From Inception to Insertion: Successful Products and Applications using Nickel Nanostrands

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Abstract

The increasing use of composites and plastics in demanding applications brings great advantages in physical and mechanical properties, but with compromises in electrical performance. Composite materials typically cannot provide adequate performance in applications where electrical conduction is required. These electrical properties are becoming increasingly critical due to an escalating reliance on digital communications and controls.

Nickel nanostrands are a unique nanomaterial that brings value to many applications through improved properties, or by enabling altogether new material systems. Nanostrands are a three dimensionally interconnected metal nanostructure, with outstanding performance characteristics for inserting conductivity and electromagnetic capabilities. The unique features of nanostrands are identified, discussed, and compared. Multiple case studies are presented to demonstrate successful commercial products that are based on nanostrand technologies, as well as several new products that are under development.

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1. Introduction

1.1 The Need for Conductive Polymers and Composites

Polymer and fiber reinforced composites play an increasingly common role in commercial, defense, and private sectors. As these materials become more common, a better understanding is gained of required performance characteristics. While polymeric systems are well suited for replacing metallic structures with respect to mechanical and processing properties, the electrical properties of polymeric systems are significantly different from metallic systems. This transition to polymeric structures and systems occurs concurrently with an increase in utilization and reliance on digital technologies. This transition to digital technology includes additional considerations in electromagnetic environments.

Metal structures present a naturally effective conducting material, as isotropic metals have free valence electrons. Composites are naturally not as well suited, consisting of dielectric fibers or moderately conducting fibers in an insulating matrix. Thus, the challenge is to find technologies to impart electrical conductivity into polymers and polymer composite systems hile preserving the desired intrinsic advantages (mechanical properties, weight, manufacturing, cost, etc). Electrically conductive polymer composites are desired in a large range of applications, including grounding, resistive heating, protection from electrostatic discharge (ESD), electromagnetic interference (EMI), and lightning strike effects (both direct and indirect). Traditional composites do not have sufficient conductivity, whereas electrically conductive composite enclosures can meet the needs of these applications while weighing only a third as much as their metallic counterparts. Likewise, electrically conductive coatings, adhesives, and sealants can solve a wide range of problems, as well as enable new uses of material classes

1.2 Nanotechnology: New Materials

Traditional solutions for conductivity have included metal filled polymers, intrinsically conductive polymers, meshes, foils, and embedded wires. Metal filled polymer solutions have been incorporated directly into structures and also applied in secondary operations. Conventional fillers materials, such as metal coated spheres or metal flakes, generally require a relatively high filler volume fraction for electrical percolation and conductivity.

The rapidly growing field of Nanotechnology has presented many novel materials that can be used more efficiently and with better performance. The ability to design and create at the nanoscale has afforded exciting new material concepts to help solve the electrical conductivity problem in composites. Specifically, newly available conductive nanoparticles have shown great advances over previously available conductive particles for increasing the conductivity of polymer composites.

These new nanomaterials demonstrate some fundamental differences from previously available conductive particles, primarily in geometry. There are many important factors in adding conductive particles to non-conductive matrixes. Particle geometry is of primary importance. While previous conductive additives (such as milled powders, coated spheres, platelets, etc.) have aspect ratios on the order of 1 to 10, newer nanoparticles (such as carbon nanofibers) have aspect ratios in the thousands. This fact, in combination with the nanoscale diameter of these particles, means that less material is required, both in terms of volume percent and weight percent, to achieve the same conductivity levels [1-4].

2. Nickel Nanostrands in Nanocomposites

A new class of conductive metal nanomaterial has shown highly improved geometric and material advantages. Nickel Nanostrands [5] are a relatively new material. They are a sub-micron diameter, high aspect ratio nano-structure. Nanostrands feature a (patented) three dimensionally interconnected structure that creates interconnecting loops and branches.

Nanostrands exhibit an interesting and unique dispersion in composites systems. They are manufactured as a continuously interconnected "cake" of nanostrand structures (Figure 1).

a) b)

Figure 1: a) Nanostrand as-manufactured "cake" can be cut into shapes, pressed into sheets, or reduced to a nanostructured powder, b) SEM of nickel nanostrands, 1000 X (20 µm scale bar).

This "cake" can be used as a pre-form, or reduced to a nanostructured aggregate powder form. The latter practice is most typical. The cake is subjected to a process which results in discrete nanostrand clusters, which likewise are composed of individual strands. These clusters will contain long nanostrands that interconnect and branch. Some of the branches will also interconnect, and some are open ended. An analogy is to imagine a pure nickel nanoscale "tumbleweed" with three dimensional interconnections. These dispersed nanostructures are the key to the performance of nanostrand polymer composites. These structures are seen in bulk in the optical micrograph shown in Figure 2. Additional images of the dispersed nanostructure, including in cured polymers, are shown in Figure 3.

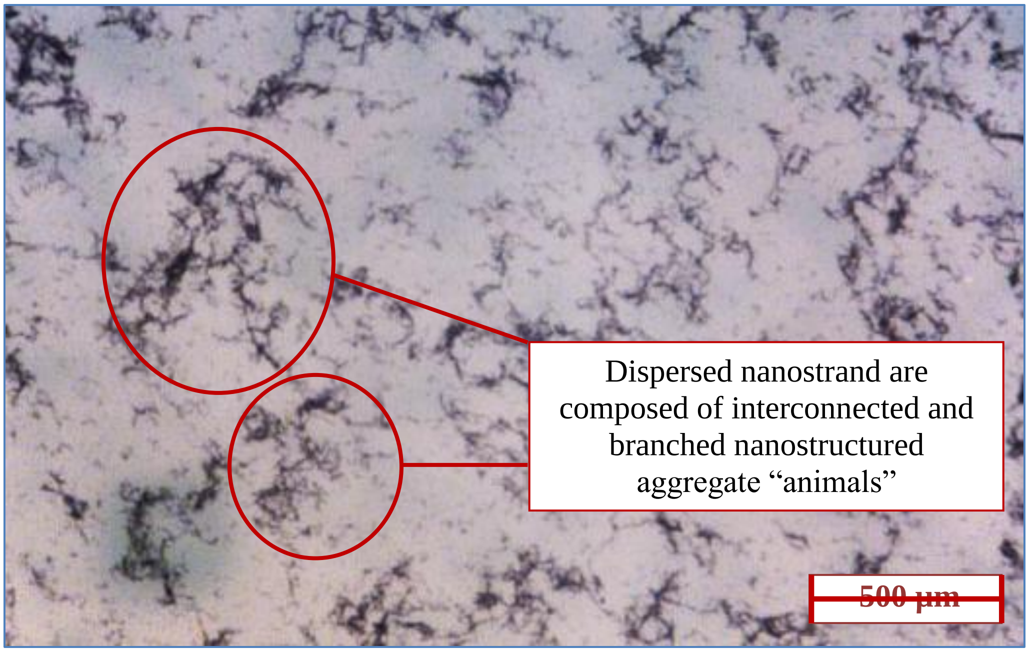
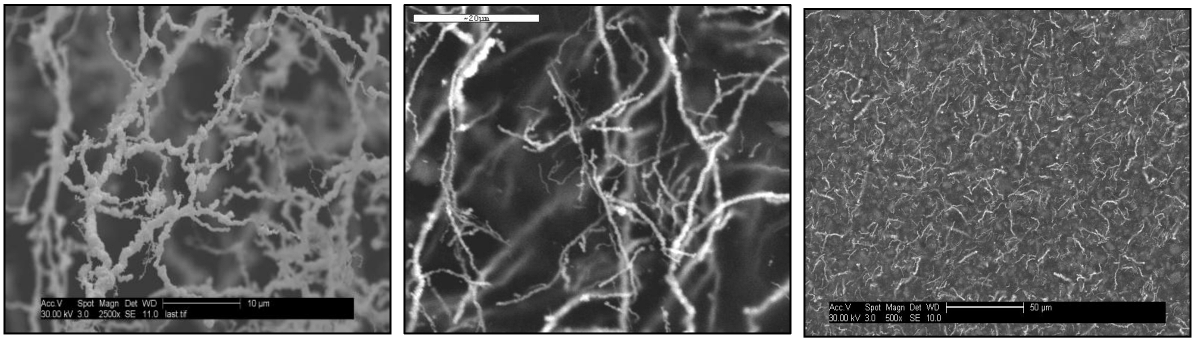

Dispersed nanostrand are composed of interconnected and branched nanostructured aggregate “animals”

Figure 2: Optical micrograph of low volume fraction dispersion of nickel nanostrands, identifying nanostrand animals



a)

b)

c)

Figure 3: Nickel nanostrands a) as manufactured, 2500 X (10 µm scale bar)
b) 10 vol% in thermoplastic polyurethane, 2500 X (10 µm scale bar)
c) 5 vol% in epoxy, 500 X (50 µm scale bar)

There are unique properties of nanostrands that are well suited to conductivity in polymers, relative to other metal fillers or nanoparticles. The high aspect ratio of individual strands requires fewer particles for effective volumetric percolative properties. The looped and branched nature of the nanostrand structure allows for a high number of three dimensional interconnects, and therefore higher conductivity. The branches of a nanostrand establish radial interconnects and provide three-dimensional connection opportunities (for example, two parallel nanostrands do not need to intersect along their major axis, as they can connect with branches extending transverse from the major axis of each). The branches can also serve as a multiplicity of antennas.

Another key feature found in nanostrand geometry is that the three dimensional particle can be viewed as a "skeleton" rather than a "body." The void space of the nanostrand structure is thus filled with the matrix material, facilitating better bonding and preservation of material properties while providing a conductive skeleton structure. The effective diameter required for inter-cluster connection displaces much less than volume than would be required with solid fillers. Nanostrand mixtures percolate to higher conductivity levels than have been demonstrated with carbon nanomaterials [1, 2, 6-8]. A comparison percolation curve for nickel nanostrands and carbon nanofibers is shown in Figure 4.

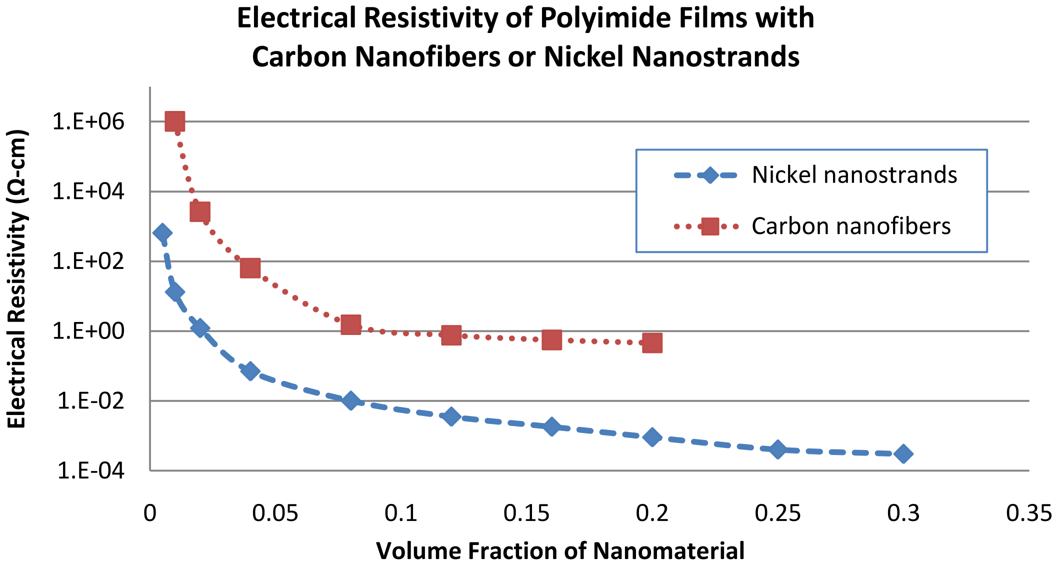


Figure 4: Percolative behaviors and resistivity of nickel nanostrands and carbon nanofibers in polyimide. Nanostrands percolate to resistivity's that are several orders of magnitude lower than carbon nanomaterials, at equal volume fractions.

Nickel is a true metal that exhibits high conductivity, and more importantly, ferromagnetic properties. The corrosion performance of nickel is good, and the raw material cost of nickel is relatively low. Nickel is also non-toxic and non-carcinogenic [9, 10].

Nanostrands are relatively weak compared to carbon nanofibers, and care must be taken when producing nanostrand mixtures to not over-mix the system and break the strands [5, 11]. Several methods have been developed (including patented technologies) using standard equipment to obtain repeatable insertion results of nanostrands into fluid systems. When nanostrands are purchased, a Nanostrand Users Guide is supplied to help formulators in achieving the best possible dispersion and conductivity results.

3. Case Studies: Commercial Applications for Nickel Nanostrand Materials Systems

Nanostrand-polymer systems have achieved conductivities in excess of 2000 Siemens/cm, and have been demonstrated in applications including electrostatic discharge [12], electromagnetic shielding [13-15], conductive adhesives [16-18], caulks and gaskets [19], paints [20, 21], lightning strike protection [13, 21-25], and even thermoplastic (e.g. PTFE, ABS, PEEK, and UHMWPE) parts [26].

The following case studies will present several platform based real world applications that are enabled by material systems based on nickel nanostrands. Both mature applications and newly developing applications will be presented. These case studies give proof to the realization of the promised benefits of nanomaterials, and also of the transition of these materials from the lab to commercial applications.

3.1 Conductive Resins for Prepregs and Composites

Nanostrands are dispersed in a solvated thermoset resin to produce an electrically conductive composite resin system. This resin is sold in solution as a ready-mixed prepregging kit. Resin can then be cast or sprayed onto fabric to make an electrically conductive prepreg. The prepreg is used to manufacture composite parts with electrical conductivity and electromagnetic shielding properties. Conductive thermoplastic resin systems are also under development.

As a specific example, Conductive Composites has partnered with Decavo (Hood River, OR) to develop, qualify, and provide an electrically conductive thermoset resin system, along with the necessary insertion and application technology. The resin system is required by specification in several fiber reinforced parts, and is supplied commercially with all necessary certifications.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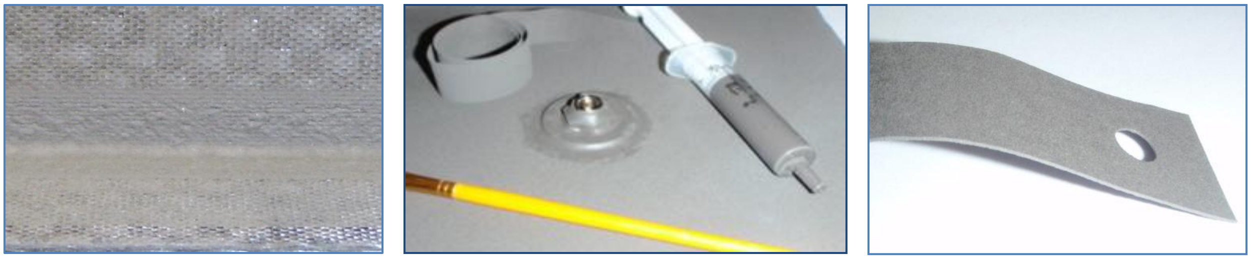
a) b) c) d)

Figure 5: Conventional insertion process for nickel nanostrands: a) nanomaterials b) commercial products (conductive resin systems) c) material systems (prepreg) d) finished parts with integrated conductive properties.

3.2 Elastomeric Sealants and Gaskets

Nanostrands are dispersed in a thermoplastic elastomer polymer system (SeamShield), which is viscosity corrected to function as a spray coating (low viscosity), a caulk or sealant (high viscosity), or a gasket (no viscosity correction). This Nanostrand Elastomer system has excellent properties, with an electrical conductivity of 0.001 ohm-cm in a nickel based system with a filler weight fraction below 50%.



a) b) c)

Figure 6: Nanostrand elastomer applications: a) Caulked carbon fiber joint,
b) caulked cable connector pass-through, c) solid strip of nanostrand elastomer gasket

3.3 Electrically Conductive Structural Adhesives

The advantageous percolative properties of nanostrands at low volume fraction enable the development of materials systems with properties that were previously not attainable. A perfect example of this is a structural conductive adhesive [18]. Structural adhesives are ubiquitous in the joining of structures, however, adhesives generally have insulating electrical properties. Current conductive adhesives (such as silver filled epoxies) have good electrical properties, but with very poor mechanical properties. Ground straps or conductive paste “bridges” are frequently used to bring joined panels into electrical contact. These methods add weight, an additional processing step, and an additional variable in the functionality of a system. An ideal solution is to have an adhesive that provides the required structural and electrical properties in a single system.

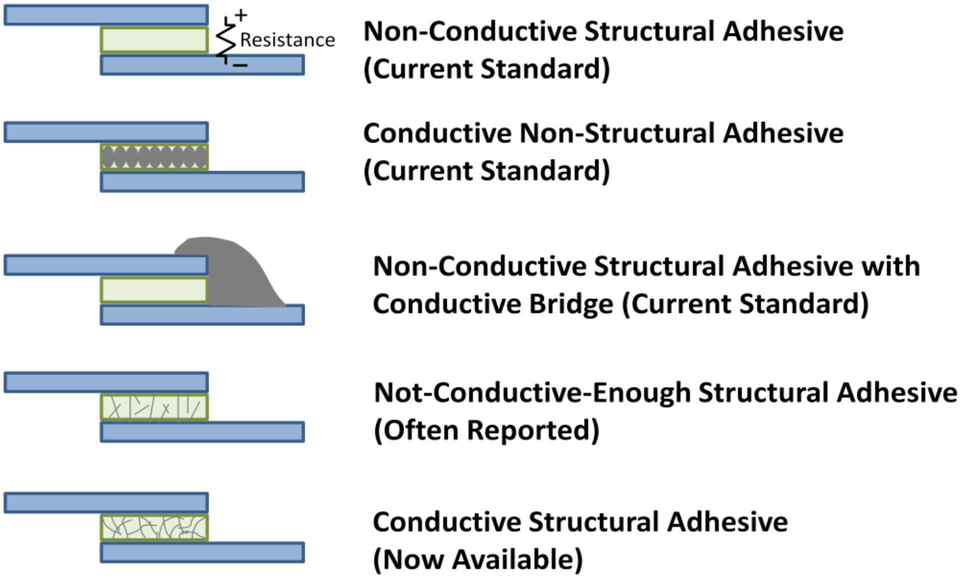


Figure 7: Approaches to Conductivity in Adhesive Joints

In partnership with Luna Innovations Incorporated (Roanoke, VA), a commercially-available conductive structural adhesive has been developed. This nanostrand adhesive bridges the gap between current market options for conductive adhesive and structural adhesives by providing both properties (see Figure 8 and Figure 9), with a lap shear strength similar to standard adhesives (27.6 MPa) and a resistivity of 0.1 to 10 ohm-cm (depending on loading and bond architecture). Product data sheets are available from Luna Innovations.

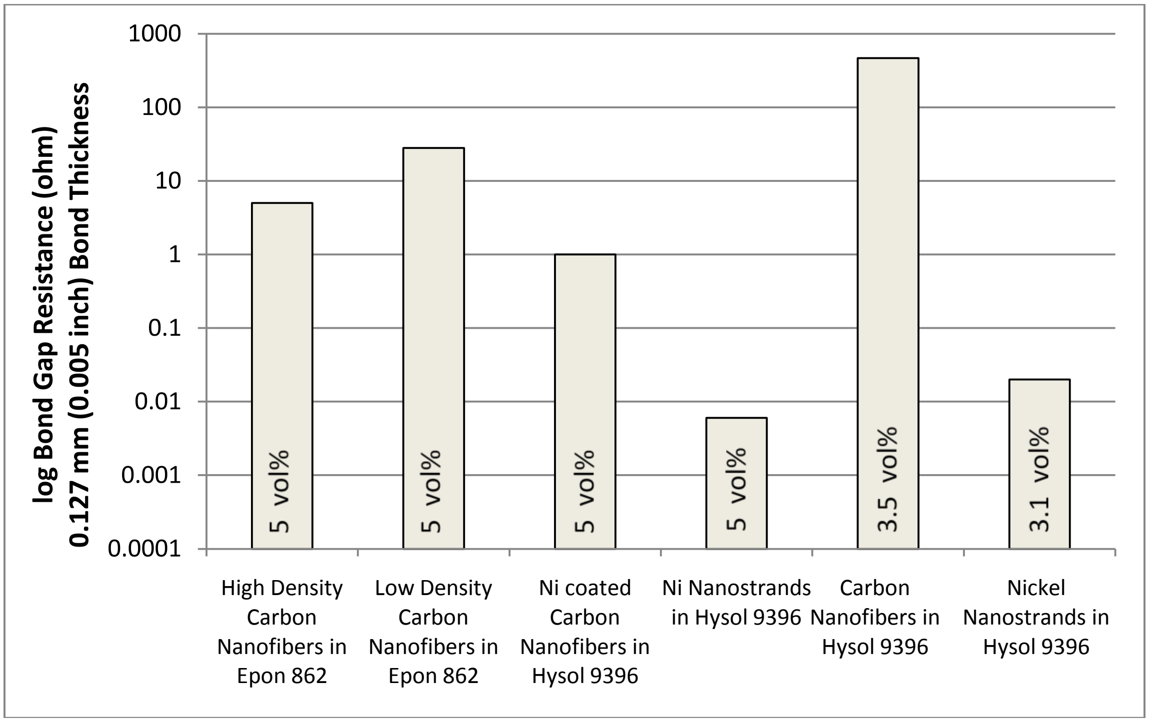


Figure 8: Reported bond gap resistance of carbon nanofibers and nickel nanostrands in selected structural adhesives.

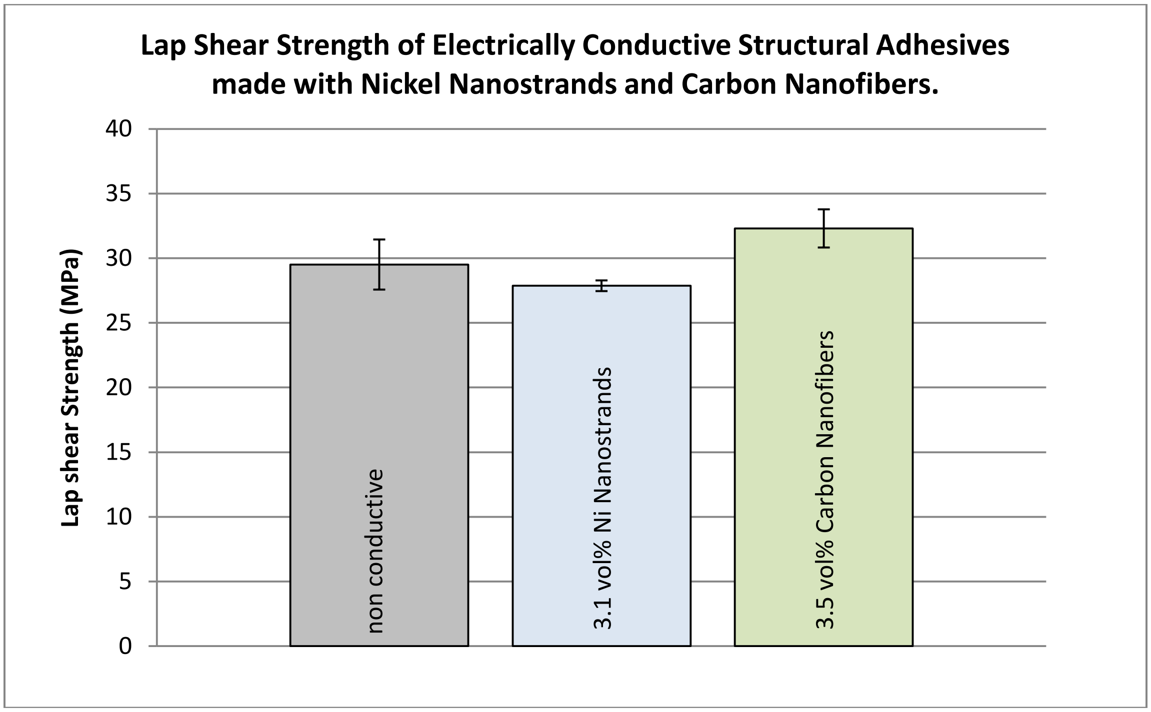


Figure 9: Lap shear strength of electrically conductive structural adhesives made with nickel nanostrands and carbon nanofibers.

3.4 Flexible Circuits

In partnership with the University of Utah, conductive rubbers have been developed to create elastomer circuits that retain electrical functionality when strained as high as 30%. Several polymeric systems, fabrication techniques, and nanostrand loadings were tested as part of a joint developmental effort, resulting in the production of a high-strain tolerant nanostrand material system for conductive circuit elements.

These conductive elastomers are used to realize circuit capabilities in applications where high strain conditions prohibit metals, and conductivity requirements prohibit traditional elastomer systems. The piezoresistive behavior of the nanostrand elastomer allows a circuit that remains conductive in a stretched state.

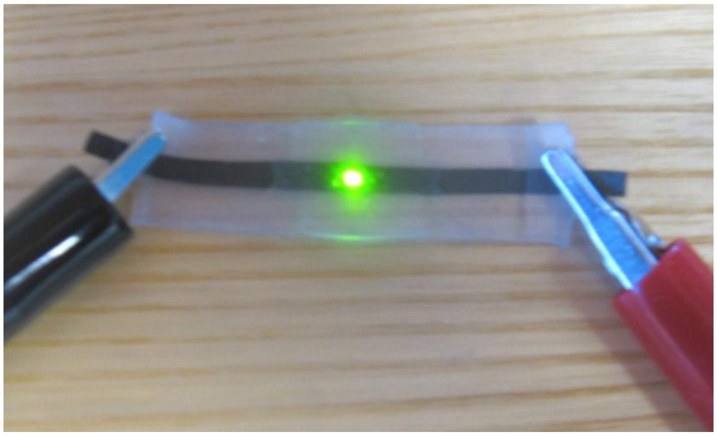


Figure 10: Embedded LED in a representative conductive nanostrand elastomer circuit

3.5 Embedded Sensors

In partnership with Brigham Young University, piezoresistive embedded sensors have been developed for *in-situ* strain monitoring of composite and polymer structures. Nanostrands present unique properties when used as a sensor [27, 28]. The strain response of nanostrand-polymer sensors can be utilized as a stand-alone sensor, an attached sensor, or as an embedded sensor.

In this case, nanostrands are used to create an embedded sensor in a fiber reinforced structure. These embedded sensors are an element that is integrated into the part during the manufacturing process. A nanostrand-polymer sensor circuit is cured directly into a prosthetic foot, and this sensor is then monitored for strain response during each mechanical loading cycle of the device, along with cumulative strain during the life of the device. The sensor can then indicate, with real time *in-situ* accuracy, the strain and fatigue conditions of the prosthetic.

Figure 11: Prosthetic foot with nanostrand-polymer strain sensor integrated directly into the structure.

3.6 Hybrid Systems

Nanostrands can be combined with other conductive materials to create hybrid systems that can benefit from the features of each constituent. For example, chopped nickel coated carbon fibers are used in many plastic systems to impart electrical conductivity. By using a combination of nanostrands and chopped fibers, the conductivity of the system is increased significantly while percolating electrically at a lower volume fraction. Thus, the additional conductivity performance of nanostrands is seen in the system, while still preserving much of the cost and weight advantages of chopped fibers.

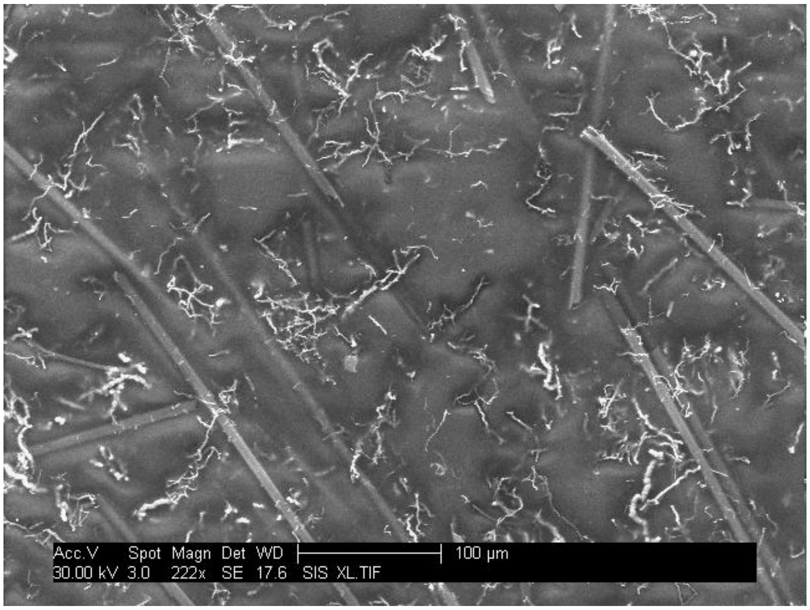


Figure 12: Hybrid mixture of nanostrands and chopped nickel coated carbon fibers. 2.5 volume percent of each, 5 volume percent total. Notice the complementary characteristic dimensions.

4. Conclusions

From inception to insertion, nanostrands continue to transition from the lab to real world applications. The performance benefits of nanomaterials are now being realized in successful commercially available products. New applications continue to be developed that benefit from or are enabled by the properties of nanostrands. Growth in demand for nanostrand materials will lead to even further cross-market utilization and continued improvements in material system performance and costs.

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