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Highly Stretchable Miniature Strain Sensor for Large Strain Measurement

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ABSTRACT: In this research, a new type of highly stretchable strain sensor was developed to measure large strains. The sensor was based on the piezo-resistive response of carbon nanotube (CNT)/polydimethylsiloxane (PDMS) composite thin films. The piezo-resistive response of CNT composite gives accurate strain measurement with high frequency response, while the ultra-soft PDMS matrix provides high flexibility and ductility for large strain measurement. Experimental results show that the CNT/PDMS sensor measures large strains (up to 8%) with an excellent linearity and a fast frequency response. The new miniature strain sensor also exhibits much higher sensitivities than the conventional foil strain gages, as its gauge factor is 500 times of that of the conventional foil strain gages .

Keywords: Large strain sensor, ultra stretchable, CNT/PDMS composite thin film, piezo-resistive response, frequency response.

Introduction

Strain, as one of the key mechanical parameters, needs to be precisely measured in engineering applications. Conventional foil strain gages that are based on the piezo-resistive effect of metals have been commonly used in both quasi-static and dynamic experiments to measure the specimen strain due to the high frequency and linearity response. However, the metal foil strain gages have a very limited measureable strain range, which limits the utilization of traditional sensors for large strain measurements. Digital image correlation (DIC) has been recently developed for the full-field strain measurement [1-3]. In this method, speckles are introduced on the surface of the specimen and a digital camera is used to capture the images of the speckles during the test. Strain can then be calculated by analyzing the movements of those speckles on the captured images. This non-contact method can measure relatively large strains. When DIC is applied for dynamic testing, it requires implementation of a high-speed camera with a high resolution to capture the dynamic images. Other challenges of the dynamic DIC technique are reliable patterning and lighting of the specimen. Some engineering circumstances where the camera and lighting are not easily installed also make the DIC not applicable. The resolution of dynamic DIC technique is limited by the frame rate of the camera and the total number of images that could be stored during a single test. Therefore, it is desirable to develop a new strain sensor with high flexibility and miniature size which can measure relatively large local deformation for an extensive range of engineering practice.

Recent studies in the field of stretchable electronics led to the development of stretchable strain sensors. Based on piezo-resistive response, Choong et al. [4] developed stretchable pressure sensors with conductive elastomeric composites. Canavese et al. [5] used piezo-resistive metal-polymer composites for the stretchable pressure sensor applications. Vatani et al. [6] developed a stretchable strain sensor [6]. In that research, carbon nanotube (CNT)/monofunctional acrylate monomers composite was encapsulated in stretchable Polyurethane (PU) rubber. The piezo-resistive property of the CNT composite yielded a linear response to strains up to 80%. However, as the sensing element (CNT composite) has to be encapsulated in the bulky PU substrate, it cannot accurately measure the strain on the surface that is in contact with the specimen. In addition, it has been challenging to bond the PU to a metallic specimen. To overcome the limitations of these current strain measurement techniques, we developed a nano-composite-based ultra flexible thin film strain sensor which can be strongly bonded to the surface of metallic specimens for large strain measurement.

Materials and Experiments Methods

Materials

The Polydimethylsiloxane (PDMS) and CNTs used in this study were Sylgard 184 by Dow Corning and single-walled CNTs provided by Timesnano, China, respectively. A primer (92-023, Dow Corning) was used to enhance the adhesion between PDMS and Aluminum (Al) substrate. The surfactant used for dispersing the CNTs was sodium dodecylbenzene sulfonate (NaDDBS)provided by Sigma-Aldrich Co., USA. In addition to CNTs, nickel microparticles with needle-like surface (Type 123, Inco Ltd., CA) was used to improve the compressive sensing performance,

Sensor fabrication

Because of the high viscosity of PDMS, it is very difficult to uniformly disperse CNTs into PDMS matrix to make the composite. In this study, PDMS was firstly dissolved in Toluene to reduce its viscosity. CNTs were also separately dissolved in Toluene with the assistance of NaDDBS. The CNT solution was then added into the PDMS solution. With continuous magnetic stirring, Toluene was evaporated and, as a consequence, a uniformly mixed CNT/PDMS composite was produced. The ultra-stretchable CNT/PDMS sensors were then deposited on aluminum substrates. Prior to deposit, the aluminum substrates were cleaned with acetone and then coated with a thin layer of pure PDMS for electric insulation. After electrodes made of gold wires were attached on the top of the PDMS layer with silver epoxy, the CNT/PDMS composite thin film was coated over the gold wires and cured for about 12 hours at 70˚C. As the last step, another layer of pure PDMS was coated on the top of the CNT/PDMS sensing composite for protection. Figure 1 shows a picture of a fabricated sensor on an aluminum specimen (the black square is the sensing area of approximately 2x2mm^2) and a schematic of the cross-section of the sensor.

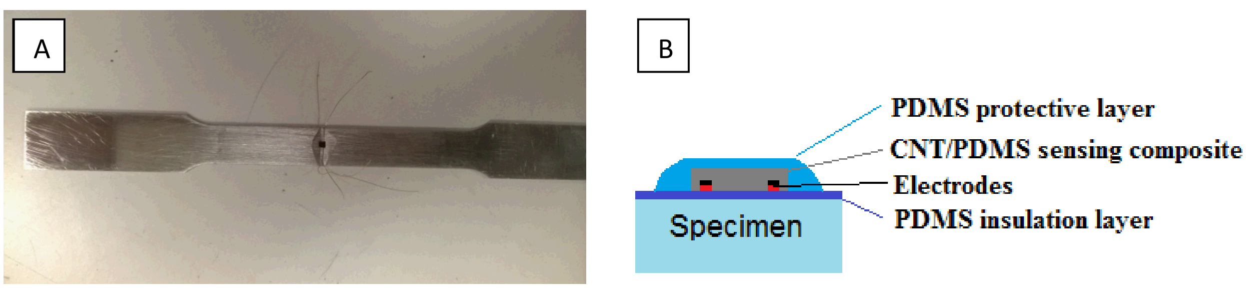

Figure 1. A picture of fabricated sensor and sketch diagram of the cross-section of the sensor.

Measurement method

The sensors were tested with a Shimadzu Universal Materials Testing Machine under quasi-static strain rate. The sensor outputs were directly compared with the extensometer (Epsilon 3442) signal attached to the specimen. The sensor was serially connected with a constant reference resistor, as shown in Figure 2. The resistance of the sensor can be calculated with the following equation,

$$R_s = \frac{V_x}{V_R} \cdot R \tag{1}$$

where V_x and V_R are voltages applied to the sensor and the resistor, respectively; R is the resistance of the reference resistor. As CNT/PDMS composite is not only a resistive element but also a capacitive element, if a constant DC voltage is applied, it could charge the internal capacitance of the sensor and lead to electrical polarization which will drift the sensor measurement. Therefore, a 18V, 60Hz AC power supply was used as the power source of the circuit. The AC power can eliminate the polarization of capacitance. The voltage output on the sensor and the extensometer are measured by a dynamic data acquisition system (DT9837, Data Translation Inc) with a sampling rate of 1000Hz.

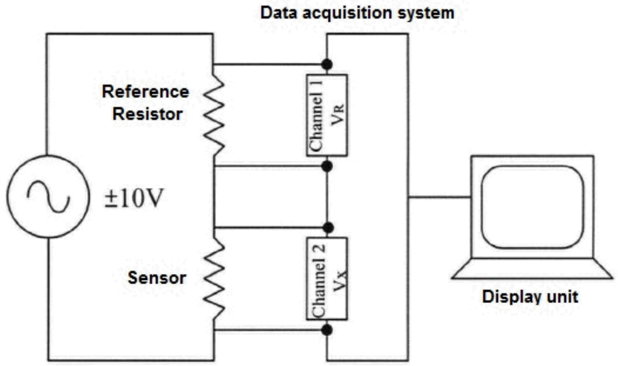

Figure 2. Sensor output measurement system

Results and Discussions

Figure 3 shows the output (ΔR/R) of a CNT/PDMS strain sensor with 20% CNTs versus the strain measurement with an extensometer. The CNT/PDMS sensor exhibits a wide range of linear response to strain up to about 8% where the aluminum specimen failed in tension. This CNT/PDMS strain sensor also exhibits a very high sensitivity. The gauge factor ($\frac{\Delta R}{R.Strain}$) of the CNT/PDMS sensor is about 1000, which is approximately 500 times higher than that of a conventional foil strain gage (typically around 2). The CNT/PDMS strain sensor was also tested under cyclic loads to examine its frequency response for potential vibration and dynamic strain measurements. Figure 4 shows the sensor response to cyclic loads. The results show that the sensor exhibits a nearly prompt response to external loading but a hysteretic response to unloading, which is possibly due to the nature of hysteresis of the polymer matrix. However, the hysteresis does not significantly affect the frequency and magnitude measurements of the cyclic loading, as evidenced by the consistency with the extensometer measurements.

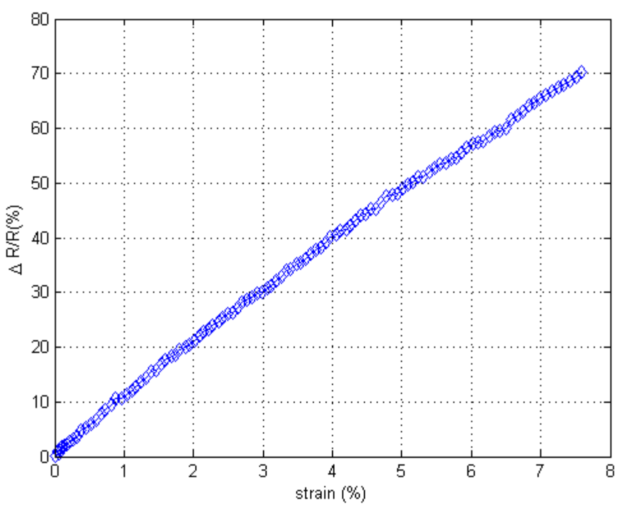

Figure 3. 20%CNT/PDMS strain sensor outputs vs extensometer strain measurement.

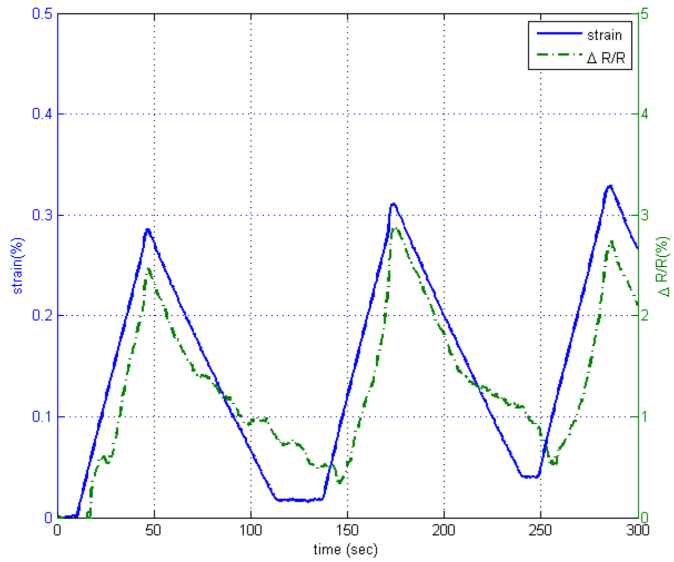

Figure 4. The output of the 20%CNT/PDMS strain sensor under cyclic loads.

To improve the compressive sensing response, micro-sized Nickel particles were added into the CNT/PDMS composites. Figure 5 shows the results of a sensor with 20%CNT/25%Ni/PDMS composite. The sensor shows quick and repeatable responses to loadings and some improved performance compared to CNT/PDMS composite, but the responses during the unloading stage still needs to be improved, especially at high frequency loads.

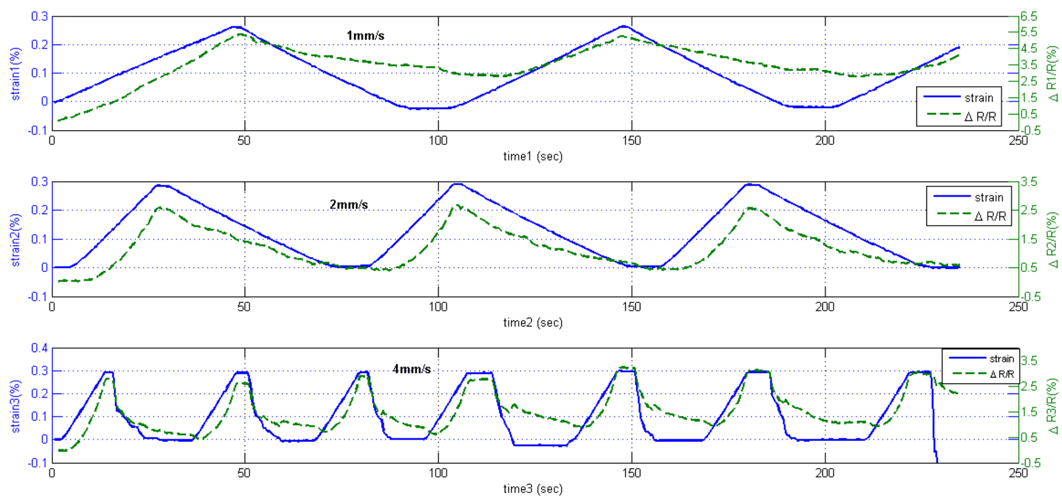

Figure 5. Sensor outputs under different loading rates of cyclic loads.

Conclusion

In this research, highly flexible CNT/PDMS composite stain sensors were designed, fabricated and tested. Experimental results show that the new sensors can measure strains up to 8% with an excellent linearity and a fast frequency response. The new strain sensor also exhibits much higher sensitivities than the conventional foil strain gages. Although the unloading performance of the CNT sensor still needs to be further improved, the developed sensor showed the potential for high-rate, large strain measurement applications.

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References

[1] T. C. Chu, W. F. Ranson, M. A. Sutton, "Applications of digital-image-correlation techniques to experimental mechanics," *Experimental Mechanics*, vol. 25, pp.232-244, 1985.

[2] M. A. Sutton, C. Mingqi, W. H. Peters, Y. J. Chao, and S.R. McNeill, "Application of an optimized digital correlation method to planar deformation analysis," *Image and Vision Computing*, vol. 4, pp. 143-150, 1986.

[3] V. Tiwari, M. A. Sutton, S. R. McNeill, S. Xu, X. Deng, W. L. Fourney, D. Bretall, "Application of 3D image correlation for full-field transient plate deformation measurements during blast loading," *International Journal of Impact Engineering*, vol. 36, pp. 862-874, 2009.

[4] C.-L. Choong, M.-B. Shim, B.-S. Lee et al., "Highly stretchable resistive pressure sensors using a conductive elastomeric composite on a micropyramid array," *Advanced Materials*, DOI: 10.1002/adma.201305182, 2014.

[5] G. Canavese, S. Stassi, M. Stralla, C. Bignardi, C. F. Pirri, "Stretchable and conformable metal-polymer piezoresistive hybrid system, " *Sensors and Actuators A: Physical*, vol. 186, pp.191-197, 2012.

[6] M. Vatani, Y. Lu, K.-S. Lee, H.-C. Kim, J.-W. Choi, "Direct-write stretchable sensors using single-walled carbon nanotube/polymer matrix," *Journal of Electronic Packaging*, vol. 135, 011009 (5pp), 2013.