A Flexible Strain Sensor Design based on Ny-6 Yarn Coated with Ag Nanoparticles for Real Time Strain Monitoring Application

Yumna Qureshi, Mostapha Tarfaoui, Khalil K Lafdi, Khalid Lafdi

HAL Id: hal-02461552

https://ensta-bretagne.hal.science/hal-02461552

Submitted on 30 Jan 2020

A FLEXIBLE STRAIN SENSOR DESIGN BASED ON NY-6 YARN COATED WITH AG NANOPARTICLES FOR REAL TIME STRAIN MONITORING APPLICATION

[1]YUMNA QURESHI, [2]MOSTAPHA TARFAOUI, [3]KHALIL K. LAFDI, [4]KHALID LAFDI

[1,2]ENSTA Bretagne, IRDL - FRE CNRS 3744, F-29200 Brest, France
[2,3,4]University of Dayton, Dayton, OH 45469-0168, United States
E-mail: [1]yumna.qureshi@Ensta-Bretagne.org, [2]mostapha.tarfaoui@ensta-bretagne.fr

Abstract- Composites show better performance than traditional materials however, they are inclined to damage formation, delamination, or fracture. So, it is necessary to detect damage or crack formation with in time in these materials to avoid any catastrophic incident. Therefore, numerous researchers have been developing in-situ sensors and monitoring systems for composite structures. The objective of this study is to create a micro scale, flexible strain sensor wire for real-time sensing applications. This strain sensor wire was developed by depositing conductive silver (Ag) nanoparticles on the surface of Ny-6 untwisted yarn using electroless plating process to achieve uniform conductive coating over each filament of the Ny-6 polymer. The electro-mechanical behavior of this Ny/Ag sensor wire was verified experimentally and gauge factor was found to be in range of 62-69. This flexible Ny/Ag sensor wire was then integrated with in a composite sample to validate the monitoring of deformation and detection of damage initiation. Experimental procedure was performed where the mechanical behavior of the composite sample was tested in a standard tensometer machine, while the electrical signal of the Ny/Ag sensor wire was recorded. The results showed that the electrical response of the sensor was correlated perfectly with the mechanical behavior of the specimen. This indicated that Ny/Ag strain sensor wire can be used for real-time damage detection and structural health monitoring (SHM) applications.

Keywords- Composites, Structural Health Monitoring, Conductive Ag-Metal Coating, Microscale Strain Sensor Wire, Electro-Mechanical Response

I. INTRODUCTION

Composites show better properties than any traditional material however, they are not exempt from damage initiation and propagation leading to ultimate fracture[1]. Therefore it is necessary to examine their behavior during working conditions to eliminate any chance of sudden failure. Structural health monitoring (SHM) is a renowned and widely spread procedure for sensingvarious types of damages in materials for example,corrosion, deformation, thermal degradation, delamination, intralaminar cracking, and fiber cracking to confirm safe and durable service life of the structures[2], [3].

Many research projects had been carried out over the past years to develop SHM sensors such as strain gauges, fiber optic sensors, piezoelectric sensors and microelectromechanical systems (MEMS). But they all had limitations such as difficult manufacturing, brittle in nature, and lots of instrumentation and data analysis[4], [5]. So, a new category of sensors, also known as smart textile or textile sensors or flexible sensors, became the focus of study. Flexible conductive wire sensors were considered to be very promising solution for SHM of composite materials. After integration, they acts as reinforcement and also have sensing response based on the working principle of traditional metal strain gauges[6], [7]. These smart textiles, fabrics and yarns were first developed by using conductive polymers for monitoring high strain applications but their instability when exposed to air and their low conductivity in comparison to nano particles limited their applications[6], [8].

Similarly, Coating or inserting conductive nano particles such as carbon nanotubes (CNTs), graphene and carbon black into the filaments were also used for real-time damage monitoring of composites with high sensitivity, flexibility and outstanding impact resistance [9], [10]. But they also had limitations such as sensitivity of CNTs was affected when inserted into the composite specimens because of tunneling effect and their porous network andgraphene had stability issue when exposed to air and is toxic in nature [11], [12]. Metal nano particles such as gold, nickel, aluminum, stainless steel, copper and silver were also used for in-situ SHM applications such as dynamic range testing, and temperature sensing applications [13]–[15].However, amongst all, silver (Ag) showed great potential as a coating materials on flexible polymeric substrate because of its excellent conductivity, competitive price, stability in air and other mechanical properties [16].Silver had already been used in anti-microbial activity andfor medical monitoringand showed better stability, responsivity, repeatability and low drift in electrical signal[17].
For example, conductive textiles with 0.8 Ω cm−1 were fabricated by coating nylon, polyester and cotton threads with Ag nano wires for a lightweight heating fabric with high flexibility [18]. But these nano wires were found to be environmental sensitive and great care had been taken during their manufacturing and fabrication process.

A Flexible Strain Sensor Design based on Ny-6 Yarn Coated with Ag Nanoparticles for Real Time Strain Monitoring Application

18

Although, silver metal coated fabric was studied numerous time for antibacterial and medical activities but its application regarding structural health monitoring purpose in composites is still under developed.

In this article, a flexible conductive strain sensor wire is developed using nylon untwisted yarn and depositing nanoscale silver metal coating on its surface for real-time sensing applications. The fabrication process was carried out using electroless plating process to ensure uniform, continuous coating with minimum possible thickness. As a second step, experimental test were performed to measure the electromechanical behavior of this sensor wire and examine its performance by calculating the gauge factor. Then, Ny/Ag sensor wire was integrated within the composite sample to determine the detection of damage initiation before the deformation of structure becomes fatal. The sample was tested in a standard tensile machine, while the electrical signal was recorded by the oscilloscope. The electrical response of the Ny/Ag sensor wire was correlated perfectly with the mechanical behavior of the composite.

II. DETAILS EXPERIMENTAL

2.1. Ny/Ag sensor fabrication

Ny/Ag sensor wire wasfabricatedby using untwisted nylon (Ny-6) yarn and depositing a silver (Ag) metal coating at nanoscale on the surface of its filaments using electroless plating process to overcome the low conductance issue of Ny-6 yarn without jeopardizing its structural integrity. Ny-6 untwisted yarn was cleaned with ethanol to remove any dust particles or surface impurities to ensure good adhesion for the nanoparticles of Ag metal. Then nylon was treated with silver nitrate (AgNO3) and sodium hydroxide (NaOH) at 130 °C for 2 hours and after that, followed by a reduction process in ammonia (NH3) environment for a period of 2 hours. The reduction process produced ethylene as a reducing agent which reduced the Ag(I) to Ag(0) ions and after post-treatment with ammonia, silver nanoparticles were deposited on the surface of Ny-6.

2.2. Experimental test for Ny/Ag sensor wires

Oscilloscope and Uniaxial tensile machine were used simultaneously to study the damage sensing performance of Ny/Ag sensor wire. Paper frame was used to provide support for the placement in tensile machine, Fig.1. However, the paper frame was cut from the sides before starting the test to avoid its effect on the behavior of Ny/Ag sensor wire during the test. In addition, probes were attached at the both ends of the sensor wire to provide better connection to the oscilloscope without any disturbance during the test, Fig. 2. The resistance of Ny/Ag sensor wire was measured using oscilloscope simultaneously with

mechanical response. Tensile test was performed at low strain rate i.e. 5mm/min. The stress-strain curve was obtained during the test along with the resistance profile. Three tests were conducted to see the reproducibility of the results.
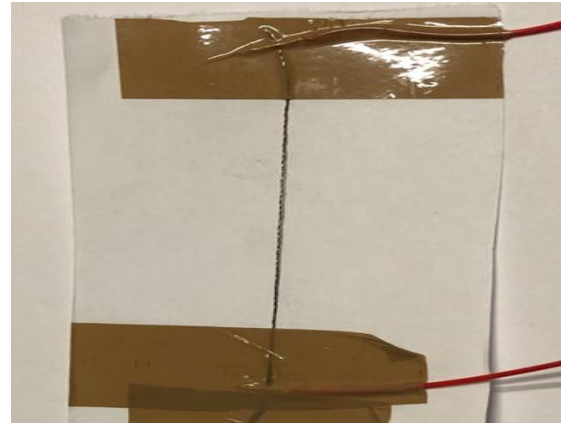

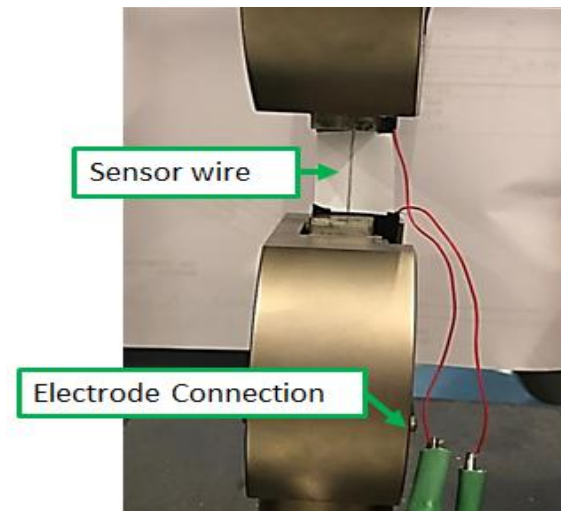**Fig.1. Ny/Ag sensor prepared for experimental procedure.**

Fig.2. Ny/Ag sensor placed inside the machine.

III. RESULTS AND DISCUSSION

3.1. Scanning Electron Microscopy (SEM) Characterization

The Ny/Ag sensor was characterized by the following dimensions length 50mm, diameter of yarn 225 μm and coating thickness was approximately 1-2 % of diameter of the individual filament i.e. 1-2 μm.Scanning electron microscopy (SEM) characterization revealed that untwisted Ny-6 yarn consisted of numerous filaments and all the filaments were uniformly coated, Fig. 3a. Ny-6 showed good adhesion bonding because of their surface roughness as these small cavities act as anchoring points for deposited metallic particles and thus show better adhesion as compared to polyester and polypropylene polymeric materials [60]. However after large magnification, SEM confirmed that the coating consisted of Ag nanoparticles bonded on the surface of nylon untwisted yarn and it also appeared that few

A Flexible Strain Sensor Design based on Ny-6 Yarn Coated with Ag Nanoparticles for Real Time Strain Monitoring Application

19

filaments hadnanoscale cracks or gaps in their coating, Fig. 3b. Regardless of this, the electrical current flow through the yarn was almost 100% because these minute imperfections of Ag coating were found in very few filaments in comparison to the whole untwisted yarn and their presence did not affected the overall path of current flow.

3.2. Electromechanical response of the Ny/Ag sensor wire

Many experimental challenges were encountered but three successful tensile tests were conducted to show the reproducibility of Ny/Ag sensor behavior. Sensitivity of the sensor wire was demonstrated by calculating the gauge factor (G.F), Fig. 4. Gauge factor was calculated by comparing the change in resistance of the sensor with respect to the applied strain, eq. (1).

$$G.F \times \varepsilon = \triangle R/R \qquad (1)$$

The gauge factor of this flexible strain sensor wire was found to be 62-69 under 0.5-0.8% strain. The results were very encouraging and the resistance change of this conductive yarn as a function of increasing load/strain seemed to be correlating very well.

3.3. Real-time SHM of Composite Structure

Standard compositesamples were prepared forthe testwith full integration of Ny/Ag sensor wires. Chopped glass fiber fabric was used as reinforcement and was cut into sections and placed in a molding frame. A Ny/Ag sensorwire was placed between the plies and then, mold was poured with the resin. After the mold was filled with resin, the sample was completely transparent and sensor wire was visible, Fig.5. Then, the specimen waskept at room temperature for 48 to cure.

The sample was tested in a standard tensile machine, while the electrical signal of the Ny/Ag strain sensor wirewas recorded by the oscilloscopesimultaneously. Moreover, probes were attached with the Ny/Ag sensor wire at both ends to provide better connection and signal, Figure 5.

The mechanical response of composite specimen in terms of Stress and electrical response of the sensor in terms of resistance were obtained and correlated perfectly. The resistance of Ny/Ag sensor wire was increased at the same time as the composite sample started to deformed. As the test progressed, the resistance of the Ny/Ag sensor wire increased more which indicated larger deformation of the composite sample and eventually went to infinity when sample was permanently damage, Figure 12. The sensor was detecting the deformation and damage formation in real-time. The results showed that theNy/Ag sensor was responding very well to the mechanical deformationof the composite sample.
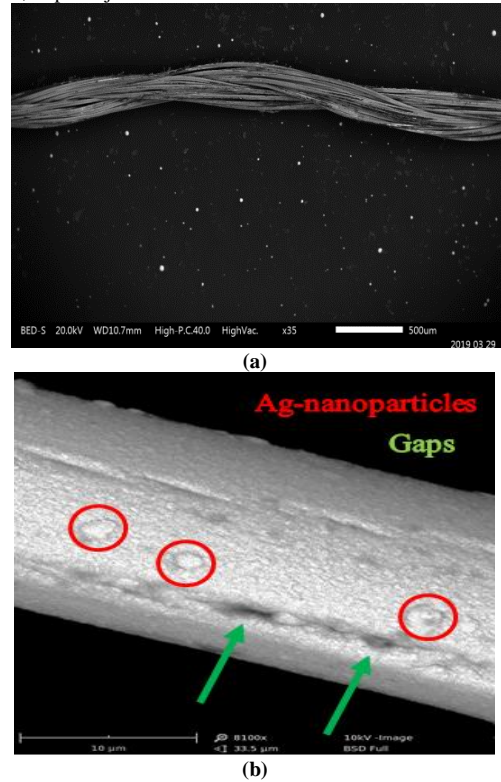

(a)

(b)

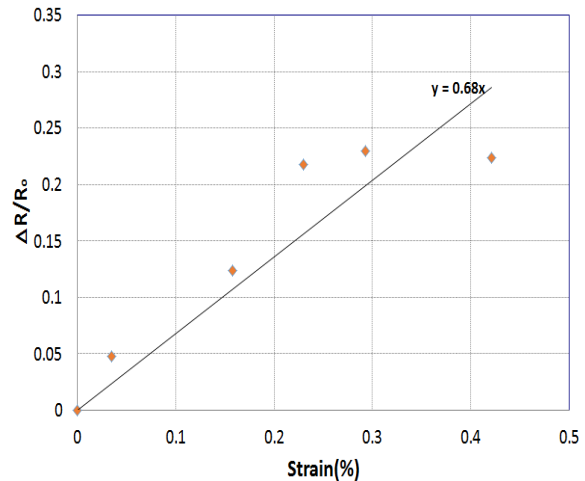**Fig.3. SEM Characterization of the Ny/Ag strain sensor wire.**

Fig.4. Example of experimental calculation of gauge factor of strain sensor wire.

Fig.5. Sensor wire integrated with in the composite specimen

A Flexible Strain Sensor Design based on Ny-6 Yarn Coated with Ag Nanoparticles for Real Time Strain Monitoring Application
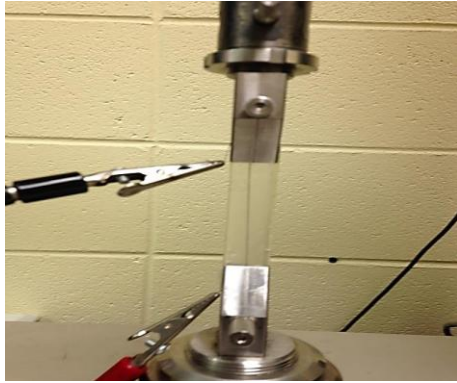
Fig.6. Composite sample placed in the machine with sensor attached to the oscilloscope
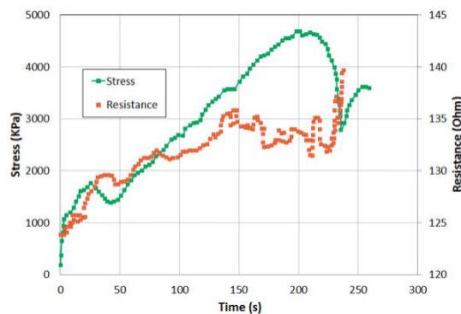

Fig.7. Real-time strain monitoring and dame detection application of Ny/Ag strain sensor wire.

IV. CONCLUSION

Anew flexible sensor design for strain monitoring and damage detection was fabricated, characterized and tested experimentally. The results were very encouraging and electromechanical response was reproducible. Next, the Ny/Ag sensor wire was used for real-time monitoring of composite specimen and good correlation between the electrical response of the sensor wire with the local stress-signal of the composite panel was found.Following were the main conclusions of this study:

• It validated the new concept of using flexible Ny/Ag strain sensor wire for real-time strain monitoring and damage detection

• In addition, it was also observed that the process of fabrication did not affect the structural integrity of the core material with 100% current flow even with minute defects in few filaments of the yarn which can be confirmed with high GF range of the sensor i.e. 62-69.

• These sensors can be use as threads/flexible wires in composite materials with minimal intrusive effect on the behavior of the structures.

REFERENCE

[1] M. Tarfaoui, A. El Moumen, and K. Lafdi., "Progressive damage modeling in carbon fibers/carbon nanotubes reinforced polymer composites.," Compos. Part B Eng., vol. 112, no. 185–195, 2017.

[2] M. Tarfaoui, A. El Moumen, and H. Ben Yahia., "Damage detection versus Heat dissipation in E-Glass/Epoxy laminated composites under dynamic compression at high strain rate.," Compos. Struct., vol. 186, pp. 50–61, 2018.

[3] J. Arbaoui, M. Tarfaoui, C. Bouery, and A. E. M. Alaoui., "Comparative study of mechanical properties and damage kinetics of two- and three-dimensional woven composites under high-strain rate dynamic compressive loading," Int. J. Damage Mech., vol. 25, no. 6, pp. 878–899.

[4] V. K. Varadan and V. Varadan., "Microsensors, microelectromechanical systems (mems), and electronics for smart structures and systems.," Smart Mater. Struct., vol. 9, no. 6, pp. 953–972, 2000.

[5] J.-B. Ihn and F.-K. Chang, "Pitch-catch active sensing methods in structural health monitoring for aircraft structures," Struct. Heal. Monit., vol. 7, no. 1, pp. 5–9, 2008.

[6] H. Cheng et al., "Textile electrodes woven by carbon nanotube–graphene hybrid fibers for flexible electrochemical capacitors," Nanoscale, vol. 5, no. 8, p. 3428, 2013.

[7] N. Trifigny, F. M. Kelly, C. Cochrane, F. Boussu, V. Koncar, and D. Soulat, "PEDOT: PSS-based piezo-resistive sensors applied to reinforcement glass fibres for in situ measurement during the composite material weaving process.," Sensors, vol. 13, no. 8, pp. 10749–10764, 2013.

[8] I. Jerkovic, V. Koncar, and A. Grancaric, "New textile sensors for in situ structural health monitoring of textile reinforced thermoplastic composites based on the conductive poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) polymer complex," Sensors, vol. 17, no. 10, 2017.

[9] S. Wang et al., "Smart wearable kevlar-based safeguarding electronic textile with excellent sensing performance.," Soft Matter., vol. 13, no. 13, pp. 2483–2491, 2017.

[10] G. Cai, M. Yang, Z. Xu, J. Liu, B. Tang, and X. Wang., "Flexible and wearable strain sensing fabrics," Chem. Eng. J., vol. 325, pp. 396–403, 2017.

[11] G. Wang et al., "Structure dependent properties of carbon nanomaterials enabled fiber sensors for in situ monitoring of composites.," Compos. Struct., vol. 195, p. 36–44., 2018.

[12] A. R. Murray et al., "Oxidative stress and inflammatory response in dermal toxicity of single-walled carbon nanotubes.," Toxicology., vol. 257, no. 3, pp. 161–171, 2009.

[13] D. Ryu, K. J. Loh, R. Ireland, M. Karimzada, F. Yaghmaie, and A. M. Gusman, "In situ reduction of gold nanoparticles in PDMS matrices and applications for large strain sensing. Smart Structures and Systems," vol. 8, no. 5, pp. 471–486, 2011.

[14] T. Kinkeldei, C. Denier, C. Zysset, N. Muenzenrieder, and G. Troester., "2D Thin Film Temperature Sensors Fabricated onto 3D Nylon Yarn Surface for Smart Textile Applications," Res. J. Text. Appar., vol. 17, no. 2, pp. 16–20, 2013.

[15] J. Xie, H. Long, and M. Miao, "High sensitivity knitted fabric strain sensors.," Smart Mater. Struct., vol. 25, no. 10, 2016.

[16] R. X. Wang, X. M. Tao, Y. Wang, G. F. Wang, and S. M. Shang., "Microstructures and electrical conductance of silver nanocrystalline thin films on flexible polymer substrates.," Surf. Coatings Technol., vol. 204, no. 8, pp. 1206–1210, 2010.

[17] O. Atalay, A. Tuncay, M. D. Husain, and W. R. Kennon, "Comparative study of the weft-knitted strain sensors," J. Ind. Text., vol. 46, no. 5, pp. 1212–1240, 2016.

[18] Y. Atwa, N. Maheshwari, and I. A. Goldthorpe, "Silver nanowire coated threads for electrically conductive textiles.," J. Mater. Chem. C, vol. 3, no. 16, pp. 3908–3912, 2015.

★★★

A Flexible Strain Sensor Design based on Ny-6 Yarn Coated with Ag Nanoparticles for Real Time Strain Monitoring Application

21