Consideration of Conductive Motor Winding Materials at Room and Elevated Temperatures

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Abstract

A brief history of conductive motor winding materials is presented, comparing various metal motor winding materials and their properties in terms of conductivity, density and cost. The proposed use of carbon nanotubes (CNTs) and composites incorporating CNTs is explored as a potential way to improve motor winding conductivity, density, and reduce motor size which are important to electric aircraft technology. The conductivity of pure Cu, a CNT yarn, and a dilute Cu-CNT composite was measured at room temperature and at several temperatures up to 340 °C. The conductivity of the Cu-CNT composite was about 3 percent lower than pure copper's at all temperatures measured. The conductivity of the CNT yarn was about 200 times lower than copper's, however, the yarn's conductivity dropped less with increasing temperature compared to Cu. It is believed that the low conductivity of the yarn is due primarily to high interfacial resistances and the presence of CNTs with low, semiconductor like electrical properties (s-CNT). It is believed the conductivity of the CNT-Cu composite could be improved by not using s-CNT, and instead using only CNTs with high, metallic like electrical properties (m-CNT); and by increasing the vol% m-CNTs.

Scope and Background

The work presented in this memorandum is in support of NASA's efforts to promote and develop hybrid electric power systems for aircraft. It is believed that significant improvements in aircraft efficiency can be achieved through use of electric propulsion and subsystems (Ref. 1); however, the current power to weight ratio and efficiency of electric motors is too low for their effective use in aviation. The windings of the electric motor has been identified as an area that could be improved resulting in power ratio and efficiency improvements. If the conductivity of the motor windings could be increased the size and thus mass of the motor could be lowered (there-by increasing the power ratio); higher conductivity also has the potential to lower i^2R electric power losses. Lowering the density of the motor windings would also improve the power ratio.

The scope of this evaluation is limited to:

- Conductive electric motor winding materials, and excludes materials used to insulate motor windings, and excludes competitive materials selection comparisons associated with all other motor components.
- Direct current (DC) resistance calculations only. Even though we expect applicable motors to use alternating current (AC) DC resistance values are appropriate because the expected AC frequency should be low enough to omit the need to consider any Skin Effect (Ref. 2) on conductivity. The skin depth δ, is defined as the depth below the surface of a conductor at which the current density has been reduced to $1/e$ times its value at the surface. The AC frequency in the windings needs to be greater than the motor rotation speed divided by 60; anticipated rotation speeds for aviation are of the order of 6000 rpm, thus a frequency near 100 Hz is expected. The skin depth for Cu wire at 100 Hz is about 7 mm, which is much greater than probable motor winding wire radii.

Some of the first electric motors were electrostatic devices created by Gordon in the 1740s (Ref. 3) which relied on the attraction and repulsion resulting from electric charge differences. Ampere's force law defined the force between current carrying wires (Ref. 4) and Faraday's demonstrations of the electromagnetic conversion of electrical energy into mechanical energy ushered in the development of motors based on coils of current carrying wires. The first demonstration of a device containing the three main components of practical direct current (DC) motors (stator, rotor, and commutator) was due to Jedik in 1828 (Ref. 5). Some of the first DC motors intended for commercial use were invented in the mid-1830s by Sturgeon in Britain, and by Davenport in America (Refs. 6 and 7). These early motors were however doomed due to the high cost of battery power which was needed due to the lack of distributed electricity at that time (Ref. 8). The dynamo patented in 1870 by Gramme enabled the production and eventual distribution of electricity from mechanical energy, and the wide spread use of electric motors (Ref. 9). The development of AC motors followed with significant contributions made by Tesla, Westinghouse, and General Electric Company. The efficiency of electric motors improved dramatically upon the realization of the importance of a small air gap between rotor and stator; such evolutionary improvements have resulted in a 100 hp motor today having the same mounting dimensions as a 7.5 hp motor from 1897 (Ref. 10). The first paper presenting the concepts of a synchronous reluctance motor appeared in 1923 by Kastko (Ref. 11). A synchronous electric motor is an AC motor in which, at steady state, the rotation of the shaft is synchronized with the frequency of the supply current where in the rotation period is equal to an integral number of AC cycles. Synchronous motors contain electromagnets on the stator that create a magnetic field which rotates in time with the oscillations of the line current. The rotor turns in step with this field, at the same rate. A reluctance motor is a type of electric motor that induces non-permanent magnetic poles on the ferromagnetic rotor. Reluctance motors can deliver very high power density, but suffer from high torque ripple (the difference between the maximum and minimum torque during one revolution). During this period of early motor development, 1800 to 1900, the price of Cu was inexpensive compared to Al and other conductive metals such as Ag; thus due to its price, properties, and availability, Cu was used nearly exclusively in early motor windings. Since 1900 the relative price of Al compared to Cu has declined such that now Al is about 1/3 the cost of Cu per unit mass, making Al more competitive compared to Cu in a very wide variety of applications.

Metals

This section presents and compares the candidate motor winding materials: Cu, Al, Au, and Ag. Table 1 lists their approximate resistivity, conductivity, density, and cost per gram, along with the properties of metallic CNT (m-CNT) which are discussed in the next section. The resistance of a conductor, R, such as the wire of a motor winding, in units of Ohms is:

$$R = \rho \frac{l}{A} \tag{1}$$

where ρ is resistivity in units of Ω-m, l is the length of the wire in meters, and A is the m^2 cross-sectional area of the wire (Ref. 4). The electrical power losses, P in watts, of the winding are:

$$P = i^2 R \tag{2}$$

where i is current in amperes. It is very important for aeronautical applications for efficiency to be as high as possible, and thus electrical losses, P, need to be as low as possible.

TABLE 1.—ROOM TEMPERATURE PROPERTIES OF CANDIDATE MOTOR WINDING
MATERIALS (REF. 17); AND COST BASED ON PURE METAL COMMODITY PRICES
AND A RECENT PURCHASE OF SORTED METALLIC ONLY CNT; m-CNT
CONDUCTIVITY AND RESISTIVITY ARE ESTIMATED BASED ON
MEASUREMENTS; m-CNT DENSITY IS ESTIMATED
BASED ON THE DENSITY OF CARBON

Material	Resistivity, Ω-m	Conductivity, S/m	Density, g/cc	Cost, $/g
Al	2.65E-08	3.77E+07	2.7	0.0286
Cu	1.67E-08	5.98E+07	8.96	0.1144
Au	2.35E-08	4.26E+07	19.3	46
Ag	1.59E-08	6.29E+07	10.49	0.7392
m-CNT	1.3E-08	7.2E+07	2	24,000

Aluminum

Aluminum motor windings are commercially available[*] and are the second most widely used material for motor windings after Cu. Aluminum has advantages over Cu which include lower density (ρ_{Al} = 2.7 g/cc, ρ_{Cu} = 8.96 g/cc) and lower cost per kg ($1.6/kg Al, $5/kg Cu) (Ref. 12). However, the conductivity of Al is 40 percent lower than Cu; thus a larger diameter Al wire must be used to achieve the same current flow compared to Cu. This larger volume of Al results in an increase in the overall size of the motor, and concomitant increases in cost, mass, and friction losses. Han et al. modeled a 3.7 kW induction motor using both Al and Cu windings and found the Al wound motor cost about 20 percent more and weighed 35 percent more due to the cost and mass of the steel in the larger Al wound motor (Ref. 12). Use of Al motor windings is summarized in Reference 13, where it is mentioned that Al wound motors are typically 10 to 20 percent larger than equivalent Cu wound motors. Low total motor mass and low electrical and friction losses are priorities for applications of interest to NASA, such as hybrid-electric aircraft, thus Al is not considered a viable material for such applications unless its conductivity can be improved; a conductivity improvement could potentially be achieved by the production of an Al-carbon-nanotube (Al-CNT) composite.

[*]For example, Al motor winding wire, coated with polyester, polyurethane, or polyester-imide, is being produced by Wujiang Xinyu Composite Materials Company, Ltd., Jiangsu province, China.

Copper

Copper has been one of the most common and widely used metals in human history (Ref. 14). The very early use of Cu is in part due to its presence in our environment in its native form, such as the specimen shown in Figure 1, rather than in the form of a metal-oxide (Ref. 15). Due to its availability and favorable properties, Cu has been the material of choice for electromagnetic winding applications (Ref. 16). Figure 2 shows the use of Cu in an early electro-mechanical fan by Thomas Edison.

To compare Cu and Al windings, R and l from Equation (1) shall be set equal for the two windings

and the area adjusted to achieve the same R: $R_{Cu} = R_{Al} = \rho_{Cu} \dfrac{l}{A_{Cu}} = \rho_{Al} \dfrac{l}{A_{Al}}$ thus the cross-sectional

area of the Al windings need to be: $A_{Al} = A_{Cu} \dfrac{\rho Al}{\rho_{Cu}} \approx 1.6 A_{Cu}$. This 60 percent increase in winding cross-

section requires the stator of the Al wound motor to be larger, and thus the rotor and motor housing also need to be larger. These resulting increases in mass, size, and materials costs associated with the Al windings exceed the cost and weight savings gained by Al in lieu of Cu windings.

Figure 1.—Native Cu, 7.1 cm wide, from the Indiana Mine, Michigan, courtesy of W.R. Kellogg, M&W Minerals.

Figure 2.—Edison DC electric fan, courtesy of Spark Museum, Bellingham Washington.

Gold and Silver

Gold and Ag have very low resistivity, however, both are very expensive and heavier than Cu. Since Au is very expensive, dense and not as conductive as Cu, it will not be considered further here. Silver however has conductivity superior to that of Cu, and many other favorable qualities such as good strength, ductility, solderability, and corrosion resistance.

To compare Ag to Cu, an analysis will be done using the electric motor drive system of a 2010 Toyota Prius (Ref. 18). There is about 5 kg of 20 American Wire Gauge (AWG) Cu windings in the electric drive motor of the Prius (Ref. 18). Based on this mass and the density of Cu, the volume of Cu, V_{Cu}, is 558 cm^3. The volume of the wire is $A \times l$ (where $A = \pi r^2$ and r is the wire radius). Twenty AWG wire has a radius of

0.04065 cm, thus the length of the Cu wire is $l_{Cu} = \dfrac{558 \, cm^3}{A} = 1.075 \times 10^5 \, cm = 1075 \, m$. The resistance of

these Cu windings is: $R_{Cu} = \rho_{Cu} \dfrac{l_{Cu}}{A_{Cu}} = 34.6 \, \Omega$.

In this comparison the length and resistance will be held constant so that the resulting magnetic fields and power losses will be similar. The cross-sectional area needed to yield the same R, and l is:

$A = \rho_{Ag} \dfrac{l}{R} = 4.94 \times 10^{-7} \, m^2$ this area is closest to 20 AWG wire. The required volume, mass, and

material cost of Ag are 531 cm^3, 5.57 kg, and \$4,118, respectively. The material cost of the Cu winding is \$572. The hope here is that the higher conductivity of the Ag would enable thinner motor winding wire to be used. The Ag wire diameter needed (to produce the same number of turns and resistance) was smaller, but only slightly (~2.5 percent smaller), thus a standard higher (smaller diameter) gauge could not be used. The small diameter difference is believe to be within the variability of wire drawing, insulation thickness, and packing factor, thus the use of Ag would not enable the overall size of the motor to be decreased; and the mass of the Ag windings was about 11 percent heavier than the Cu.

Another option would be to compare Ag and Cu using the same wire length and gauge, thereby solving for R and enabling Ag to improve efficiency through lower losses. Power losses in the windings are proportional to R. In this case the ratio of R_{Ag}/R_{Cu} is equal to $\rho_{Ag}/\rho_{Cu} = 0.952$ therefore the use of Ag would decrease losses due to motor winding resistance by about 4.8 percent. The peak efficiency of the Prius motor is 95 percent. If 3/5th of these losses are due to resistance losses, the other 2/5th being attributed to stator and mechanical losses, the switch to Ag windings would result in an efficiency improvement to 95 percent + (3 percent × 0.048) = 95.144 percent. This moderate improvement in efficiency might be worth the cost of the Ag if, for example, it significantly lowered battery mass or costs. The Ag mass in this case is 5.85 kg (a 17 percent increase over Cu).
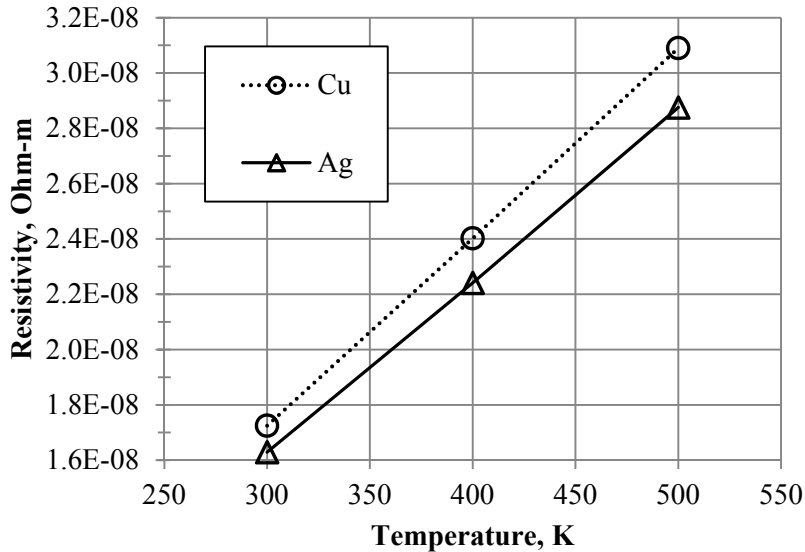
Figure 3.—Cu and Ag resistivity at moderately high motor temperatures (Ref. 19).

Silver has an electrical resistivity temperature coefficient approximately 10 percent lower than copper's. So as temperature rises, silver's resistivity increases less than copper's. The resistivity of Cu and Ag as a function of temperature (Ref. 19) are shown in Figure 3 in a temperature range applicable to most motor operations. If we consider motor operations at 450 K (177 °C) R_{Ag}/R_{Cu} is equal to 0.931 which would improve overall efficiency to 95.21 percent for our example using the 2010 Prius motor.

Carbon

There has been much interest in improving the conductivity of motor windings and power transmission lines through the use of carbon-nanotubes (CNT) either by themselves, or by adding CNTs to a supporting matrix such as Al or Cu. The following sections discuss CNTs and recent efforts to improve magnetic wires with their use.

Carbon Nanotubes

Background

There are theoretical expectations that the electrical and thermal conductivity of CNTs are very high (Refs. 20 and 21) however, these expectations have not yet materialized (Ref. 22), particularly in assemblies large enough for engineering applications (Refs. 23 and 24). Ebbesen et al. have measured the electrical conductivity of individual CNTs and found the conductivity of each fiber to be unique with a very high degree of variation among fibers, and that abrupt jumps in conductivity occur with variations in temperature (Ref. 25). In an effort to improve the thermal conductivity of rocket nozzle materials Bhat incorporated multiwalled carbon nanotubes (MWCNT) into a Cu alloy which resulted in decreases in thermal and electrical conductivity (Ref. 22). Bhat measured the thermal conductivity of MWCNTs supplied by vendors claiming conductivities of 2400 W/m-K (the conductivity of Cu is ~400 W/m-K) but measured thermal conductivities of these MWCNTs were in the 16 to 200 W/m-K range (Ref. 22).

CNT Testing

Carlos Morrison acquired a 4 m long 28 AWG wire yarn made of CNTs from Nanocomp Technologies Concord New Hampshire. The measured resistivity of this yarn was $\rho_{CNT} = 3.60 \times 10^{-6} \, \Omega - m$; this is about 220 times higher than copper's. The density (based on the measured mass and assumed 28 AWG diameter of 0.0126 in.) of this CNT yarn was only 0.83 g/cm^3; copper's density is 8.94 g/cm^3. Such CNT yarn is very flexible and claims to be more durable and damage resistant than Cu wire. Thus CNT yarns might have application as rough service, light weight signal wires that do not carry a lot of current. Such CNT yarns are frequently sold bare, uninsulated. In order to use such yarns, for example, for windings in a motor, they must be insulated. The following coatings/methods were considered to insulate the Nanocomp CNT yarn:

- Cotronics Corp. Brooklyn NY (www.cotronics.com) makes a two part (resin and hardener) low viscosity coating: Durapot 861.
- Schulte and Chow report a method for insulating carbon fiber microelectrodes using anodic electrophoretic deposition of paint (Ref. 26).
- MG Chemicals (http://www.mgchemicals.com) make several coating of interest: a) Red GLPT Insulating Varnish, 4228-225ml; b) Connector Coating 4229, which seemed a bit too think for thinly coating wire, but might be useful for potting; c) Super Corona Dope 4226.

Based on product descriptions and availability, Super Corona Dope (Cat. No. 4226-1L, Batch No. 09350) was chosen to coat and electrically insulate the Nanocomp CNT yarn. To become familiar with the handling of the coating Al and Cu wires were first coated. Super Corona Dope (SCD) wet the Al wire nicely, with a dip coating depositing a smooth layer 0.002 in. (0.051 mm) thick. Super Corona Dope did not coat the Cu wire well however because it beaded up and did not wet the metal. To coat the yarn it was immersed in a vat of SCD, quickly withdrawn from the liquid, and hung to dry. The desired coating thickness was of the order of 0.001 in. (0.0254 mm) since this is the thickness of the Kapton (DuPont, Wilmington, DE) coating on our baseline 28 AWG Cu magnetic wire. The thickness of the SCD on the yarn was 0.003 in. (0.076 mm). The resistance of the entire length was 180 Ω. The resistance measured between the wire and the outer surface of the SCD coating was approximately 20 MΩ, indicating sufficient electrical isolation of the yarn.

The rather high resistivity of the CNT yarn tested is believed to be due to the short length of individual fibers, contact resistances between fibers, and the high resistivity of some of the CNTs in the yarn. Several groups are attempting to improve the conductivity of CNTs by incorporating them into a composite with the idea of lowering interfacial contact resistances. This is worthwhile, however this is not expected to overcome the negative effects of the presence of CNT of high resistivity.

A CNT is essentially a long and narrow piece of graphene rolled along its length to form a tube. The details of its structure and how it bonds to itself is referred to as its chirality (Ref. 23). The properties of each CNT are strongly dependent on its structure, or chirality. When CNTs are made about 66 percent of them have a structure that results in very poor conductivity, or semiconducting properties (s-CNT), and about 33 percent have relatively high electrical conductivity, or metallic properties (m-CNT) (Ref. 27). The conductivity of any composite made with CNTs is expected to follow rule-of-mixture (or weighted mean (Ref. 28)) behavior where the conductivity of the composite σ_{Comp}, is given by

$$\sigma_{Comp} = \sigma_M(\varphi_M) + \sigma_{m-CNT}(\varphi_{m-CNT}) + \sigma_{s-CNT}(\varphi_{s-CNT}) \tag{3}$$

where σ is conductivity, φ is volume fraction in the composite, and the subscripts M, m-CNT, and s-CNT refer to the matrix, metallic-CNTs, and semiconducting-CNTs, respectively. As mentioned, normally there is a 2:1 ratio of s-CNT:m-CNT, thus $\varphi_{s-CNT} = 2(\varphi_{m-CNT})$. The conductivity of s-CNT is orders of magnitude lower than m-CNT, making $\sigma_{s-CNT}(\varphi_{s-CNT})$ in Equation (3) effectively zero, thus the presence of

s-CNT in such a composite is very detrimental to its conductivity. Removal of the s-CNT in the supply of CNT used in the composite is essential to creating a composite with high electrical conductivity. Several groups are working on a variety of CNT separation and sorting techniques (Refs. 29 to 37).

Composites With Carbon

Carbon Nanotubes and Metal

CNT-Cu Composites

Thus far only moderate improvements to conductivity have been made with the addition of CNTs to Cu; however, significant gains are apparent in conductivity at elevated temperatures and in ampacity (the current carrying capacity of the composite) (Ref. 38). Temperature and resistivity increases that normally accompany increases in applied current have been shown to be lower in CNT-Cu composites compared to pure Cu. It has been theorized that this is due to the involvement of phonons in the composite (Ref. 38), where a phonon is a quantum of energy associated with lattice vibrations within the CNT. Current driven heating is caused by collisions (interactions) between electrons and atoms; the frequency of these collisions increases as the flow of electrons increase. The number of these collision may decrease due to phonon contributions to thermal and electrical conductivity. The resistance of CNTs is dominated by electron-phonon scattering (Ref. 39). Subraniam et al. showed that in Cu-CNT composites the CNTs tend to be located at the grain boundaries of the Cu; the presence of the CNTs at the grain boundaries dramatically lowers the level of Cu diffusion at the grain boundaries. The result of this is that the diffusion of Cu in the Cu-CNT composite is much lower than in pure Cu, which may contribute to the observed high ampacity (Ref. 38).

Testing of CNT and CNT-Cu Composites

Tests were done on TeraCopper specimens provided to NASA GRC by Kyle Kissell, Director of Technology Development at NanoRidge Materials Incorporated. TeraCopper is a proprietary composite of Cu and CNTs. Two TeraCopper samples were provided, detailed in Table 2; a similar length of 20 AWG Cu magnet wire was included in the tests for comparison. Also tested were 4 m long pieces of 28 AWG Cu magnet wire, and CNT yarn supplied by Nanocomp Technologies Inc., detailed in Table 2. The lengths of the TeraCopper and 20 AWG Cu wires were measured and the length of wire between the clips used to measure resistance estimated to within 0.5 mm. The lengths of the 4 m wires were measured by wrapping them round a large cylinder of known diameter.

Different methods were used to measure the diameter and resistance of the wire samples. The diameters of the TeraCopper specimens were measured at four locations along their lengths; the 20 AWG Cu wire was measured at three locations along its length. The 28 AWG Cu wire was measured at its ends. At each of these locations, the diameter was measure at four azimuthal locations around the circumference of the wire, at 0°, 45°, 90°, and 135°. The diameter of the 28 AWG CNT yarn was assumed to be the nominal 28 AWG wire diameter of 0.0126 in., however the conductivity of the yarn was also determined based on a theoretical calculation of the diameter of the CNTs themselves, with this diameter determined through length and mass measurements combined with an assumed density of 2 g/cm^3. The diameters of the Cu and composite wires were measured first with calibrated calipers with an estimated accuracy of ±0.0005 in. (0.013 mm); and then measured again using an optical comparator

TABLE 2.—PRELIMINARY RESISTANCE MEASUREMENTS MADE WITH AGILENT 34401A, Ohm

TeraCopper W110114-0019-T01		20 AWG Cu	4 m Nanocomp CNT yarn	4 m 28 AWG Cu
Short	Long			
0.003835	0.006785	0.01026	183	0.869

with an accuracy of ±0.0001 in. (0.00254 mm). The accuracy of the comparator measurements was confirmed using two NIST traceable 0.0309 in. diameter (±0.0001 in.) PIN gages. The caliper and comparator diameter measurements are shown in Appendix Tables A2 and A3, respectively, along with resulting cross sectional areas. The consistency of the caliper measurements appears to be very good; with the average diameter of the long and short pieces of –0019 TeraCopper being nearly identical. The standard deviations of the average diameter along the length of the TeraCopper and 20 AWG Cu wires were also very small (0.00022 and 0.00015 in., respectively) for the caliper measurements. The standard deviations of the average diameter along the wire length measured by the comparator were 0.0001 and 0.0004 in. for the 20 AWG Cu and TeraCopper pieces, respectively.

The resistances of the wires were first measured using a calibrated Agilent 34401 A 6-1/2 Digit Multimeter with a accuracy estimated to be ±0.4 mΩ using the 4-wire method. A reading with the leads shorted together was made; then the resistance of the 20 AWG Cu wire; then the long TerraCopper wire; then the short wire. This series of measurements was repeated three more times. The reading with the leads shorted was subtracted from the following specimen resistance measurement. Table 3 shows the preliminary resistance measurement averages for the wires studied.

More accurate resistance measurements were then made using a calibrated Agilent 43320A 7-1/2 digit micro-Ohm meter (4-wire leads) with an accuracy specification of ±0.015 mΩ. Prior to testing the leads were sanded with 500 grit silicon carbide paper, cleaned with isopropyl alcohol, and coated with DeoxIT cleaner and contact enhancer (Caig Labs, Poway California). The ends of each wire were also coated with DeoxIT. The resistance of the 20 AWG Cu, and the long and short TeraCopper pieces were each measured four times, with the resulting averages listed in Table 3; with a standard deviation of 0.04 mΩ. Next the resistance was measured using the 4-point probe technique shown in Figure 4, an un-calibrated Keithley 220 programmable current source set to 100 mA, and an un-calibrated Keithley 181 nanovoltmeter. The 20 AWG Cu and long TeraCopper wires were measured four times, the short TeraCopper piece was measured twice. The wires were bonded to the test slide with conductive Ag paint (Fig. 4). The results of the tests using the Keithley 181 equipment are provided for completeness in Appendix Table A1, however, these results are not believed to be accurate because: the length was short and could not be measured very accurately; the average wire diameter for the specific length tested was not measured; the deviation among similar tests was relatively high; and the equipment was not calibrated.

TABLE 3.—AVERAGE RESISTANCE MEASUREMENTS, Ohm

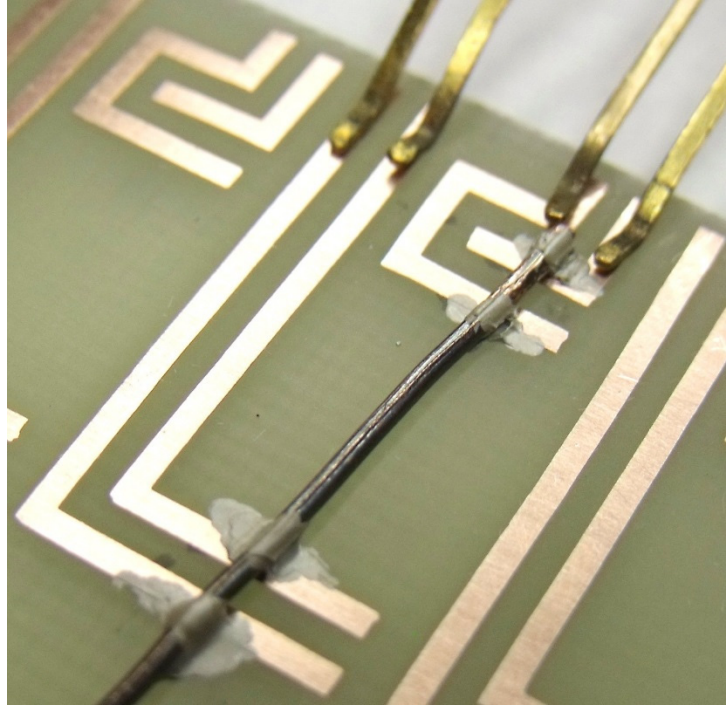|	TeraCopper W110114-0019-T01		20 AWG Cu	4 m Nanocomp CNT yarn	4 m 28 AWG Cu
	Short	Long			
Preliminary measurements with Agilent 34401A	0.003835	0.006785	0.01026	183	0.869
Measurements with Agilent 34420A Micro-Ohm meter	0.0040588	0.0066910	0.0106875	179.64	0.8664

Figure 4.—TeraCopper wire bonded to slide for voltage drop measurements using 0.1 A current.

TABLE 4.—WIRE LENGTH AND CONDUCTIVITY RESULTING FROM
AGILENT 34420A MICRO-OHM METER MEASUREMENTS
[The conductivities of the 4 m long 28 AWG wires are based on the nominal diameter of 0.321 mm.]

| | TeraCopper W110114-0019-T01 | | 20 AWG Cu | 4 m Nanocomp 28 AWG CNT yarn | 4 m 28 AWG Cu |
	Short	Long			
Length, m	0.1	0.173	0.303	4.044	4
Conductivity, caliper dia., S/m	5.111E+07	5.353E+07	5.564E+07	2.782E+05	5.705E+07
Conductivity comparator dia., S/m	5.021E+07	5.413E+07	5.471E+07		

The conductivities resulting from the resistance measurements made using the Agilent 34420A Micro-Ohm meter are provided in Table 4. Conductivity was calculated using both the caliper and comparator measurements of diameter and a circular cross section assumed (Area = πr^2, see Appendix Tables A2 and A3). Oxygen-free Cu alloys used for magnet wire include alloys such as CDA 10100, 10200, and 1100, which are expected to have electrical conductivity close to 100 percent of the International Annealed Copper Standard (IACS) of 5.8×10^7 S/m (Ref. 40). The room temperature conductivity results for the 20 and 28 AWG Cu wires were approximately 3 percent lower than IACS. The conductivity of the TeraCopper range between 6.7 and 13 percent lower than IACS. The conductivity of the Nanocomp yarn was approximately 200 times lower than the IACS.

A Keithley 580 micro-ohmmeter was acquired and calibrated. The stability, ease of use, and accuracy of this meter was excellent, thus this meter was used in a campaign which measured the conductivity of the Cu, composite, and CNT yarn in air at elevated temperatures (60, 120, 240, and 340 °C). In calibration tests at 100 mΩ the resistance measurement error of this meter was less than 0.01 mΩ. Type K thermocouples were tied to each wire at four locations equally spaced along its length. The test temperature was the average of these four measurements. The wire was placed on a hot plate, with insulation layered on top of it, with the two current (source) and two voltage (sense) leads used to measure resistance fed through the insulation. A 0.121 m long length of uncoated CNT yarn was used in this study (previous measurements used a 4 m long piece of coated (insulated) CNT yarn). The surface of the hot plate was enameled and not electrically conductive.

Figure 5 shows the conductivity of the test specimens at various imposed elevated temperatures. These temperatures were imposed; the elevated temperature was not the result of current flow through the specimens. The conductivity of Cu taken from the literature (Ref. 19) is included for comparison (noted as Cu Ref. in the legend of Figure 5). The conductivity of the TeraCopper wire was less than the pure Cu 20 AWG wire included in these tests at all temperatures. It is believed that the conductivity of the TeraCopper composite is relatively low because approximately 66 percent of the CNTs in the composite were semiconducting.
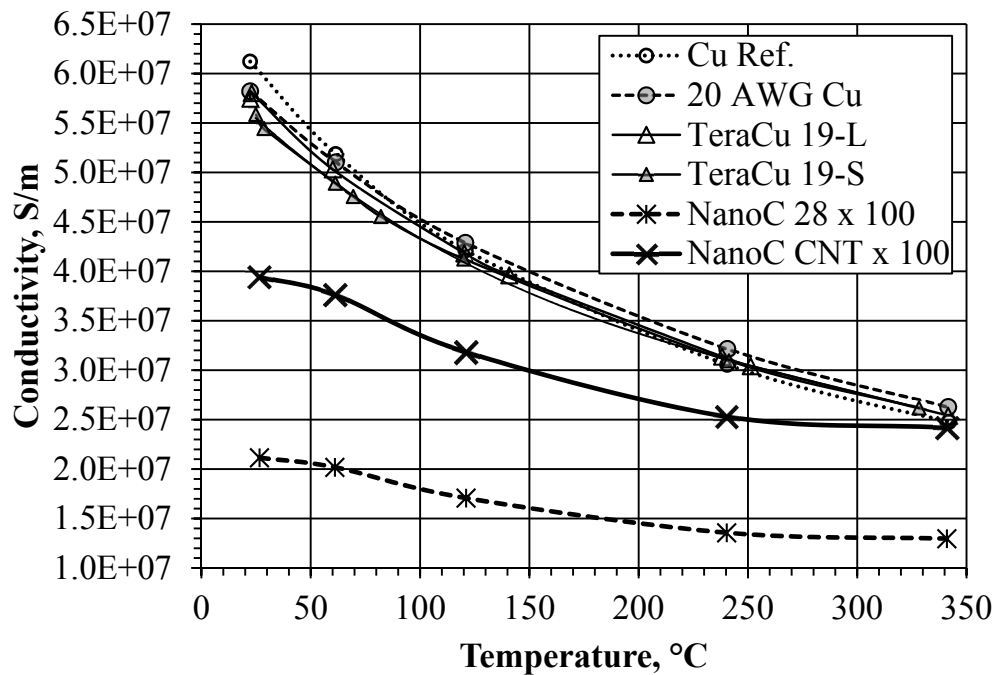

Figure 5.—Conductivity at various elevated temperatures for pure Cu, TeraCu which is a Cu-CNT composite, and a CNT yarn (NanoC); the conductivity of the CNT yarn was: multiplied by 100 so it could be shown on the same graph; and calculated based on a 28 AWG wire diameter, and on the basis of the area of CNT's themselves based on a density of 2 g/cm^3.

The conductivity of the CNT yarn is about 200 times lower, thus its conductivity was multiplied by 100 so it could be shown on the same graph. The conductivity of the yarn was measured and calculated based on two cross sectional areas: (1) based on its advertised 28 AWG diameter, and (2) base on the cross section of just the CNTs found by measuring the length and mass of the wire and assuming a density of 2 g/cm^3 for the CNTs. From 23 to 315 °C the conductivity of the Cu-rich materials dropped 55 percent; over this same temperature increase the conductivity of the CNT yarn dropped by 40 percent with the S/m versus T curve becoming very flat at the higher temperatures. It is believed that the low conductivity of the CNT yarn is a result of high interfacial resistances, and a high fraction of poorly conducting semiconductor CNTs. It is hoped that conductivity can be dramatically improved by lowering the interfacial resistance with the presence of a well bonded highly conductive matrix, and by increasing the fraction of metallic CNTs.

We can estimate the conductivity of the metallic CNTs (m-CNT) over the temperature range examined by averaging the conductivity and applying Equation (3). The measured *average conductivity* of the TeraCopper composite (σ_{Comp}) over the temperature range 25 to 340 °C was

$$\sigma_{Comp} = 40.9 \text{ MS/m} = \sigma_{Cu}(\varphi_{Cu}) + \sigma_{m\text{-}CNT}(\varphi_{m\text{-}CNT}) + \sigma_{s\text{-}CNT}(\varphi_{s\text{-}CNT})$$

where σ_{Cu} is the average conductivity of the Cu matrix over the five temperatures. The conductivity measurements of the 20 AWG Cu wire provide $\sigma_{Cu} = 42.1$ MS/m. The last term $\sigma_{s\text{-}CNT}(\varphi_{s\text{-}CNT})$ is effectively zero because $\sigma_{s\text{-}CNT}$ is relatively small. A density measurement of the composite, an assumed density of 2 g/cm^3 for the CNTs and the relations $1 = \varphi_{Cu} + \varphi_{m\text{-}CNT} + \varphi_{s\text{-}CNT}$; and $2(\varphi_{m\text{-}CNT}) = \varphi_{s\text{-}CNT}$ were used to determine $\varphi_{m\text{-}CNT}$. The effective average conductivity of the metallic-CNTs in the composite was found to be 50.7 MS/m, 20 percent higher than Cu. This includes contact resistances. If contact resistances are lowered, the effective conductivity of the m-CNTs would be higher. Specific details associated with composite density and volume fraction CNTs are proprietary (owned by NanoRidge) and have been intentionally omitted. However, based on these results, if a similar composite was made with 50 vol% m-CNT, 50%Cu, zero s-CNT, the expected conductivity would be $= 0.5(1.2\sigma_{Cu}) + 0.5(\sigma_{Cu}) = 1.1(\sigma_{Cu})$ or 10 percent greater than that of pure Cu. Hopefully this could be further improved by lowering interfacial resistances, and increasing CNT vol%.

Future work is expected to include: determination of cross sectional area of the wires Cu and composite wires through metallographic analysis; and measurement of current carrying capacity.

CNT-Al Composites

Kwon and Leparoux made dilute 1 vol% CNT-Al matrix composites by mechanical ball milling and hot extrusion which resulted in enhanced hardness and tensile strength (Ref. 41); multiwalled CNTs and pure Al were used; conductivity of the resulting material was not measured. A review of CNT-Al composite research reports various mechanical property improvements in the composites and a lowering of electrical conductivity with the addition of CNTs to Al (Ref. 42). Carey et al. reported good wetting for CNTs by Al deposited using chemical vapor deposition (CVD), and during current versus voltage tests observed a phenomenon referred to as negative differential resistance, which is believed to be due to a transition from classical conductance to electrical tunneling (Ref. 43). Liu et al. made composites of CNT and pure Al, and the alloy 6061 through powder metallurgy and friction stir processing and observed improvements in tensile properties, a decrease in conductivity in the CNT-Al composite, and an increase in conductivity in the CNT-6061 Al due to segregation of Mg and Si to the CNT-Al interfaces, there-by increasing the purity of the matrix and improving the conductivity of the matrix (Ref. 44); note that the conductivity of the pure Al decreased, as expected due to the presence of semiconducting CNTs, and that the conductivity of the alloy increased due to the movement of alloying elements to the CNT-matrix interface. This may be helpful in the development of CNT-matrix bonding strategies where in the element designed to improve the bond is alloyed in the matrix prior to deposition on the CNTs with the

expectation that the bonding element will move out of the matrix and to the CNT-matrix bond interface, there-by decreasing its detrimental effect on the matrix conductivity, and improving the electrical intimacy among matrix and CNTs.

Even though the conductivity of Al is 37 percent less than Cu, Al's low price, low density, and good mechanical and electrical properties make it a matrix material worth considering. Al costs about \$0.8/lb (\$1.76/kg; \$47.5/m^3); Cu costs about \$2.70/lb (\$6/kg, \$530/m^3). Let us consider an example of how these differences in cost, conductivity, and density might play out: If the m-CNTs have an effective conductivity double that of Cu (2 × σ_{Cu}) and we use 50 vol% m-CNT in the composite, what will the cost, conductivity, and density be of Al, and Cu CNT composites? The conductivity of the Cu composite, $\sigma_{Cu\text{-}CNT}$, will be approximately

$$\sigma_{Cu\text{-}CNT} = 0.5(2{\times}\sigma_{Cu}) + 0.5(\sigma_{Cu}) = 1.5 \times \sigma_{Cu}.$$

With an assumed m-CNT density of 2 g/cm^3 the density of m-CNT-50vol%Cu composite is expected to be = (8.9 + 2)/2 = 5.45 g/cm^3.

- Cost of the m-CNT-Cu for 1 m^3 of composite, assuming the m-CNT cost twice as much as Cu, is = (\$530 + \$1,060)/2 = \$800/m^3.
- The conductivity of the m-CNT-Al composite is expected to be = 0.5(2{\times}σ_{Cu}) + 0.5(σ_{Al}) = σ_{Cu} + 0.5(0.63σ_{Cu}) = 1.315 × σ_{Cu}.
- The density of m-CNT-50vol%Al = 2.35 g/cm^3 and the cost for 1 m^3 = (\$47.5+\$1,060)/2 = \$554/m^3.

In this scenario the m-CNT-Cu composite has 14 percent better conductivity compared to m-CNT-Al, but the m-CNT-Al weighs 57 percent less, and costs 30 percent less. It is not immediately obvious which is better, thus Al as a matrix material warrants significant interest.

Concluding Remarks

Since CNT composites are mixtures of discrete phases, the conductivity of CNT composites follow rule-of-mixtures, which is a weighted average based on volume fractions (Eq. (3)). Any constituent that takes up space (and thus cross sectional area) will influence conductivity, for better, or for worse. This very simple concept does not seem to be fully appreciated; for example, multi-walled CNTs (MWCNT) containing two or three tubes have been recommended for high conductivity applications because the outer tube is predominately metallic in nature and only the outer tube contributes to electrical properties thus most of the tubes are "metallic." However, the inner tubes take up space, increasing the diameter of the MWCNT and lowering its effective conductivity. To maximize CNT composite conductivity the volume fraction of highly conductive constituents such as m-CNTs should be maximized, and the volume fractions of poorly conductive constituents such as s-CNTs and MWCNTs should be minimized. Other factors affecting conductivity include interfacial resistances, matrix conductivity, and void fraction. Several groups have made CNT composites which have resulted in conductivity decreasing with the addition of CNTs. It is believed that this is due primarily to the presence of s-CNTs. Tests done on a dilute CNT/Cu mixture indicate m-CNTs have an effective conductivity higher than copper's. This implies a CNT/Cu composite could be made with improved conductivity and density compared to copper's.

Appendix

TABLE A1.—4-POINT PROBE MEASUREMENTS USING KEITHLEY 181, 0.1 A CURRENT SOURCE; CONDUCTIVITY CALCULATED USING THE AVERAGE OF THE CALIPER AND COMPARATOR DIAMETER MEASUREMENTS

		TeraCopper W110114-0019-T01				20 AWG Cu	
		Short		Long			
		Voltage, V	Length, m	Voltage, V	Length, m	Voltage, V	Length, m
		4.41E-05	0.011	4.58E-05	0.011	4.35E-05	0.011
		4.32E-05	0.011	4.67E-05	0.011	4.41E-05	0.011
				4.62E-05	0.011	4.50E-05	0.011
				4.61E-05	0.011	4.30E-05	0.011
Conductivity, S/m	Caliper diameter measurements	5.23E+07		4.93E+07		4.92E+07	
	Comparator	5.14E+07		4.99E+07		4.84E+07	

TABLE A2.—CALIPER DIAMETER MEASUREMENTS IN INCHES AND RESULTING CROSS SECTIONAL AREAS IN SQUARE METERS

Azimuthal location, deg.	Caliper Diameter measurements of TeraCopper wires W110114-0019-T01, in.								Caliper Diameter measurement of 20 AWG Cu magnet wire, Heavy Armored Poly-Thermaleze Mar. 74, Belden.			Mitutoyo measurement of 28 AWG Cu 4 m long wire		28 AWG nominal dia. 4 m long Nanocomp CNT yarn
	Short sample 19 Length location, mm				Long sample 19 Length location, mm				Length location, mm			Location		
	3	33	70	101	21	62	105	150	2	152	304	End	Other end	
0	0.033	0.0315	0.0325	0.0315	0.028	0.029	0.0315	0.0325	0.032	0.032	0.0315	0.0122	0.0124	----
45	0.031	0.031	0.0315	0.032	0.033	0.029	0.0295	0.0275	0.0315	0.0315	0.0315	0.01205	0.01235	----
90	0.0275	0.0275	0.03	0.0315	0.032	0.0315	0.0315	0.0315	0.032	0.0315	0.0315	0.0124	0.0128	----
135	0.031	0.0325	0.03	0.0295	0.033	0.032	0.032	0.0315	0.032	0.032	0.0315	0.0121	0.0124	----
Average diameter, in.	0.03084				0.03088				0.03171			0.01234		0.01260
Average area, m²	4.821E-07				4.830E-07				5.095E-07			7.713E-08		8.045E-08

TABLE A3.—WIRE DIAMETER MEASUREMENTS USING THE OPTICAL COMPARATOR

Azimuthal angle, degrees	0.0309 in. PIN gage, black	0.0309 in. PIN gage, silver	20 AWG Cu magnet wire, in.			TeraCopper W110114-0019-T01, long				TeraCopper W110114-0019-T01, short wire			
			End	Center	Other end	26 mm from end	68 mm from end	112 mm from end	157 mm from end	3 mm from end	33 mm from end	70 mm from end	101 mm from end
0	0.03083	0.03091	0.032	0.03205	0.03201	0.02842	0.02815	0.0281	0.02858	0.03217	0.03154	0.032	0.03055
45	0.03087	0.03083	0.0324	0.03205	0.03201	0.03087	0.02921	0.03281	0.03128	0.02831	0.02803	0.02891	0.03256
90	0.03102	0.03091	0.03177	0.03169	0.03221	0.03236	0.03158	0.0323	0.03091	0.03113	0.03126	0.03201	0.03176
135	0.03075	0.03091	0.03185	0.03158	0.03213	0.03161	0.03228	0.03207	0.03073	0.031	0.03209	0.03248	0.03209
Local average, in.	0.030868	0.030890	0.032005	0.031843	0.032090	0.030815	0.030305	0.031320	0.030375	0.030653	0.030730	0.031350	0.031740
Total average, in.				0.031979			0.030704					0.031118	
Standard dev. of ave. dia. along the length, in.				0.000103			0.000405961					0.000449428	
Average area, m²				5.18194E-07			4.77685E-07					4.90665E-07	

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