

Conductive Coatings Eliminate Static Discharge Risk on Aircraft

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ABSTRACT

Electrically insulating aircraft materials and coatings increase the likelihood of dangerous charge buildup due to static electricity accumulation and cannot protect from lightning strikes. An electrically conductive coating that will prevent static charge buildup and increase lightning strike survival of aircraft using carbon nanomaterials homogeneously distributed in a durable coating material, will greatly advance aircraft coating technology. This coating fabrication technique will replace the heavy & hard to maintain & repair metal mesh currently used to provide the needed electrical conductivity. Additionally, it will also reduce the time required to apply anti-static coatings to non-conductive surfaces on conventional aircraft including the B-1B.

Keywords: aircraft coating, carbon nanotube, electrical resistivity, anti-corrosion, adhesion.

1 INTRODUCTION

Aircraft coatings are typically not electrically conductive and usually do not contain nanoparticles. Static discharge is a serious safety concern, especially when refueling aircraft, as a static discharge may ignite the fuel vapors. More conductive, corrosion-resistant, and longer-lasting coatings would greatly benefit the Air Force's safety requirements and budget. Current composite-based aircraft rely on heavy, hard-to-repair metal meshes integrated into the composite material. Metal additives such as copper increase the density of the sealant and lead to galvanic corrosion reactions. Higher electrical conductivity in aircraft coatings is required to fabricate a safer, more corrosion-resistant, and easy-to-repair surface.[1-4]

The approach of using carbon nanotube (CNT) materials provides a highly thermally and electrically conductive material with lower density and higher corrosion resistance than current alternatives.[5-9] Shen et al. started with an epoxy of $1.2 \times 10^8 \Omega \cdot \text{cm}$ and added 2.0 wt.% MWCNTs to obtain an electrical resistivity of $7.6 \times 10^{-2} \Omega \cdot \text{cm}$ when applied to a steel substrate by electrostatic spraying. They also noticed a two-order of magnitude decrease in the corrosion rate over the carbon

steel substrate.[10] The homogeneous distribution of 1.0 wt.% MWCNTs in the epoxy showed a 97% decrease in corrosion rate compared to neat epoxy-coated steel.[11]

Here, the ability to dramatically lower the electrical resistivity of Air Force Rain Erosion coating materials by adding a low weight percentage of CNTs and introducing hydrogen bonding into the coating formulation has been demonstrated.

2 EXPERIMENTAL

The rain erosion paint solution was prepared by dispersing a certain amount of MWNT-OH in Absolute EtOH using ultrasonication in an ice bath for 20 min, at an amplitude of 20%. The EtOH suspension and rain erosion paint were mixed in the desired ratio and shaken thoroughly using a paint shaker, followed by the addition of the curing agent. The paint formulation was then sprayed on the substrate several times until the surface was fully covered. The sprayed solution was cured at room temperature for at least 48 hrs. The solution was also sprayed on the non-stick sheet to prepare additional samples, of which the contact angle and the electrical resistivity are measured. Figure 1 shows the rain erosion samples with different concentrations of MWNT-OH.

The electrochemical method was used to evaluate the anti-corrosion property of the coating sample. A Gamry Instruments Reference 600 Potentiostat/Galvanostat/ZRA was connected to a three-electrode cell composed of a counter electrode (platinum), a reference electrode (Ag/AgCl in 1.0 M NaCl solution), and the working electrode (coated sample). The potentiodynamic polarization scan (PPS) was performed by scanning from -1.4 to $+1.0$ V with a scan rate of 1.0 mV/s. The bare substrate was measured as well for reference. The anti-corrosion performance of the sample was immediately quantified by varying the open circuit potential and plotting the logarithm of the resulting current against the applied potential. This plot was called Tafel polarization curves, as shown in figure 4.

The adhesion of the coating material to the copper substrate was evaluated following the ASTM standard test method D3359. The adhesive property of the coating was assessed by applying and removing the pressure-sensitive

tape over cuts made in the coating. After required cuts were made, the surface was brushed gently with a soft brush to remove any detached flakes of the coating. A transparent tape was firmly attached to the surface, and a pressure application device was utilized to achieve good and uniform contact between the tape's adhesive and the coating surface. After 90 s of application, the tape was removed rapidly at an angle as close to 180° as possible. The adhesion property was rated by inspecting the percent area of the coating removed by the tape. Optical microscope images of the sample were taken before and after the tape test.

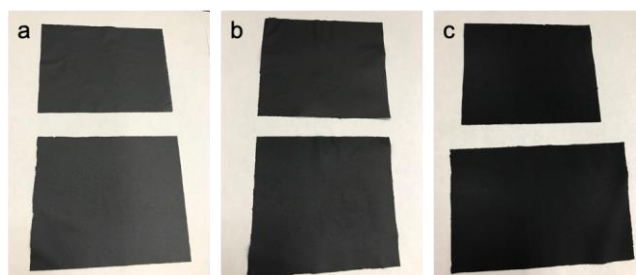


Fig 1. Rain erosion coating sheet samples of MWNT-OH weight concentration of (a) 1 wt.%; (b) 2 wt.%; (c) 4 wt.%

3 RESULTS AND DISCUSSIONS

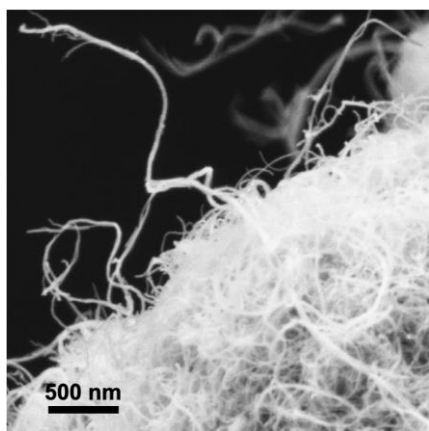


Fig 2. SEM image of MWNT-OH

Scanning electron microscopy was used to characterize the “as-received” hydroxyl functionalized multiwalled carbon nanotubes (see figure 2). The average diameter of the carbon nanotubes was confirmed to be 20-40 nm, as claimed by the manufacturer. MWNT-OH has a substantial aspect ratio. These tube-like structures of the raw carbon nanotubes tend to entangle and form agglomerates due to their strong van der Waals forces. The sonicating process breaks these intermolecular forces and uniformly distributes the carbon nanotubes into the base coating. When the nanoparticles are homogeneously dispersed, a network structure will be created for the electrons or thermal energy to travel. Therefore, the carbon nanotube-based composite

material yields excellent thermal and electrical performances.

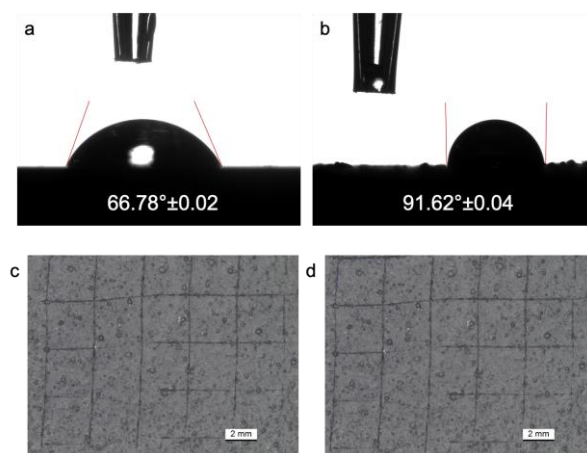


Fig 3. Water contact angle of the bare substrate (a) and the coated sample (b); Optical microscope image of the coated sample before (c) and after (d) the adhesion test.

The static water contact angle measurement was performed on the bare substrate and the coated sample to investigate the surface hydrophobicity. The surface of the bare substrate is intrinsically hydrophilic, with a water contact angle (figure 3a) of $66.78^\circ \pm 0.02$. With the protection of a coating layer, as shown in figure 3b, a higher water contact angle was achieved ($91.62^\circ \pm 0.04$). This indicated that the coating material is hydrophobic, and water resistance ability was achieved due to the low surface energy of the coating.

The adhesion of the coating material to the copper substrate was evaluated following the ASTM standard test method D3359. The optical images of the sample were shown in figure 3. A six-tooth blade with 3 mm between each tooth was used to make straight cuts. It is seen that after removal of the tape from the coating surface, no-flake was observed, the edges of the cuts were still completely intact and smooth, and none of the squares of the lattice were detached. The results indicated that the coating had 0% area removed by the tape, representing that the coating belongs to class 5. This means that the CNT coating materials have excellent adhesion properties.

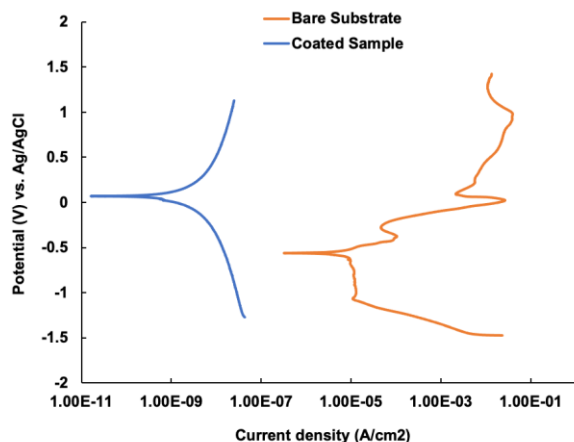


Fig 4. Tafel plots of the bare substrate and the coated sample.

The coating material was expected to exhibit superior anti-corrosion properties due to the inherent corrosion resistance of the carbon nanotubes. Upon performing the potentiodynamic polarization scans, a reduction in the cathodic current was observed for the coated sample compared to the bare substrate (fig 4). This reduction is due to the hydrophobicity and the coating's barrier effect, effectively preventing the corrosive medium from penetrating the substrate surface. Also, the coated sample showed a significant decrease in the current, which means that the corrosion process of the substrate is slowed down because of the protection of the coating. The corrosion rate value was automatically calculated by Tafel fitting the obtained curve. The bare substrate had a corrosion rate of 4.850×10^3 mils per year penetration (mpy), while the coated sample showed a corrosion rate of 2.480×10^{-3} mpy. Herein, 1 mil equals to 1/1000 inch. So, the corrosion rate of the bare substrate was 123.19 mm/year, while the corrosion rate of the coated sample was 63.0×10^{-6} mm/year. The corrosion rate of the coated sample was dramatically decreased compared to that of the bare substrate, which indicated that the coating material maintained excellent anti-corrosion property and this CNT coating well protected the substrate.

Table 1. Measured resistance values of Air Force Rain Erosion samples with various concentrations of MWNT-OH

Sample	Base Paint	wt.%* of MWNT-OH	Resistance (ohm)
1	Air Force Rain Erosion	1 %	Out of range (>200M)
2		2 %	16.8M
3		3 %	0.2M
4		4 %	9.2K
5		6 %	2.4K

Table 1 shows the measured resistance results of the Air Force Rain Erosion coatings with various concentrations of MWNT-OH. While resistance cannot be directly compared to resistivity, trends can be seen as conditions or concentration providing the best results. With the increase of the amount of MWNT-OH, coating samples' resistance values decrease dramatically. When 6 wt.% MWNT-OH was added, the resistivity of 2.4K ohm was obtained, which was a considerable improvement over the super high resistance of the sample with only 1 wt.% MWNT-OH added.

25% EtOH was added to each sample to form hydrogen bonding with carbon nanotubes. Hydrogen bonding is an interaction between an electronegative atom, usually F, O, N, that possesses a lone pair of electrons and a hydrogen atom bonded to an electronegative atom. By using functionalized carbon nanotubes and organic solvents, the hydrogen bonding formed between nanotubes themselves or between nanotubes and liquid molecules is attributed to the enhancement of the electrical conductivity of the coating mixtures. Though the hydrogen bonding was not directly observed or measured, the results have shown solid proof that the electrical conductivity has been dramatically increased by introducing any form of hydrogen bonding. Even though all samples were measured after being allowed to cure for at least 24 hours, these improvements were obtained from adding hydrogen bonding solvents that evaporated during the curing process. The curing process must lock the carbon nanotubes in place. This provides a simple method to obtain natural application enhancement that is scalable and easily implemented into manufacturing processes.

4 CONCLUSION

In this paper, a scalable manufacturing process to dramatically lower the electrical resistivity of Air Force Rain Erosion coating materials by adding a low weight percentage of CNTs and introducing hydrogen bonding into the coating formulation is demonstrated. The resistance of the rain erosion coatings can be easily adjusted by changing the loading percentage of the carbon nanotubes to meet the Air Force requirements regarding the resistance. Resistance as low as 2.4K ohms was obtained by adding only 6 wt.% MWNT-OH. The fabricated electrically conductive rain erosion coatings yielded a 63.0×10^{-6} mm/year corrosion rate, indicating an excellent anti-corrosion property against the corrosive environments. These highly conductive coatings can be applied by conventional high pressure low volume (HPLV) spray methods. This produces a superior coating that is much faster to apply than the current method saving time and increasing operational capability. Moreover, CNTs are commercially available and have become cost-effective over the past years, giving this research a high likelihood of producing an affordable solution for aerospace applications.

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