Self-Assembled Nanocomposite Combines Electrical Conductivity and Mechanical Flexibility

A novel nanocomposite material that combines the electrical conductivity of metals with the low elastic modulus of elastomers, called Metal Rubber™, has been developed by NanoSonic Inc. The material is a multilayered nanocomposite made by electrostatic self-assembly (ESA) and consists of polymers and metal nanoclusters in which multiple nanocluster layers are deposited on a charged substrate. It may be formed as a conformal coating on a substrate surface or as free-standing, mechanically robust sheet material. Similar to other composite materials, its macroscopic properties are determined by the individual material constituents, their relative mixture percentages, and the way they are combined during production.

In the basic ESA process for the self-assembly of polymer molecules a substrate surface is typically cleaned and prepared so the outermost surface layer has a net negative charge. The resulting negatively charged substrate is then dipped into an aqueous solution containing water-soluble cation polymer molecules that have positively charged functional groups fixed to the polymer backbone. Because the polymer chain is flexible, it is free to orient with respect to the underlying substrate so that a relatively low-energy configuration can be achieved.

As a result, some of the positively charged functional groups along the polymer chain experience attractive ionic forces toward the negative substrate, and the polymer chain is bent in response to those forces. The net negative charge on the substrate is masked from other positive groups along the polymer chain. Those groups feel a net repulsive force due to the fixed positive functional groups at the substrate surface, so they move away from that surface to form a net positive charge distribution on the surface of the substrate. Since the total polymer layer is neutral, negative charges with relatively loose binding to the polymer network pair up with positive ions. Subsequent polyanion and polycation monolayers are then added to produce the multilayer structure. The properties of the multilayer thin films fabricated by this method are determined by both the properties of the molecules in each monolayer and the physical ordering of the multiple monolayers through the composite multilayer structure.

This method can be extended to form thicker materials simply by continuing the described process. Materials as thick as 1 cm have been formed, consisting of as many as 1000 layers. The materials can be removed from the substrate on which they are formed by depositing a chemical release layer prior to the desired molecular layers, then chemically removing this layer to free the material once deposition is completed. For example, gold nanoclusters and polymers have been used to form millimeter-thick coatings on substrates treated with such release layers. An example of such a free-standing, mechanically robust, and electrically conducting material is shown in Figure 1. The example is a piece of gold nanocluster/polymer Metal Rubber in which the concentration of gold is low enough that the material is semitransparent.

Representative properties obtained for these materials are a Young's modulus from 1 MPa to 100 MPa and a maximum electrical conductivity on the order of 10^6 Ω^{-1} m^{-1}. These values may be varied through control of the precursor molecules used to form the initial film on the substrate surface. The properties of Metal Rubber can be achieved by modifying the volume percentages of the metal nanoclusters and polymers incorporated during fabrication. For example, near the electrical percolation threshold, a simple model of the behavior of the material is that the clusters are numerous enough and close enough together within the polymer matrix to allow efficient electron transport. If such a material is mechanically elongated, the physical separation between the particles increases in the direction of the tensile strain, so the material locally is effectively shifted downward on the percolation curve and the electrical conductivity decreases. This allows Metal Rubber to be used as a low-modulus strain sensor capable of measuring large strains of up to several hundred percent. However, if the percentage of conducting species is initially above the percolation threshold, the decrease in conductivity caused by elongation is significantly lower.

Technology Advances provides up-to-date reports of materials developments that show potential to bridge the gap between research innovation and application of advanced materials technologies. If you encounter or are involved with materials research that shows potential for commercialization and would like to present these developments, contact Renée G. Ford, Renford Communications, renford@comcast.net.

Figure 1. Metal Rubber material.

The mechanical properties of the material are primarily determined by the polymer, since the volume percentage of the conductive nanoclusters is very small, typically on the order of 1%. Failure strains of several hundred percent, and the ability to withstand thousands of cycles of strains of tens of percent, have been observed.

The optical properties of Metal Rubber can also be controlled in combination with modulus and conductivity. Due to the relatively low volume percentage of the conducting nanoclusters, the nanocomposites have good optical transmission in the visible portion of the spectrum. This is of potential interest for a wide range of mechanically flexible optical and optoelectronic devices that require both good conductivity and optical transmission.

Due to its multifunctional properties, the potential applications for this nanocomposite material include flexible conformal electromagnetic shielding and packaging; low-modulus conducting electrodes for actuators and sensors that undergo repetitive large physical displacements; sensor elements for the measurement of large strains; and flexible optical coatings, electrodes, and claddings for optical and optoelectronic materials and devices.

Opportunities

NanoSonic is seeking collaboration with end users for cooperative development. Metal Rubber is available for licensing.

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Integrated Passive–Active "SMART Layer" System Monitors Structural Defects

Fiber-reinforced composite materials are widely used in aerospace, automotive, shipbuilding, and other major construction industries because of their high strength and high stiffness-to-weight ratios. Monitoring the integrity of in-service composite structures is of particular concern to manufacturers as well as to maintenance personnel in order to improve safety and reliability significantly. Structural health monitoring (SHM) is a method of determining the integrity of structures. It involves the use of multidisciplinary fields including sensors, materials, signal processing, system integration, and signal interpretation and is increasingly being explored by the composites industry as a promising method to improve the safety and reliability of structures and reducing their operation costs. Acellent Technologies Inc. is developing an integrated passive–active SHM system for monitoring the integrity of composite material structures based on its patented SMART Layer® technology—a built-in inspection system that uses an array of sensors.

The integrated passive–active SHM system consists of three components: (1) the SMART Layer system, (2) the SMART Suitcase™, and (3) ACESS™ diagnostic software, integrated together to perform *in situ* monitoring, data collection, signal processing, real-time data interpretation, and information management.

The SMART Layer is a thin dielectric film with an embedded network of piezoelectric transducers that perform dual functions as sensors and actuators. It has the ability to provide wide structural coverage for gathering data by means of a network of transducers embedded on a layer, thus eliminating the need for each sensor to be installed individually. During fabrication, the layer can either be surface-mounted on existing structures or integrated into composite structures, thereby providing a built-in nondestructive assessment of the internal and external states of the structure.

The SMART Suitcase is a portable, powerful signal-generation and data-acquisition instrument. It can generate a specific waveform for structural diagnostics—to collect sensor data at high sampling rates and resolutions—and it exhibits multichannel capability to accommodate a network of sensors.

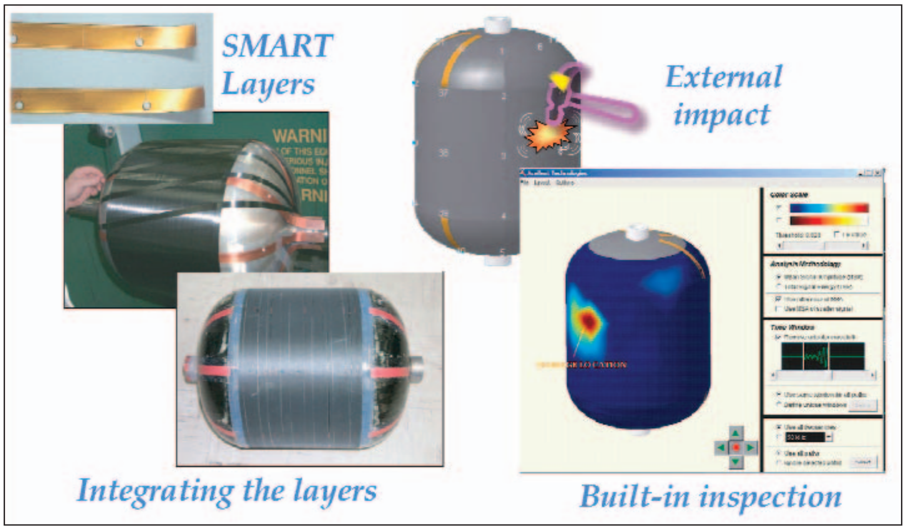

Figure 1. Acellent's integrated structural health monitoring system, consisting of the SMART Layer® sensor network, SMART Suitcase™ diagnostic hardware, and ACESS™ diagnostic software. SMART Layers are designed to be embedded in or surface-mounted on a structure. The sensor network, together with the hardware and software, provides real-time information on internal and external damage occurring in metal and composite structures. The figure shows SMART Layers being embedded into filament wound composite material structures. Upon cure, the integrated sensors can be used for built-in damage detection in the filament wound composite structures. The inset within the section on "Built-in inspection" shows controls for color scale, analysis methodology, time window, and frequencies.

ACESS diagnostic software is used to generate selected actuator signals and assign the appropriate sensors to listen for and record the response. The software links each sensor with its neighbors to form a network covering the structure.

The integrated passive–active SHM system is shown in Figure 1. It utilizes spatially distributed sensors and actuators to detect external impacts on a structure and to monitor structural changes due to the impacts. A sensor network integrated with the structure is used passively to detect and locate impacts on it. Once an impact has been detected, actuators are used to actively excite and interrogate the structure at the site and assess structural changes caused by the impact. The integrated system incorporates the advantages of both a purely passive system and an active one. Depending on application requirements, the passive and active modes can be used separately.

SMART Layer technology is capable of networking with any type of sensor, thereby enhancing its monitoring capabilities and eliminating the need to place each type of sensor individually on the structure. Its major features include actuating and sensing capabilities, a built-in sensor network for area sensing, signal consistency and sensor reliability, simple installation, and module design for application customization. The structural diagnostic system permits quantitative characterization and event determination for structures in hostile service environments.

The system can be used for:

- monitoring and estimating a structure's condition during its service life and usage;
- detecting and assessing damage, monitoring crack growth, and analyzing debonding; and
- monitoring processes such as material curing and ensuring quality control for mass production.

Opportunities

Acellent is seeking partners for applying SMART Layer technology. The company is also interested in licensing its integrated passive–active SHM system.

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