties in predicting how well a material will actually behave in space when the majority of the testing is done on a terrestrial body (Earth). However, there have been 8 Materials on International Space State Experiment (MISSE) from 2001 to 2011 that have provided true data on how materials behave in space (Finckenor et al., 2013). These experiments are difficult and expensive because the samples must be placed in and retrieved from outer space, thus testing methods on Earth (ground simulation facilities) to predict materials life span and behavior in outer space have been developed.

There is a commonly used method to characterize the exposure to hyperthermal atomic oxygen flux in space applications by ground simulation facility. This method uses a reference coupon of Kapton that is exposed at the same time as the sample coupon from material of interest (Banks et al., 1989). Once a known level of erosion has occurred to the Kapton coupon, it is assumed that the sample coupon has also been exposed to that level of hyperthermal atomic oxygen flux (Finckenor et al., 2013). This

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http://dx.doi.org/10.1016/j.asr.2016.08.020
0273-1177/Published by Elsevier Ltd on behalf of COSPAR.

method is not perfect as there are multiple degrading variables in space environment that may have synergistic affects which could cause the coupon to erode at a faster/slower rate in ground simulation facilities compared to space (Doan, 2013). In spite of this, it provides a good characterization without resorting to very expensive and not easily available real space exposure test.

Space systems/objects encounter temperature oscillations when orbiting planetary bodies. The space object will cool down when the planetary body is blocking the sun, and heat up when there is direct exposure of the sun. The temperature swing will cause the materials and their products to expand/contract leading to fatigue due to the coefficient of thermal expansion. The thermal fatigue can ultimately reduce/degrade the mechanical properties of the material. The design temperature range for space devices protected by the satellite is recommended from −40 to 70 °C by the Institute for Environmental Sciences (Vallado and McClain, 2001). Therefore, it is important for the material used in space to be able to withstand thermal fatigue, and be usable over this temperature range.

Another important consideration in selection of space materials is specific properties, i.e. enhanced property and lower density are highly preferable. Carbon nanotube (CNT) yarns are one of such novel materials that may be able to resist degradation due to extreme temperatures and hyperthermal atomic oxygen with considerable mass savings (Misak et al., 2013). CNTs were discovered in the 1990s, and have been the subject of much attention due to their extraordinary properties (O'Connell, 2006). Recently, CNT yarns have been produced by using the ancient art of fiber spinning (Zhang et al., 2004). There has been a wide range of physical and mechanical properties reported due to variation of density, helix angle, treatment, diameter of yarn, number of yarns, etc., to name a few variables (Miao, 2012; Misak and Mall, 2015a, 2015b; Misak et al., 2014; Sabelkin et al., 2012; Zhang et al., 2004, 2007). Further, their mechanical and physical properties are more complex than of the conventional materials as the structure of CNT-yarn has multitudes of nano structures, micro structures, and macro structure (Misak and Mall, 2014). This leads to the possibilities that not only the individual CNT may be damaged by the extreme temperature and radiation of outer space, but the nano, micro and macro structures may be affected to a greater degree.

In a previous study by the authors, the effects of exposure to the atomic oxygen and thermal fatigue on the CNT-yarn were evaluated when applied separately (Misak et al., 2013). This study showed that CNT-yarn's performance is not affected when exposed to atomic oxygen or to the thermal fatigue; however there was a slight loss of conductivity (2.5% reduction) under thermal fatigue. The thermal fatigue involved cycling between 70 and −50 °C (Misak et al., 2013). However, as far as the authors are aware, it is still unknown if there are additive effects of thermal fatigue and atomic oxygen, when applied at the same time, on the CNT-yarn's performance such as tensile strength and electrical conductivity. It is difficult or would require very elaborate test facility to expose a material with both thermal fatigue and atomic oxygen exposure simultaneously. However, if the material is exposed to these two test conditions sequentially, i.e. exposure to thermal fatigue followed by the atomic oxygen, or the other way around i.e. exposure to atomic oxygen followed by the thermal fatigue, these two sets of tests would provide a good indication of the additive effect of thermal fatigue and atomic oxygen. This was the objective of the present study. The tensile strength, tenacity, strain to failure and electrical properties of CNT yarn were evaluated after exposure to the above mentioned two test conditions which were then compared to the counterparts from the unexposed CNT yarn. Further, CNT yarn's properties were evaluated at two extended temperatures: −150 °C and 120 °C, unlike at −50 °C to 70 °C of the previous study (Misak et al., 2013), since some components of satellites could experience these extended temperatures.

2. Materials and methods

2.1. CNT-yarn

CNT-yarn was procured from Nanocomp, Inc. The CNT-yarn consisted of 60 single yarns, hence they will be referred to as the 60-yarn in this paper. A scanning electron microscopy (SEM) image of the tested yarn is shown in Fig. 1 showing the 60-yarn. Briefly, Nanocomp Inc. produces CNT-yarn by injecting grain alcohols and iron-based catalysts into a horizontal reactor furnace with hydrogen as the carrier gas. Free CNTs and CNT bundles are produced and exit the reactor as an aerogel-like material. In a post processing operation, the CNT-yarn is drawn through an acetone bath and twisted prior to collection on a spool.

2.2. Tex

CNT-multi yarn contains nanoscale gaps, micro voids and gaps among individual yarns which make determination of the cross-sectional area extremely difficult, and hence accurate determination of tensile strength and electrical conductivity due to their dependence on the cross-sectional area. The area of CNT yarn measured by the conventional method is an apparent measure of area. Therefore, tensile strength and electrical conductivity based on the apparent area have been referred to by the use of "Apparent" in front of the property (Misak and Mall, 2015a, 2015b; Sabelkin et al., 2012). These properties can change due to variance in the packing factor of the CNTs used in the manufacturing process. Therefore, linear density (tex = g/km) is commonly used in the textile industry which allows the accurate comparison of properties, by referring the strength in terms of tenacity, i.e. N/tex. This is preferred for the sake of comparison between different studies and fabrication methods. The mechanical proper-