Article

JOURNAL OF COMPOSITE MATERIALS

Journal of Composite Materials
0(0) 1–7

DOI: 10.1177/0021998314540196
jcm.sagepub.com
SAGE

Tensile behavior of carbon nanotube multi-yarn coated with polyester

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Abstract

The behavior of a carbon nanotube (CNT) multi-yarn consisting of 30 yarns and coated with a thin layer of polyester is investigated under tensile loading condition. The coated and uncoated CNT multi-yarns are loaded until fracture occurred inside a scanning electron microscope. In situ photographs were undertaken to investigate the helix angle, diameter, yarn twist, and damage and failure mechanisms. The coated CNT multi-yarn has a higher ultimate tensile strength than the uncoated counterpart. The coated multi-yarn fails at a single location and remains tight after the failure. The uncoated yarn fails at multiple locations along its length and also unravels. The adhesive coating adheres to the CNT yarn surface and does not penetrate into the yarn. These results provide insights into how CNT multi-yarn would behave when used as the reinforcement in the nanocomposites.

Keywords

Nanocomposites, carbon nanotubes, yarns, coating, strength, fracture

Introduction

Carbon nanotubes (CNTs) are cylindrical tube-shaped materials with diameter ranging from 1 nm to 100 mm (in single-walled case) and over 100 nm (in multi-walled case).[1] Lengths of CNTs are typically several microns, but some recent studies have reported that the nanotubes could be much longer, i.e. of the order of centimeter.[1–3] CNTs are more or less a rolled-up graphitic layer with a continuous hexagonal mesh of the carbon molecules. They can have multiple structures, differing in thickness, length, type of helicity, and number of layers.[2] Even though CNTs are essentially formed from the same graphite sheet, their physical, chemical, and physicochemical characteristics differ depending on these variations, especially the electrical properties.[3] The sp^2 bonds between the corresponding carbon atoms and densely packed honeycomb crystal lattice structure offer excellent mechanical (tensile strength of 150 GPa), thermal (1500–3000 $W/m{\cdot}^{\circ}K$), and electrical (10^4 S/cm) conductivities of CNTs.[4] Because of these extraordinary properties, these materials are considered to be the next generation of materials for lighter aircraft, faster vehicles, more capable computers/satellites, more sensitive sensors, better micro- and nano-chips, fuel cells and solar cells, and batteries for different industrial applications, such as electronics, optics, medical, energy, chemical, defense, aircraft and spacecraft, etc.[2]

Recently, there has been a considerable interest in stronger, lighter, flexible, and thermally and electrically conductive materials for aerospace applications.[5–7] It has been reported that CNT multi-yarn-based products may meet these needs in the applications requiring high electrical and thermal conductivities, flexibility, and mechanical strengths.[6–9] CNT yarns are arrays of CNTs which are twisted together in a single dimension.[10] Lately, many studies have focused on the fabrication and characterization of CNT multi-yarns to determine their unique properties and to take advantage of these properties for further advancement.[11–15] CNT multi-yarns have numerous potential industrial applications, including high strength composite, photonic waveguides, transparent and flexible electrodes, electronic transducers/actuators, biosensors, and military use.

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Furthermore, several studies have been also conducted on the CNT multi-yarns in the effort to produce lighter, stronger, and more functional materials.[10–13] Yu et al.[16] reported that when 15 single-walled CNTs were bundled together and pulled, an average tensile strength of 30 GPa was measured. Zhang et al.[17] stated that when a large number of CNTs were bundled and twisted together into a two-yarn with a diameter of around 10 μm, the strength of the CNT multi-yarn was reduced to 460 MPa. It has been shown that the increase in diameter of CNT yarns would decrease the mechanical properties of CNT yarns.[18] Several studies have shown that mechanical properties of CNT yarns are significantly lower than the individual CNTs, which may be due to the lack of lateral forces (weak van der Waals forces) between the CNTs and sliding of CNTs under the applied forces.[6,8,9]

In an effort to improve mechanical (e.g., fatigue, creep, stiffness, and strength), as well as other physical (e.g., magnetic, electrical, thermal, and optical), chemical, and physicochemical properties of CNT yarns, the scientific community has been investigating the CNTs and their products. The cross-linking of CNT yarns has recently received much attention worldwide. Cai et al.[19] reported that the modified CNT yarns with aryldiazonium salts resulted in an improved tensile strength and Young's modulus. These authors also stated that the functional groups grafted on surfaces of CNTs make the surface available to form cross-links in the yarns to further increase mechanical properties. Research by Misak et al.[20,21] has shown that it is possible to functionalize/cross-linked CNTs in the yarns; however, cross-linking temperature needs to kept low for increasing the mechanical properties. Thiagarajan et al.[22] used chemical vapor infiltration to deposit pyrocarbon into the CNT yarn increasing the strength and stiffness. There have been also several studies which have dealt with preparation, characterization, and application of CNT-reinforced composites. A good overview and summary of these nanocomposites can be found elsewhere.[23]

To the author's knowledge, there has been no or little research on CNT multi-yarn-reinforced composites. The present study is precursor in this direction where CNT multi-yarn was coated with a thin layer of polyester, and then it was investigated under tensile loading condition inside a SEM. In situ photographs were undertaken to investigate the helix angle, diameter, yarn twist, and damage and failure mechanisms. Similar characterization was also undertaken with the uncoated CNT multi-yarn. This provided comparison of their tensile behaviors between coated and uncoated CNT multi-yarn. This information would be useful to extrapolate the behavior of CNT multi-yarn when used as the reinforcement in composites or when are cross-linked to develop some bonding among the yarns on the surface.

Experimental

Materials

A batch of CNT multi-yarn, consisting of 30 yarns, was procured from the Nanocomp Technologies, Inc. The tex (weight per linear length) of the 30 yarns was measured, which was 65 ± 1.8 g/km. Figure 1(a) shows the SEM image of as-received CNT 30-yarn. Commercially available AC glue (ethyl-2-cyanoacrylate) was used without any further modification. The glue was applied by holding the CNT 30-yarn vertical and letting a glue bead roll down in a controlled manner. The average thickness of the polyester coating was 8 ± 4 μm. Figure 1(b) shows the glue-coated CNT 30-yarn. It should be noted that the hierarchy of the CNT multi-yarn structure is as follows: CNT, CNT bundles, yarns, strands, and multi-yarns. CNT bundles are composed of multitudes of CNTs. Yarns are composed of multitudes of CNT bundles. Strands are composed of three yarns twisted together in the present multi-yarn. The 30-yarn is composed of 10 strands.

Methods

Tensile tests were conducted on the CNT 30-yarn specimens using a MTS Tytron 250 bench-type unit with a 40-N load cell. Figure 2 shows MTS Tytron 250 tensile and the custom-made straining device for the mechanical characterization of CNT yarns outside and inside an SEM, respectively. The CNT 30-yarn specimens with a length of approximately 50 to 100 mm were held in the grips of the MTS test unit and loaded. Similarly, 30 to 50 mm length specimens of CNT 30-yarn were attached to a straining device where by rotating the screw, the strain was increased. After each increment of strain, SEM images were taken, and the diameter, helix angle changes, and dot movement of the yarn were recorded. The dot movement was used to qualitatively measure the helix angle and twist movement of a yarn when strained. This is done by measuring the distance of the dot from the bottom surface of the yarn, i.e. dot position relative to the bottom edge of the yarn. The change in dot movement can then be found by subtracting the original dot position to the strained dot position. Upon straining, the helix angle and twisting of the yarn will change which would change the position of the reference point (i.e. dot). The measured dot position is an apparent value of movement since the three-dimensional rotation of the yarn was projecting onto a two-dimensional plane of the observation and has been discussed elsewhere.[15]

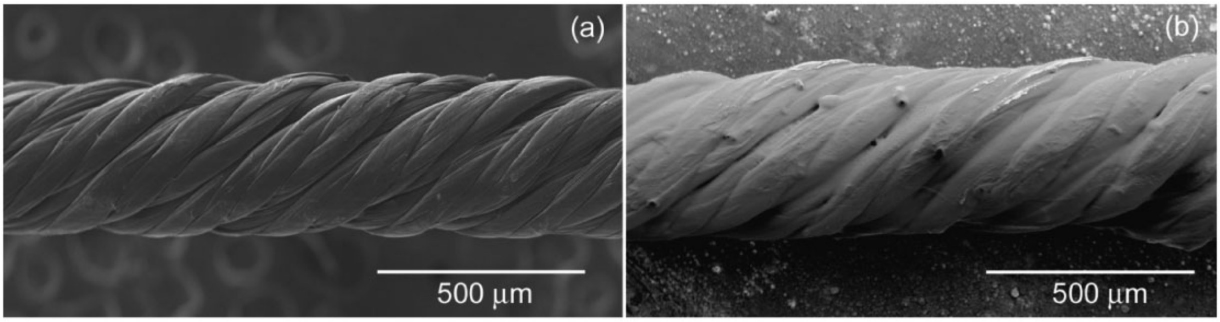

Figure 1. SEM images of (a) as-received and (b) adhesive coated 30-yarn.

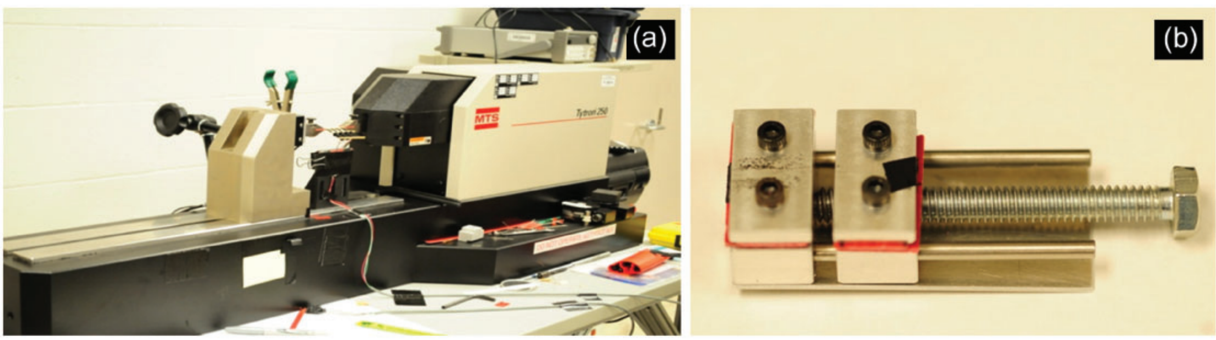

Figure 2. (a) the MTS Tytron 250 unit and (b) a custom strain device.

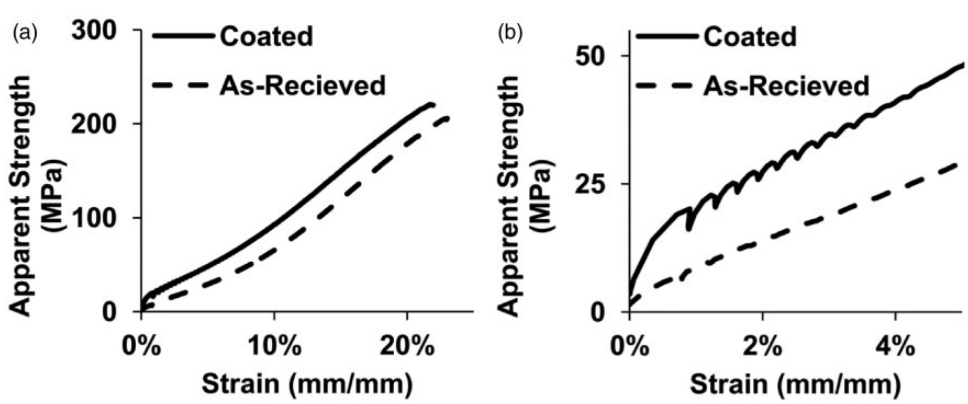

Figure 3. (a) apparent strength versus strain of the coated and as-received yarn and (b) magnified region of its initial part.

SEM images and photographs were also taken to study the fracture/damage formations.

Results and discussion

Tensile behavior of coated and uncoated CNT multi-yarns

The apparent tensile strength of the as-received yarn is 209 ± 4.9 MPa, while the average apparent tensile strength of the coated multi-yarn is larger, i.e. 220 ± 6.1 MPa. Figure 3(a) shows the stress–strain diagrams for both multi-yarns. The coated sample has a higher stress for the same strain throughout the test. Magnifying the region near the start of the test (Figure 3(b)), the coated yarn has also larger initial stiffness. This can be attributed to the coating which would try to prevent the helix angle change. The jagged stress versus strain profile of the coated sample can be due to the coating which would increase friction and mechanical interference between yarns relative to smooth helix angle change in the case of uncoated multi-yarn. Beyond an apparent strength of 50 MPa, the stress versus strain profile is smooth.

Helix angle

Figure 4 shows the SEM images for the helix angles of CNT 30-yarn coated with the polyester. Depending on the location, thickness of the adhesive coatings varies between 4 and 12 µm. At 0% strain, the helix angle and diameter of the coated CNT 30-yarn is 32° and 405 µm, respectively; however, after straining the multi-yarn to 8.2%, 15.4%, and 18.6%, these values are reduced to 27° and 370 µm, 19° and 339 µm, and 16° and 321 µm, respectively.

Helix angle and diameter are shown in a graphical way in Figure 5. From these graphs, it is easy to see that the coated and as-received multi-yarn follow the same trend as far as helix angle and diameter are concerned. The diameter is larger for the coated multi-yarn as the addition of the coating increases the diameter. Up to about 10% strain, the diameter stays much larger compared to the as-received. After the applied strain of

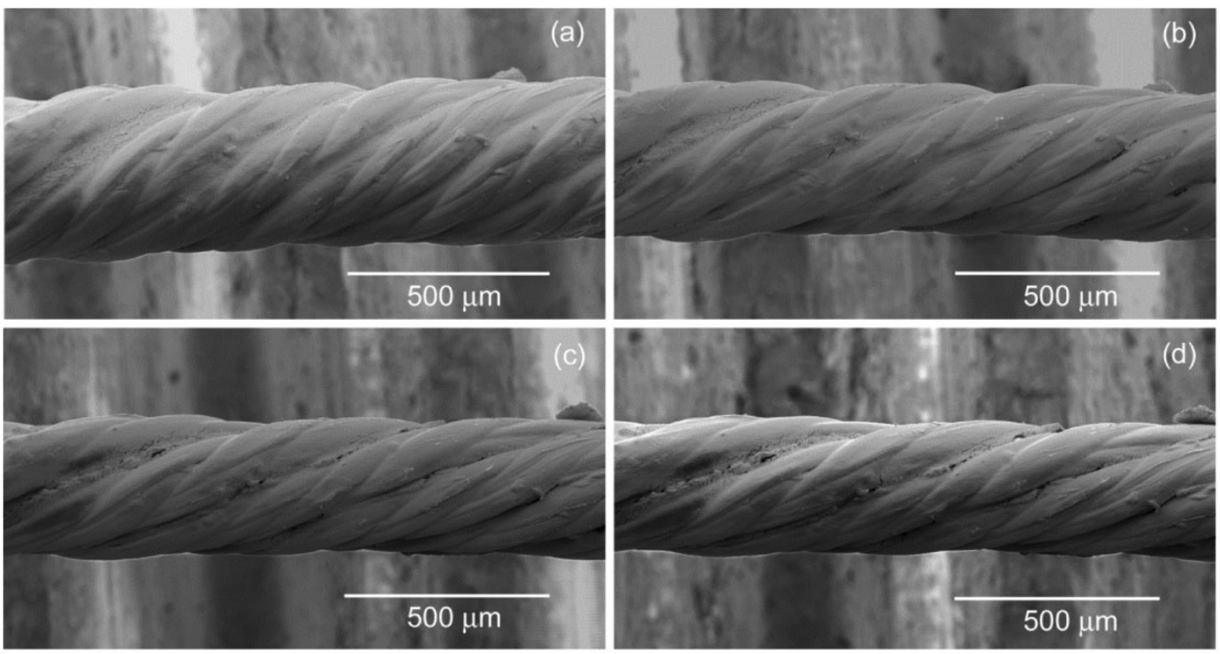

Figure 4. SEM images showing the helix angles of CNT 30-yarn coated with the adhesive at different strain rates: (a) 0%, (b) 8.2%, (c) 15.5%, and (d) 18.5%.

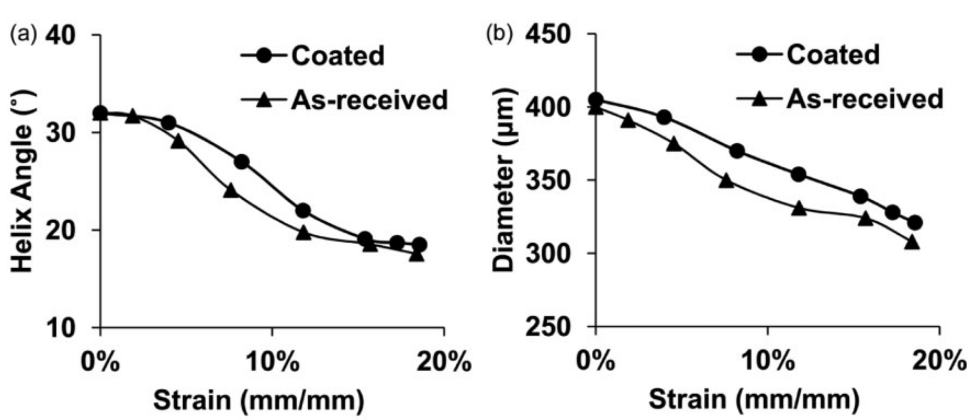

Figure 5. (a) helix angle change with increasing strain and (b) diameter change with increasing strain for coated and as-received yarns.

10%, the difference in the diameters between them decreases. Another way which provides qualitatively to investigate the relationship between the way the yarn's strain from helix angle movement and/or yarn tightening is the dot movement (Figure 6). In this case, a spot is identified on the yarn and the change in its distance from the original location is recorded. In the case of the as-received multi-yarn, the helix angle is reduced initially causing the spot to move down; however, after 8% strain the yarn began to tighten as the helix angle is locked and yarn is twisted up after tightening of the yarn. The coated yarn did not experience this phenomenon.

Failure

At failure, the as-received CNT-yarn fractures at multiple locations, while the coated yarn fractures at one location. This can be observed in Figure 7 where an (a) optical image of the as-received intact yarn, (b) as-received fractured multi-yarn, and (c) coated multi-yarn are shown. The as-received fracture yarn has unraveled, while the coated CNT multi-yarn has not, which can be attributed to the coating.

After fracture, the multi-yarns were imaged through an SEM. Figure 8 shows the (a) as-received yarn's failure and (b) the coated multi-yarn's failure. The as-received shows yarns/strands have been unraveled from multi-yarn, in contrast the coated sample strands stayed wrapped. The coating has flaked off in high strain areas. Looking away from the fracture location, the yarns have untangled as shown in Figure 9(a) in the as-received case, while the coated yarn has stayed intact (Figure 9(b)). The coated CNT multi-yarn has, however, cracks in coating at locations away from the failure location (Figure 9(b)).

Figure 10 shows the thickness and penetration of adhesive on CNT 30-yarn. The adhesive coating with a thickness of around 5 μm did not penetrate inside the individual CNTs in the multi-yarn, rather stayed on the surface of the yarns (i.e. very small penetration). Even with this little penetration, the tensile strength of the coated CNT 30-yarns is increased. The adhesive coating kept the yarns together and prevented untwisting after failure.

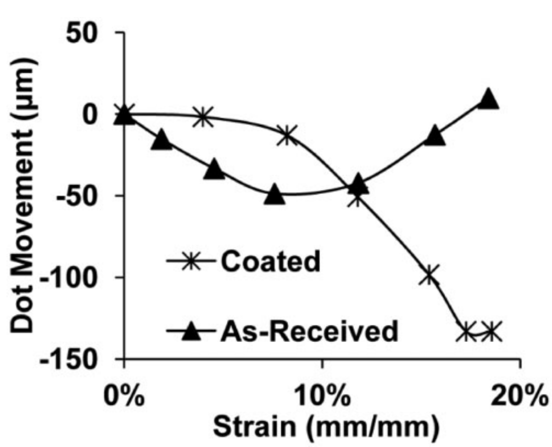

Figure 6. Dot movement versus strain for the coated and as-received yarns.

CNT yarn-based composite

CNT multi-yarn has capability to withstand large amount of strain compared to a conventional carbon fibers; thus, this would complicate the engineering analyses and fabrication process when used as the reinforcement in composite in comparison to commonly and presently widely used carbon fiber/epoxy composite. Also due to the helix angle change, a gradient strain distribution could be created within the matrix of a reinforced CNT multi-yarn composite. This could result in matrix cracking between strands as seen in Figure 9. Matrix materials with more ductility may be better suited for CNT multi-yarn composites. CNT multi-yarns are made up of many one-dimensional objects to which the matrix can adhere easily. However, the aligned one-dimensional objects can get pulled off the surface easily, as seen in Figure 10 making adhesion to the matrix difficult, which would require some innovative considerations or processes to develop a good fiber/matrix bond. Applications requiring high specific conductivity, high specific strength, bendable, and resistant to harsh environments are highly desirable in many applications; therefore, reinforced CNT multi-yarn composite

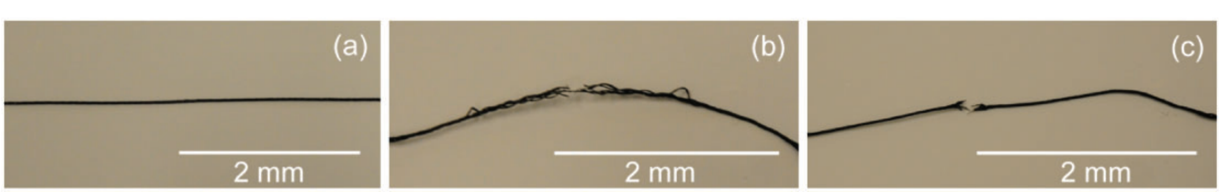

Figure 7. Optical images of 30 ply CNT wires: (a) as-received, (b) fractured as-received, and (c) fractured coated.

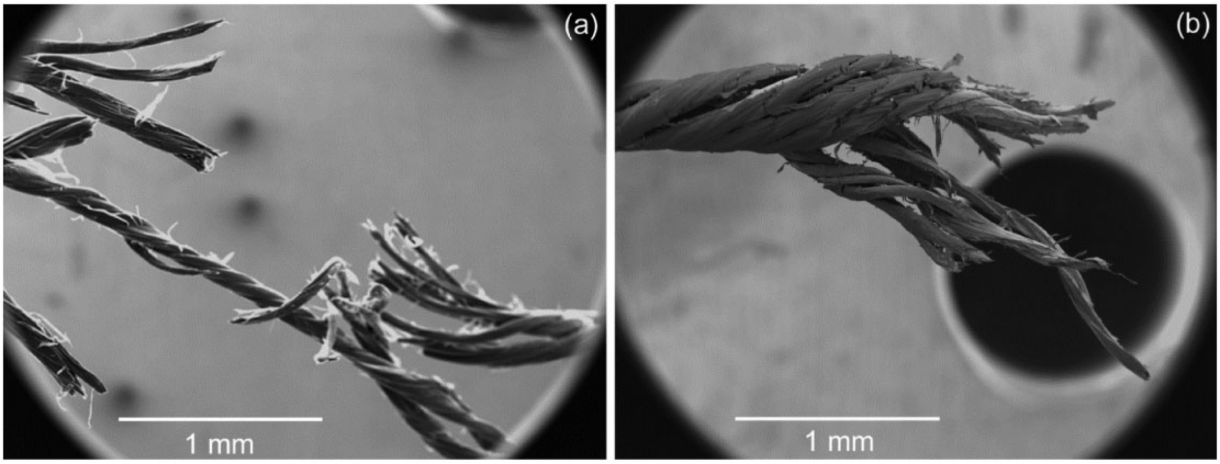

Figure 8. Fractured (a) uncoated yarn and (b) coated yarn.

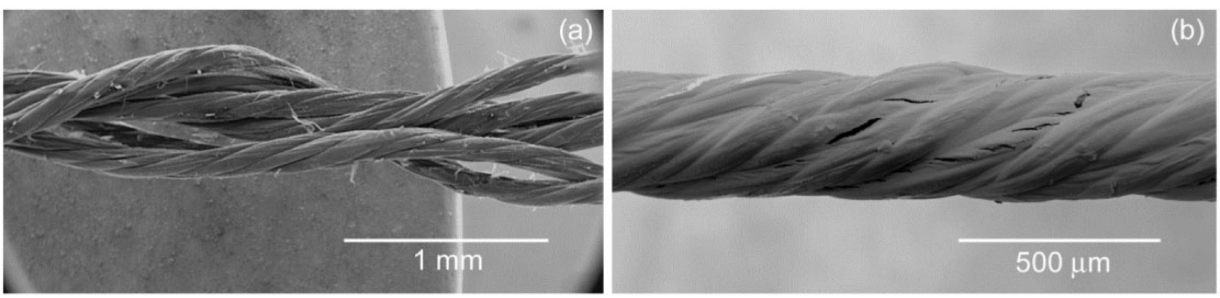

Figure 9. SEM images showing the failed yarns away from the fracture: (a) uncoated and (b) coated yarns.

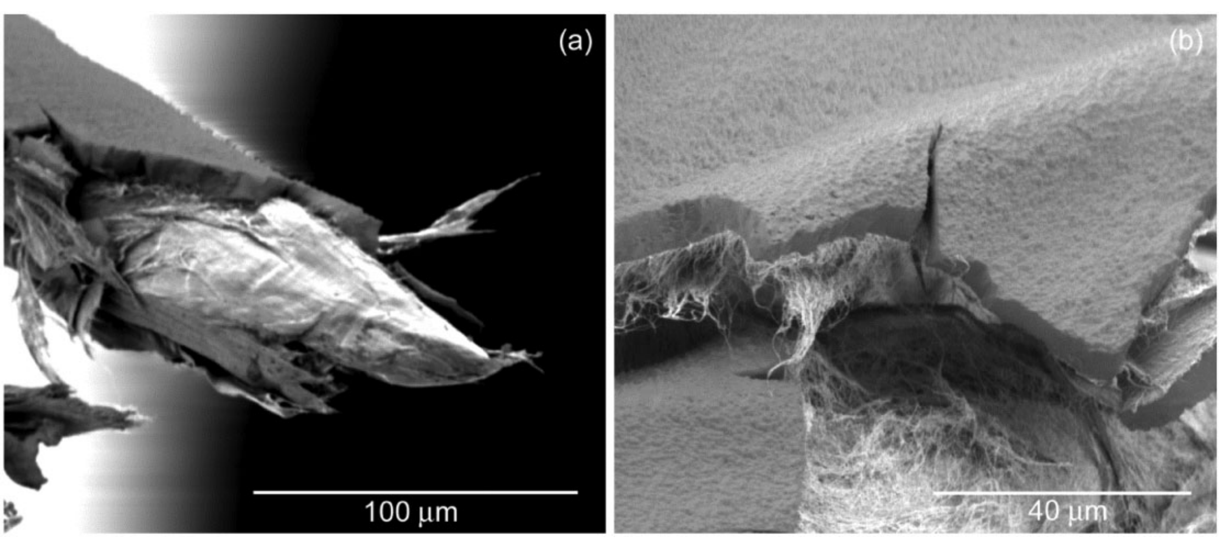

Figure 10. SEM images showing coating thickness and lack of penetration.

materials may be ideal in these cases. However, further studies are needed before CNT multi-yarn can be used as the reinforcement, and the current study provides useful data and information in this direction.

Conclusions

CNT 30-yarns were coated with polyester having a coating thickness that ranged from 4 to 12 μm. The coated yarn has higher apparent strengths of

220 ± 6.1 MPa compared to the uncoated of 209 ± 4.9 MPa. The stiffness of the coated yarn is also higher than the uncoated up to 1% strain due to the coating requiring a larger loading to change the helix angle. Beyond 50 MPa, the coating does not contribute to the tensile performance of the yarn; however, it does prevent tightening of the yarn as shown by no reverse dot movement. Without the tightening, wear is reduced and failure is localized to one location. Also, the coating keeps the yarns from untwisting after fracture. The coating did not penetrate inside the CNT yarn but good adhesion to the outer surface occurred. CNT multi-yarn appears to have a good potential as the composite reinforcement in applications requiring high specific conductivity, high specific strength, bendable, and resistant to harsh environments but requires further studies.

Disclaimer

The views expressed in this article are those of the authors and do not reflect the official policy or position of the United States Air Force, Department of Defense, or Government.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Conflict of interest

None declared.

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