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Piezoresistive in-situ strain sensing of composite laminate structures

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A B S T R A C T

Various methods have been developed to monitor the health and strain state of carbon fiber reinforced polymers, each with a unique set of pros and cons. This research assesses the use of piezoresistive sensors for in situ strain measurement of carbon fiber and other composite structures in multidirectional laminates. The piezoresistive sensor material and the embedded circuitry are both evaluated. For the piezoresistive sensor, a conductive nickel nanocomposite sensor is compared with the piezoresistivity of the carbon fiber itself. For the circuit, the use of carbon fibers already present in the structure is compared with the use of nickel coated carbon fiber. Successful localized strain sensing is demonstrated for several sensor and circuitry configurations. Numerous engineering applications are possible in the ever-growing field of carbon-composites.

1. Introduction

Carbon fiber reinforced polymers (CFRP) possess a unique set of material properties that include high strength-to-weight ratio, low thermal expansion, and good fatigue characteristics; these benefits have led to rapid expansion in numerous areas of engineering [1–3]. Given the various loading conditions and environments that this relatively new material has to endure, there is a pressing need for a wide range of structural health and condition monitoring solutions. A monitoring solution that includes instantaneous strain sensing could provide useful feedback for control, actuation and data logging functions.

This paper discusses the development of piezoresistive sensing solutions for carbon fiber structures. Of particular interest is the embedded circuitry that enables the sensing of local strain in a component via connection to an external resistance meter. The two in-situ piezoresistive sensors that are evaluated are 1. embedded nickel nanostrand (NiN) nanocomposites and 2. neat prepreg carbon fiber. For the connecting circuitry, nickel coated carbon fibers and carbon fiber prepreg alone are compared as pseudo-wires to the piezoresistive sensor; the probing configuration of the external meter is also considered. Envisaged applications include strain and health monitoring of structural members, as well as the sensing of deflection in compliant components such as sports equipment and actuation devices. For control and data logging purposes. Actual engineering components might include bridge decks, composite beams, wind turbine blades, golf clubs, compliant mechanisms, etc. The reported examples of a tensile specimen, a beam under bending, and a carbon-fiber pressure vessel, illustrate uses of the methodology that could be adapted for various engineering applications.

1.1. Current strain sensing methods

Various methods exist for measuring strain in carbon fiber structures. Fiber Bragg gratings, using embedded fiber optics measure strain [4,5], and other exotic and novel methods (e.g. [6–8]) are making tremendous progress towards providing a suite of solutions that will no longer be confined to expensive laboratory situations.

More traditional methods include strain gauges composed of thin metal films [9]. The advantages of these types of gauges are that they are fairly simple to install, low cost, and have proved to be successful through years of use in industry. However, metal foils also have a very limited strain range, and because these gauges are adhered to the surface they are susceptible to damage. Furthermore, wires must be routed across or though the structure to carry the required signal to the monitoring unit.

Carbon fiber is itself piezoresistive by nature, and can thus act as a strain gauge [10–12]. However, transverse plies in a multidirectional laminate largely short circuit the piezoresistive response of the carbon fiber structure [13]. The issue of routing circuitry to the point of interest must also be considered for this approach. Carbon nanotubes [14,15], carbon black [16], and nickel nanostrands [17]. This paper will focus on nickel nanostrand composites due

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to their extremely large piezoresistive effect. Johnson et al. discovered that directly embedding a nickel nanostrand patch into unidirectional carbon fiber laminates yielded a significant piezoresistive response [18,19]. However, when the same method was applied to multidirectional laminates the signal quickly short-circuited and no piezoresistive effect was found. To measure piezoresistivity in multidirectional CFRP layups, a nickel nanostrand nanocomposite was insulated in fiberglass to resolve the short-circuiting issue, and embedded between the layers of carbon fiber. This method not only proved successful for measuring strain but also for detecting damage to the structure. However, due to the large stress concentrations induced by the embedded insulated patch, the strength of the composites was severely compromised.

The current paper will evaluate methods to measure strain in multidirectional carbon fiber laminates without significantly altering the strength of the carbon fiber structure. Piezoresistive sensing material will compose of either the carbon fiber structure itself, or local regions of nano-composite with nickel nanostrands added to the matrix. The signal path to the monitoring system will be generated using only the carbon fiber or using embedded nickel coated carbon fibers (NCCF). These coated fibers are at least three times more conductive than bare carbon fiber [20] thus reducing the amount of noise in the piezoresistive signal. The optimized configuration of probes for detecting the composite strain will be evaluated, and the resultant methodology will be tested in an engineering situation: a cylindrical carbon fiber pressure vessel.

2. Materials and methods

2.1. Materials

Nickel nanostrands (NiNs) display a high strand aspect ratio and a bifurcated structure that allows conductivity of a nanocomposite to be obtained at small volume fractions of nanostrands [21]. When combined with a polymer matrix they form a piezo-resistive material that has been used as the basis for strain sensors [22].

The piezoresistivity of such nanocomposites has been most successfully modeled using percolation theory and a quantum tunneling mechanism [23,24]. With a sufficiently large volume fraction of conductive filler material nanojunctions will form between filler particles in which electrons can tunnel through the insulating barrier. Once this occurs an electrical network is created through the nanocomposite and it becomes conductive. The resistivity of a nanojunction can be calculated using Eq. (1):

$$\rho = \frac{h^2}{e^2\sqrt{2m\lambda}} \exp\left(\frac{4\pi\sqrt{2m\lambda}}{h}s\right) \tag{1}$$

where h is the Planck constant (J s), e is the electron charge (C), m is the electron mass (kg), λ is the tunneling barrier height (J), and s is the distance between particles (m) [17]. Thus the resistivity of a nanojunction is a function of the inter-particle distance, s. As a nanocomposite is strained s will change and a piezoresistive signal is obtained.

Another novel material, nickel coated carbon fiber (NCCF), is tested as the basis for the sensor circuitry in this paper. Carbon fiber receives a uniform coating of nickel through a chemical vapor deposition process. These coated fibers are much more conductive than bare carbon fiber and are often used to aid in electrical shielding in carbon fiber structures [25]. Both the nickel nanostrands and the nickel coated carbon fiber were produced and provided by Conductive Composites Company (Heber, Utah). The structure of these materials can be seen in the SEM images depicted in Fig. 1. Along with these novel materials, a traditional unidirectional carbon fiber prepreg is used as the structural material that is to be monitored: ZR6-P35, provided by Zoltek.

Components with various pre-preg layups were created to determine the capability and limitations of the embedded conductive materials for in situ strain sensing. For initial sensor evaluation, laminates were formed in configurations suitable for tensile testing. Each carbon fiber laminate was composed of layers of prepreg cut to 250 mm × 25 mm. Woven fiber glass tabs were adhered to the ends of the carbon fiber samples to insulate the sample from the metal grips of the tensile tester and ensure that these did not interfere with the signal.

Each sample consisted of a sensor patch location and a sensor patch material. The patch location refers to the area that strain is to be measured and the patch material was either prepreg embedded with NiNs or simply the carbon fiber prepreg itself. To limit variation and guarantee uniformity in the samples with embedded nanostrands, 0.02 g of nickel nanostrands were filtered through a 60 mesh screen (250 μm) before being placed in a patch area of 19 mm by 12 mm. For carbon fiber and NiN patches the [0] direction (prepreg oriented parallel to the applied strain) and [90] direction (prepreg oriented transverse to the applied strain) were evaluated as the sample was strained in the direction of its length.

As mentioned previously, the use of NCCF was assessed as a means of forming the sensor circuit. The alternative to NCCF was to allow the signal to carry along the carbon fibers in the prepreg itself. It was hypothesized that the NCCF would better control the signal flow and limit scatter and short-circuiting across the cross plies of prepreg. Thus nickel coated carbon fiber was embedded onto the surface of various samples and compared to control samples with no embedded materials. Fig. 2 is an example of a sample with embedded nanostrands and nickel coated carbon fiber. As can be seen in Fig. 2 a small gap was placed between NCCF bundles at the patch location. The gap in the NCCF was required to ensure the signal traveled through the carbon fiber or NiN patch at the patch location. Table 1 shows the various sample configurations tested. Also included in Table 1 are signal-to-noise ratio

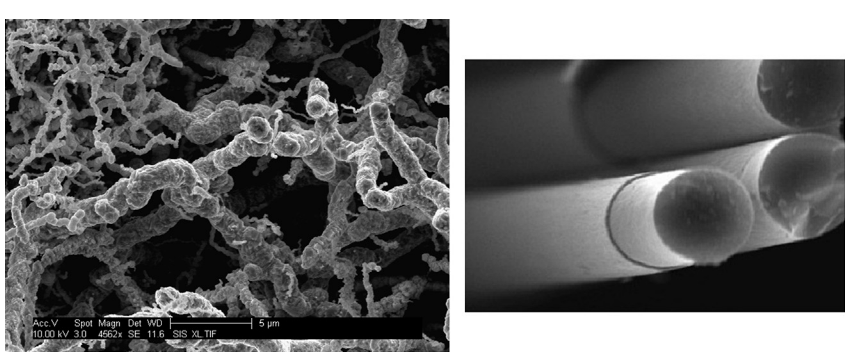

Fig. 1. SEM images (from left to right) of nickel nanostrands and nickel coated carbon fiber (NCCF used courtesy of Nathan Hansen, Conductive Composites Company).