



Conductive Carbon Nanotube Inks for Use with Desktop Inkjet Printing Technology

A mixture of carbon nanotubes and silver or gold nanoparticles could be applied by inkjet printing to flexible substrates.

John F. Kennedy Space Center, Florida

Inkjet printing is a common commercial process. In addition to the familiar use in printing documents from computers, it is also used in some industrial applications. For example, wire manufacturers are required by law to print the wire type, gauge, and safety information on the exterior of each foot of manufactured wire, and this is typically done with inkjet or laser printers.

The goal of this work was the creation of conductive inks that can be applied to a wire or flexible substrates via inkjet printing methods. The use of inkjet printing technology to print conductive inks has been in testing for several years. While researchers have been able to get the printing system to mechanically work, the application of conductive inks on substrates has not consistently produced adequate low resistances in the kilohm range.

Conductive materials can be applied using a printer in single or multiple passes onto a substrate including textiles, polymer films, and paper. The conduc-

tive materials are composed of electrical conductors such as carbon nanotubes (including functionalized carbon nanotubes and metal-coated carbon nanotubes); graphene, a polycyclic aromatic hydrocarbon (e.g., pentacene and bis-peripentacene); metal nanoparticles; inherently conductive polymers (ICP); and combinations thereof. Once the conductive materials are applied, the materials are dried and sintered to form adherent conductive materials on the substrate. For certain formulations, increased conductivity can be achieved by printing on substrates supported by low levels of magnetic field alignment. The adherent conductive materials can be used in applications such as damage detection, dust particle removal, smart coating systems, and flexible electronic circuitry.

By applying alternating layers of different electrical conductors to form a layered composite material, a single homogeneous layer can be produced with improved electrical properties. It is be-

lieved that patterning alternate layers of different conductors may improve electrical pathways through alignment of the conductors and band gap optimization.

One feature of this innovation is that flexible conductive traces could be accomplished with a conductive ink having a surface resistivity of less than 10 ohms/square. Another result was that a composite material comprising a mixture of carbon nanotubes and metallic nanoparticles could be applied by inkjet printing to flexible substrates, and the resulting applied material was one to two orders of magnitude more conductive than a material made by printing inks containing carbon nanotubes alone.

This work was done by Luke Roberson, Martha Williams, LaNetra Tate, Craig Fortier, David Smith, and Kyle Davia of Kennedy Space Center; Tracy Gibson of ASRC Aerospace; and Sarah Snyder of Sierra Lobo. For more information, contact the KSC Technology Transfer Office at (321) 867-5033. KSC-13343

Enhanced Schapery Theory Software Development for Modeling Failure of Fiber-Reinforced Laminates

This tool captures the physics of the damage and failure mechanisms.

John H. Glenn Research Center, Cleveland, Ohio

Progressive damage and failure analysis (PDFA) tools are needed to predict the nonlinear response of advanced fiber-reinforced composite structures. Predictive tools should incorporate the underlying physics of the damage and failure mechanisms observed in the composite, and should utilize as few input parameters as possible.

The purpose of the Enhanced Schapery Theory (EST) was to create a PDFA tool that operates in conjunction with a commercially available finite element (FE) code (Abaqus). The tool cap-

tures the physics of the damage and failure mechanisms that result in the nonlinear behavior of the material, and the failure methodology employed yields numerical results that are relatively insensitive to changes in the FE mesh. The EST code is written in Fortran and compiled into a static library that is linked to Abaqus. A Fortran Abaqus UMAT material subroutine is used to facilitate the communication between Abaqus and EST.

A clear distinction between damage and failure is imposed. Damage mech-

anisms result in pre-peak nonlinearity in the stress strain curve. Four internal state variables (ISVs) are utilized to control the damage and failure degradation. All damage is said to result from matrix microdamage, and a single ISV marks the microdamage evolution as it is used to degrade the transverse and shear moduli of the lamina using a set of experimentally obtainable matrix microdamage functions. Three separate failure ISVs are used to incorporate failure due to fiber breakage, mode I matrix cracking, and mode

II matrix cracking. Failure initiation is determined using a failure criterion, and the evolution of these ISVs is controlled by a set of traction-separation laws. The traction separation laws are postulated such that the area under the curves is equal to the fracture toughness of the material associated with the corresponding failure mechanism. A characteristic finite element length is used to transform the traction-separation laws into stress-strain laws. The ISV

evolution equations are derived in a thermodynamically consistent manner by invoking the stationary principle on the total work of the system with respect to each ISV.

A novel feature is the inclusion of both pre-peak damage and appropriately scaled, post-peak strain softening failure. Also, the characteristic elements used in the failure degradation scheme are calculated using the element nodal coordinates, rather than

simply the square root of the area of the element.

This work was done by Evan J. Pineda of Glenn Research Center and Anthony M. Waas of the University of Michigan. Further information is contained in a TSP (see page 1).

Inquiries concerning rights for the commercial use of this invention should be addressed to NASA Glenn Research Center, Innovative Partnerships Office, Attn: Steven Fedor, Mail Stop 4-8, 21000 Brookpark Road, Cleveland, Ohio 44135. Refer to LEW-18954-1

High-Performance, Low-Temperature-Operating, Long-Lifetime Aerospace Lubricants

John H. Glenn Research Center, Cleveland, Ohio

The synthesis and characterization of six new ionic liquids, with fluoroether moieties on the imidazolium ring, each with vapor pressures shown to be $<10^{-7}$ Torr at 25 °C, have been demonstrated. Thermal stability of the ionic liquids up to 250 °C was demonstrated. The ionic liquids had no measurable influence upon viscosity upon addition to perfluoropolyether (PFPE) base fluids. They also had no measureable influence upon corrosion on steel substrates upon addition to base fluids. In general, 13 to 34% lower COFs (coefficients of friction), and 30 to 80% higher OK load of base

fluids upon addition of the ionic liquids was shown.

The compound consists of a 1,3-disubstituted imidazolium cation. The substituents comprise perfluoroether groups. A bis(trifluoromethanesulfonyl)imide anion counterbalances the charge. The fluorinated groups are intended to enhance dispersion of the ionic liquid in the PFPE base fluid. The presence of weak Van der Waals forces associated with fluorine atoms will limit interaction of the substituents on adjacent ions. The longer interionic distances will reduce the heat of melting

and viscosity, and will increase dispersion capabilities.

This work was done by Bryan Bergeron, David Skyler, Kyle Roberts, and Amy Stevens of Physical Sciences, Inc. for Glenn Research Center. Further information is contained in a TSP (see page 1).

Inquiries concerning rights for the commercial use of this invention should be addressed to NASA Glenn Research Center, Innovative Partnerships Office, Attn: Steven Fedor, Mail Stop 4-8, 21000 Brookpark Road, Cleveland, Ohio 44135. Refer to LEW-19039-1.

Carbon Nanotube Microarrays Grown on Nanoflake Substrates

This process creates materials comprised predominantly of single-walled carbon nanotubes.

Lyndon B. Johnson Space Center, Houston, Texas

This innovation consists of a new composition of matter where single-walled carbon nanotubes (SWNTs) are grown in aligned arrays from nanostructured flakes that are coated in Fe catalyst. This method of growth of aligned SWNTs, which can yield well over 400 percent SWNT mass per unit substrate mass, exceeds current yields for entangled SWNT growth. In addition, processing can be performed with minimal wet etching treatments, leaving aligned SWNTs with superior properties over those that exist in entangled mats.

The alignment of the nanotubes is similar to that achieved in vertically aligned nanotubes, which are called “carpets.” Because these flakes are

grown in a state where they are airborne in a reactor, these flakes, after growing SWNTs, are termed “flying carpets.”

These flakes are created in a roll-to-roll evaporator system, where three subsequent evaporations are performed on a 100-ft (≈ 30 -m) roll of Mylar. The first layer is composed of a water-soluble “release layer,” which can be a material such as NaCl. After depositing NaCl, the second layer involves 40 nm of supporting layer material — either Al_2O_3 or MgO. The thickness of the layer can be tuned to synthesize flakes that are larger or smaller than those obtained with a 40-nm deposition.

Finally, the third layer consists of a thin Fe catalyst layer with a thickness of

0.5 nm. The thickness of this layer ultimately determines the diameter of SWNT growth, and a layer that is too thick will result in the growth of multi-walled carbon nanotubes instead of single-wall nanotubes. However, between a thickness of 0.5 nm to 1 nm, single-walled carbon nanotubes are known to be the primary constituent. After this three-layer deposition process, the Mylar is rolled through a bath of water, which allows catalyst-coated flakes to detach from the Mylar. The flakes are then collected and dried. The method described here for making such flakes is analogous to that which is used to make birefringent ink that is coated on U.S. currency.