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Application of carbon nanotubes (CNT) to design of the strain sensor

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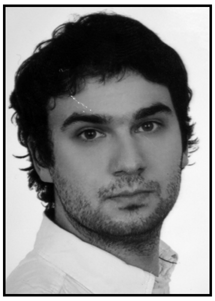

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Abstract

The aim of this work was to develop a sensor which could be easily applied to the tested material and integrated with it. Therefore, this paper is focused on the development of the Carbon Nanotube – a polymer strain sensor – which should fulfill such requirements. The development of such a sensor is discussed and the test of its performance are presented. Multiwalled CNTs were mixed with polymer and applied to the materials with use of screen printing. The sensor was tested for different types of loads. Manufacturing technology and sensor test results are presented in this work.

Keywords: carbon nanotubes, CNT, epoxy, strain gauge, nanotechnology, screen printing.

Zastosowanie nanorurek węglowych do konstrukcji czujnika odkształceń

Streszczenie

W pracy opisano prototyp czujnika zrealizowany przy użyciu nanorurek węglowych oraz epoksydu. Czujnik został naniesiony na badany materiał (kompozyt włókna szklanego) przy użyciu sitodruku. Struktura sensora (rozłożenie nanorurek w epoksydzie) została zbadana przy użyciu mikroskopu elektronowego. Wykazano, że przy stosunkowo dużych zawartościach procentowych (powyżej 7.5%) nanorurki węglowe tworzą zbite skupiska, przy czym mniejsze zawartości procentowe pozwalają na stosunkowo równomierne rozłożenie nanorurek węglowych w epoksydzie. Dodatkowo czujniki zostały poddane badaniom statycznym jak i dynamicznym. Przy badaniach statycznych miało to na celu zbadania odpowiedzi sensora (czy jest zachowana jego liniowość). Przy obciążeniach dynamicznych celem było sprawdzenie czy dochodzi do uszkodzenia struktury sensora przy stosunkowo dużej ilości cykli obciążeń. Zmiany rezystancji zostały porównane ze zmianami odkształceń badanego materiału (uzyskanymi z maszyny wytrzymałościowej). Otrzymano liniowe odpowiedzi czujników zarówno przy małej jak i dużej liczbie cykli obciążeń.

Słowa kluczowe: Nanorurki węglowe, nanotechnologia, tensometry, czujnik odkształceń, sitodruk, epoksyd.

1. Introduction

Since the discovery of carbon nanotubes in 1991 by Iijima [1] they have received high attention [2, 3]. Multiwalled carbon nanotubes (MWCNT's) as well as single walled carbon nanotubes (SWCNTs) were found to show a strict correlation between mechanical deformation and electrical conductance [4-6]. With their unique properties, they have gained interest from different fields of technology. There have been numerous reports on their different applications as gas detection sensors [7], power harvesting sensors [8] or application in biomedical systems [9]. The aim of this work, however, is the development of a high reliability strain sensor. Classical strain gauges are widely used in the Structural Health Monitoring (SHM) systems design. However, their use is limited to measuring strain only in specific direction and location. Therefore there is demand for a sensor which could be embedded in the material. There are several papers showing the possible usage of the carbon nanotubes (CNTs) for strain sensing using different approaches. Zhang *et al*. [10] studied the sensor with the usage of MWCNT/polycarbonate composites. Park *et al.* [11] used MWCNT/PEO, Kang *et al*. [12] measured strain sensing with the usage of MWCNT/PMMA, Vemuru S M *et. Al* [13] on the other hand used buckypaper to measure the strain at the macroscopic level. Gang et al. made the experiment on the CNT/epoxy stand-alone sensor [14]. All of these studies, however, concerned a sensor which was attached to the material with a specific adhesive (or investigated just the behavior of the pure sensor). In this paper the authors investigate the MWCNT mixed with epoxy as the coating material, determining its potential usage in the SHM system design.

Epoxy resin is very often used as a matrix for composites due to its mechanical, electrical and thermal properties. Epoxy resin has excellent adhesion to various surfaces, to metal surfaces especially. There is a very wide range of the epoxy coatings used for the specific purposes. They are great insulators and very often are used as adhesives for strain gauges. Most common epoxy resins are produced from a reaction between bisphenol-A and epichlorohydrin, very often with the supplement for specific chemical, mechanical or electrical properties.

The CNT-epoxy composites are quite simple to manufacture. This paper shows the results of tests of CNT-epoxy sensors loading with static and dynamic loads.

2. Manufacturing of a CNT-epoxy sensor

For the matrix of coating we chose the bisphenol-A, epichlorohydrin with Glycidyl butyl ether -Epidian E52 (produced by "Organika – Sarzyna", Poland). The multiwalled carbon nanotubes were ordered from the Sigma-Aldrich (O.D. × L: 6-9 nm × 5 μm, diameter: 5,5 nm-mode, 6,6 nm-median). The hardener PAC was produced by "Organika-Sarzyna", Poland.

The Base-Material was the composite of the glass-fiber which had silver-paste contacts screen-printed and dried before CNT/epoxy was applied to it (in order to improve measurements).

The preparation was as follows: the MWCNT were dispersed in the pure acetone using an ultrasound probe with 22,5 kHz for 30 minutes. Later the sonication epoxy was added to the MWCNT/acetone resin and mechanically stirred for 30 minutes. When the resin and MWCNT were mixed well, the hardener PAC(60% w/w) was added to the mixture. The resulting paste was printed on the base-material and then dried in a vacuum oven for 1 hour at 80^{o} C. There were prepared samples with 3,5%, 5% and 7,5 % of CNT in the CNT/epoxy resin (Fig.1) which were then tested using measurement hardware and software presented in Fig. 2.

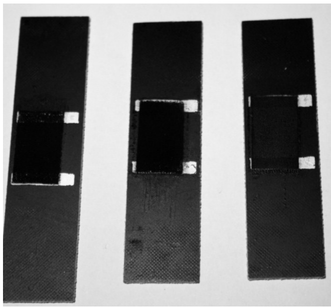

Fig. 1. Samples with screen printed CNT/epoxy (from left to right: 3,5%, 5% and 7,5%)
Rys. 1. Próbki z nadrukowanymi CNT/Epoksyd (od lewej kolejno: 3,5%, 5% i 7,5%)

The structure of the sensors was investigated using TEM (Figs. 3, 4, 5).

3. Experimental testing of the CNT-epoxy sensor

The samples were then tested using the Instron 8872 servo hydraulic machine (see Fig. 6 for the test setup). There were two separate cases:

1. Static tests were made with the load from 0 to 4000N (200N/s);
2. Static-dynamic where sensors were first loaded to 1,5 kN, then the load was oscillating for 5 cycles with the amplitude of 500 N.

The results were recorded simultaneously. The Instron testing machine recorded the strain and the force. For the voltage measurement there was used the common Wheatstone bridge approach along with ADC/DSP hardware and software (see Fig. 2). The measurements were made by LMS TestLab.

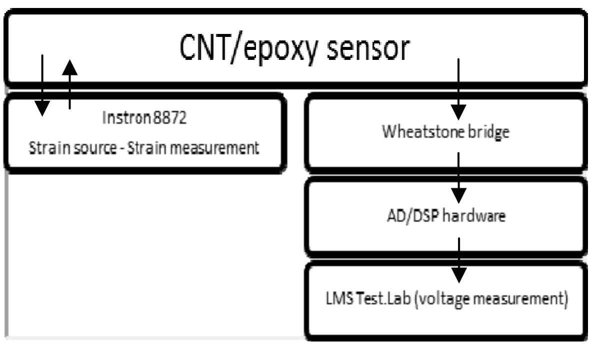

Fig. 2. Scheme of the measurement configuration
Rys. 2. Schemat toru pomiarowego

4. Results

The first noticeable problem concerns concentration of the CNT in the epoxy. In Fig. 3 we can easily distinguish the pattern, which is the result of the printing mesh. The sensors were very highly saturated with the CNT which caused that they formed large "bundles" (Fig. 5). As the comparison there are images from 3,5% CNT (Fig. 4) were we can notice better dispersion of the CNT in the epoxy.

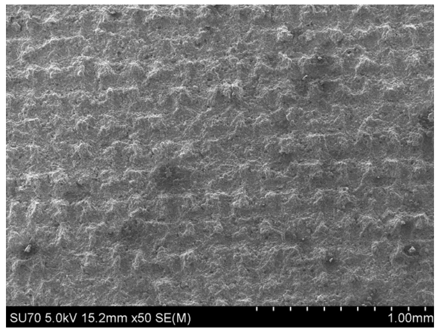

Fig. 3. Image of 7,5 % CNT/epoxy printed on glass-fiber composite
Rys. 3. Zdjęcie 7,5 % CNT/epoksydu nadrukowanego na kompozycie z włókna szklanego

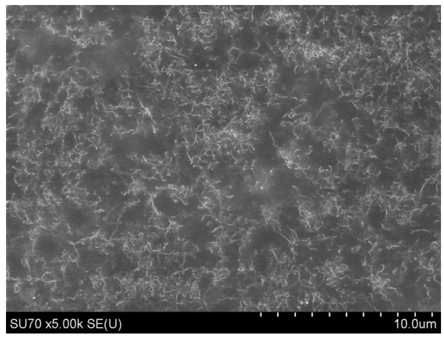

Fig. 4. Image of 3,5 % CNT/epoxy printed on glass-fiber composite
Rys. 4. Zdjęcie 3,5% CNT/epoksydu nadrukowanego na kompozycie z włókna szklanego

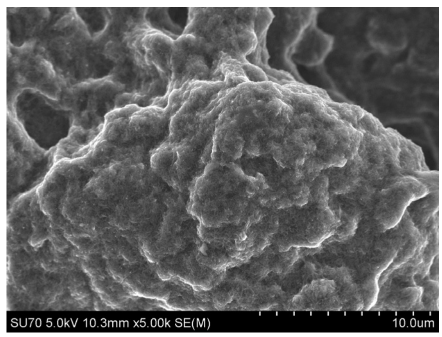

Fig. 5. Image of 7,5 % CNT/epoxy printed on glass-fiber composite
Rys. 5. Zdjęcie 7,5% CNT/epoksydu nadrukowanego na kompozycie z włókna szklanego

As far as the voltage measurement is concerned, there is linear change in the voltage caused by the strain (Fig. 7).

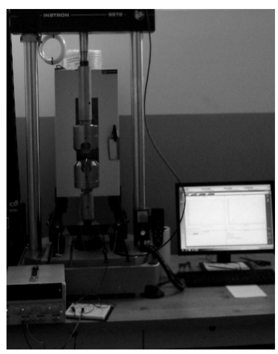

Fig. 6. Test setup for the voltage/strain measurements
Rys. 6. Widok stanowiska pomiarowego

Moreover, the gauge factors were calculated (Tab. 1).

Tab. 1. Gauge factors of the tested samples
Tab. 1. Stałe tensometryczne badanych sensorów

% of CNT	3,5%	5%	7,5%
Gauge Factor	3,7	3,8	3,2

The 3,5% and 5% CNT/epoxy sensors seemed to have the highest gauge factor compared to 7,5% ones. Most likely that was due to the oversaturation of the 7,5 % sensor.

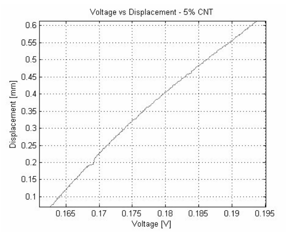

Fig. 7. Voltage change during linear load
Rys. 7. Zmiana napięcia podczas stałego - liniowego obciążenia

The sensors also responded with relatively good results to the more complex load (Fig. 8). Even when the 3,5% was tested for 10000 cycles (Fig. 9) with the 20Hz and 500N amplitude load, the sensors with the lower percentage of CNT did not show any influence of creep or fracture of the material. 7,5% CNT, however, showed the fracture resulting in the great resistivity change of the tested sample after the tests (approx. 52% increased resistance). Most likely that was due to the boundless of CNT which caused the isolating breaks during the test of the material.

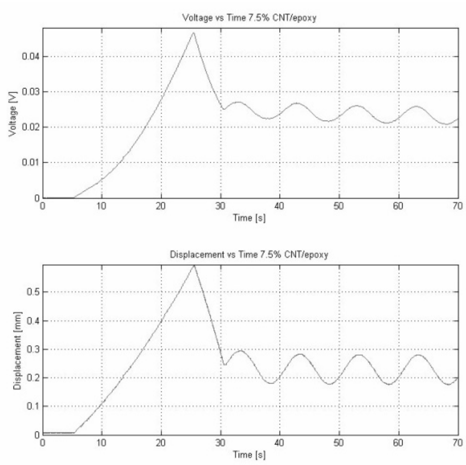

Fig. 8. Voltage change during dynamic load with a small number of cycles
Rys. 8. Zmiana napięcia podczas dynamicznego cyklu obciążenia przy małej ilości cykli

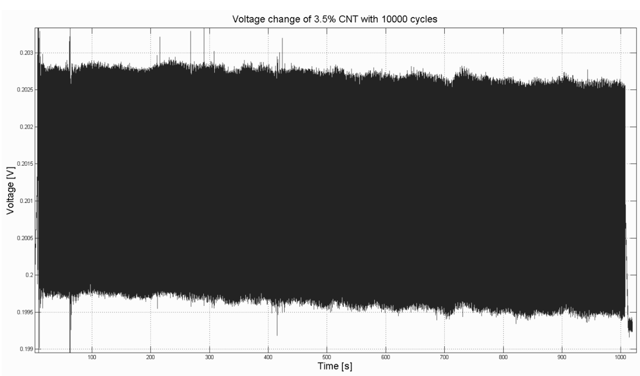

Fig. 9. Voltage change during dynamic load for 10000 cycles
Rys. 9. Zmiana napięcia podczas 10000 cykli

The sensors were initially calibrated using a potentiometer and the Wheatstone bridge. Then the curvature and the gauge factor were obtained for each sensor, which might be used for read-outs of the voltage and transferred to the strain.

5. Conclusions

The completed research showed that the screen printing might be a good solution for application of the sensing material to the purposes of the structural health monitoring. A linear change in the voltage was recorded similarly as in the papers which were the bases for the development of these sensors. High agglomeration of the CNT (7,5%), however, showed the loss in the reliability during the dynamic testing of the samples.

Moreover, tests in the real environment should be carried out to check the influence of other factors crucial for strain sensors, such as temperature and humidity.

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