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Polymer Composites with Nanoscale Additives for Strain Gauge Applications: a Brief Review

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Abstract

The article discusses various types of polymer composites with nanomaterials that are intended for strain measurement tasks. Despite the obvious advantages of strain gauges based on polymers modified with dispersed conductive structures, there are problems in creating effective ones that can operate under large deformations with high sensitivity and measurement accuracy. This can be realized by implementation of the strain gauge self-compensation effect when combining a semiconductor material (with negative temperature coefficient of resistance) with high calibration coefficient and metal (with positive temperature coefficient of resistance) as well as improved lifetime characteristics allowing for long-term operation with multiple compression/decompression modes. Carbon nanotubes play an important role in the technologies to create polymer composites for strain measurement tasks. It is also possible to change the properties of such composites by varying the type of polymer matrix. This paper analyzes various designs of strain gauges, as well as methods of calculation and modeling of their performances.

Keywords: Nanocomposites; Polymers; Carbon nanotubes; CNT; Strain gauge

1. INTRODUCTION

Measuring strains acting on various types of surfaces is relevant in a wide range of scientific and technical problems [1]. The ability to measure strains is required in such applications as wearable electronics, soft robotics, detection of human motion parameters, virtual reality technologies [2,3], human health monitoring [4], rock fracture studies [5] and other various technical applications [6]. Strain gauges are highly relevant for measuring equipment, control and management systems, mechanical engineering technologies, automotive industry, and aviation technology [7–10]. Commercial metal strain gauges have limited sensitivity and cover very small areas, and their typical operating stress range is less than 3% [11]. Recently, there has been significant interest in the development of strain gauges based on polymers with conductive fillers [12]. One option for manufacturing strain gauges is the use of polymers filled with conductive materials and, in particular, carbon dispersed structures [13].

2. STRAIN GAUGE NANOCOMPOSITES

Multi-walled carbon nanotubes (MWCNTs) have shown good results in the field of strain gauge creation [14,15], which is due to their unique electromechanical properties. The ongoing studies in the field of strain gauges show which aspects of using CNTs to measure deformation, both at the nano- and macrolevels, are important. First of all, CNTs undergo changes in their band structure under the influence of mechanical deformations.

It should be noted that polymer nanocomposites have a high calibration coefficient and a stable response to mechanical action [16]. Nanocomposites based on polymer

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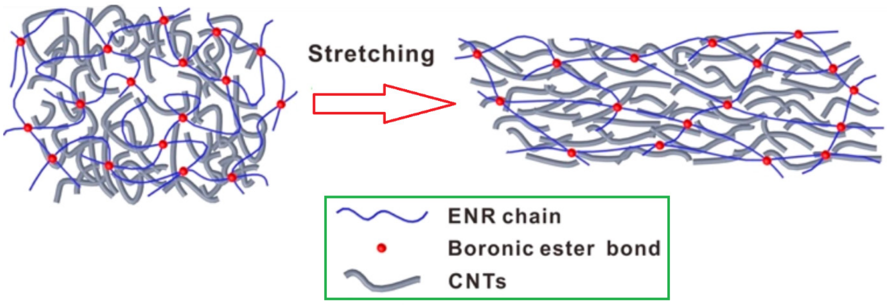

Fig. 1. Elastic composite with dispersed filler. Adapted from Ref. [17].

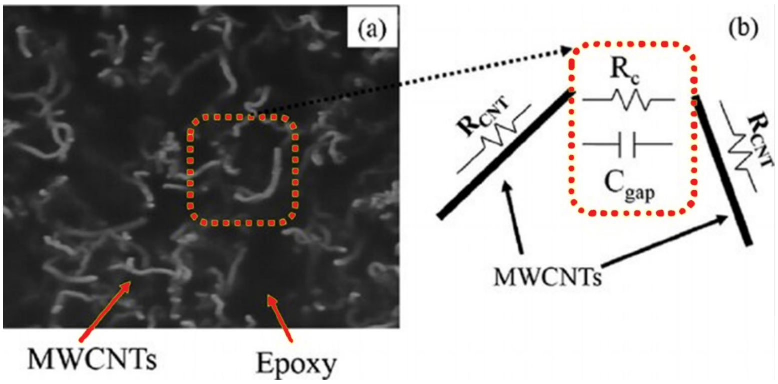

Fig. 2. Scanning electron microscopy images of MWCNT/epoxy resin composite.

matrices are optimally suited for measuring large deformations (> 10%), which is especially important for applications such as intelligent robots and human movement monitoring. When a densely packed array of CNTs is stretched, the configuration of their network changes, which leads to a change in its electrical resistance (Fig. 1).

This is mainly influenced by the contact between individual CNTs, tunneling and electron hopping, which depend on the distance between individual CNTs. The polymer coating of the CNT array affects its piezoresistive response not only during the first loading but also during subsequent (cyclic) loading. Such a response may depend on the dielectric and mechanical properties of the polymer coating. Thin-film CNT sensors also exhibit resistance hysteresis under cyclic strain loading [18], which is associated with irreversible deterioration of the CNT/polymer interface. Temperature can also cause changes in the electrical resistance of the strain gauge. For piezoresistive strain gauges, these temperature-induced changes in electrical resistance can be misinterpreted as deformation. Thus, the thermistor response of strain gauges also needs to be characterized to account for potential temperature compensation factors of the strain gauges.

A highly robust piezoresistive pressure sensor with excellent repeatability and fast response has been developed [19]. The developed sensor has the characteristic of silicone rubber coating, which extends the pressure measurement range and improves the response time. The sensor is capable of measuring pressure below 100 Pa and above 200 kPa, and can measure oscillatory pressure well above 50 Hz. The sensor showed high repeatability and durability, and worked normally after 1000 cycles under an applied pressure of 360 kPa. The geometry of the conductive mesh of the CNT strain gauge has an important effect on its piezoresistive response [20]. The main physical mechanism of sensitivity to mechanical stress is based on the change in geometric dimensions that occurs during deformation from an external force, which leads to a change in the electrical resistance of the sensor material [21].

3. EFFECT OF THE POLYMER MATRIX TYPE ON THE CHARACTERISTICS OF THE STRAIN GAUGE TRANSDUCER

The use of the polymer matrix type is of key importance when forming a strain gauge. It affects the cohesion of filler particles and their dispersion in the composite, which affect the mechanical and electrophysical characteristics of strain gauges based on them.

In Ref. [22], the piezoresistive properties of flexible, strain-sensitive MWCNT/epoxy composites were studied. The strain over the sensor area was tested using digital image correlation under quasi-static uniaxial tension. The piezoresistive characteristics of the films were quantitatively studied using electrochemical impedance spectroscopy in a wide frequency range from 40 Hz to 110 MHz. Scanning electron microscopy (SEM) analysis (Fig. 2) confirmed that MWCNT/epoxy composites with different CNT concentrations have good homogeneity and dispersion.

In Ref. [23], the optimization of MWCNT/epoxy resin-based film dispersions was performed. Dispersions in the range from 0.3 wt.% to 1 wt.% MWCNTs were synthesized and deposited on a flexible substrate using screen printing technique at different deposition rates up to 90 mm/s. Improving the distribution of MWCNTs in the polyurethane (PU) matrix reduces the percolation threshold and improves the electrical conductivity and strain-sensitive properties of MWCNT-filled PU nanocomposites [24]. In this way, it is possible to improve the calibration coefficients in both small and large deformation modes. Elastomers with uniform CNT distribution have increased resistance to deformation, as well as improved strength and tunable sensitivity. In Ref. [25], it was shown that the resistance of strain gauges based on polymers with CNTs changes over time, both with and without deformation.

The resistance of thin CNT films varies depending on a number of factors, such as deformation, defects, temperature, chemical effects and size effects [26]. With increasing deformation or under compressive stress, the geometry and length of the conductive networks present in the matrix change, which in turn leads to a deformation-dependent change in electrical resistance [27]. In most cases, such changes are reversible and have a wider range than the changes observed in their metal counterparts. It is necessary to take into account modern technological capabilities when using polymer composites associated with the use of 3D printers [28], which allows obtaining sensors with stable parameters [29]. Thus, despite the obvious advantages of strain gauges based on polymers modified with dispersed conductive structures, there are problems in creating effective strain gauges capable of operating under conditions of large deformations with improved sensitivity and measurement accuracy (implementation of the effect of strain gauge self-compensation with a combination of a semiconductor material with a negative temperature coefficient of resistance and a high calibration coefficient and metal with a positive temperature coefficient of resistance), as well as improved resource characteristics allowing for long-term operation with multiple compression/decompression modes. It should also be taken into account [30] that defects can form in elastomers that have not even been subjected to external loads and are manifested in the appearance of cracks during aging. When comparing non-aged and aged samples, no significant changes were found in viscoelastic behavior at low deformation, adhesion and friction. The elongation at break, and therefore the viscosity of the rubber, is determined by the largest crack-like defects that grow during the aging process, which leads to a strong decrease in these indicators during the aging process.

4. METHODS FOR ASSESSING THE STRUCTURAL PROPERTIES OF POLYMERS

To analyze the parameters of polymer composites, Fourier spectra of acoustic emission signals can be used, which are suitable for the Kohonen self-organizing map. For the obtained clusters, their nature was determined by peak frequencies and their critical accumulation periods were calculated. In addition, the peak frequencies of the wavelet decomposition levels were analyzed [31].

To evaluate the parameters of composites, special attention should be paid to the molecular dynamic’s method as one of the promising methods for studying mechanical interactions in polymer composites with carbon nanotubes. [32]. One of the methods for describing adhesion in tribological systems is Green's function molecular dynamics [33]. Given the applied pressure and the updated percolation paths, a multi-stage approach is used to estimate the piezoresistivity [34]. After adjusting the positions of the CNTs in the deformed state using the finite element method, new paths are identified using the critical distance criterion for the percolation paths that contribute to the resistance network. The simulation results show good agreement with experimental data on the resistance and piezoresistive sensitivity of various CNT elastomer nanocomposites. The finite element method helps to analyze the influence of the CNT volume fraction, geometric properties, and orientational configurations on the onset of percolation at the critical distance. Lower CNT content leads to more significant changes in relative resistance due to fewer percolation paths.

The classical methods of polymer research include electron microscopy, which allows visualization of polymer morphology and microstructure at the nano- and microlevel. Atomic force microscopy is also used to study polymer surfaces, including topography and mechanical characteristics. Classical mechanical testing, including compressive, tensile and flexural strength measurements, is also used to study polymers, providing useful information on the mechanical properties of polymers [32].

5. CONSTRUCTION OF POLYMER STRAIN GAUGES

Polymer strain gauges can have different designs depending on their application and performance requirements. They can be either flat, where linear elements with a flat configuration can be attached to the surface to be measured. Or curved, for measuring stresses on curved surfaces. Multi-sensor devices include multiple sensors in a single device for simultaneous measurement of different types of stresses (e.g., tension and compression). The article [35] presents a method for determining the orientation of strain gauges

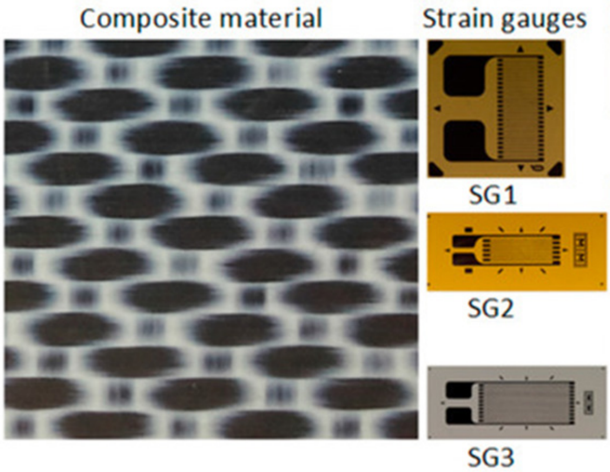

Fig. 3. Scheme for the method of determining the orientation of strain gauges glued to composite materials with a polymer matrix. Adapted from Ref. [35].

bonded to polymer matrix composites (Fig. 3). Automatic identification of both the direction of the reinforcing fibers and the orientation of the strain gauge, respectively, allows the angle between these two directions to be calculated. Knowing the difference between the nominal value of this angle and the value actually obtained after gluing the strain gauge, corrections obtained by calculation can be applied.

In Ref. [36], it was found that the strain in a silicon resistor can vary by orders of magnitude depending on different substrate materials, while the strip length or substrate thickness only slightly affect the strain level. While the average strain in silicon reflects the strain gauge factor, the maximum strain in silicon determines the extensibility of the system. Thus, there is a trade-off between the strain gauge factor and the extensibility of silicon-on-polymer strain gauges (Fig. 4).

In Ref. [37], piezoresistive pressure sensors capable of detecting low compressive stress ranges were fabricated and characterized. The 5.5×5×1.6 mm^3 sensors consist of a flat aluminum top electrode and a microstructured bottom electrode containing a two-by-two truncated pyramid array with a piezoresistive composite layer sandwiched between them. The responses of two different piezocomposites, a MWCNT–elastomer composite and a quantum tunneling composite (QTC), were characterized as a function of the applied pressure and the effective contact area (Fig. 5). The MWCNT piezoresistive composite-based sensor was able to detect pressures down to 200 kPa. The QTC-based sensor was able to detect pressures down to 50 kPa depending on the bottom electrode contact area.

6. CONCLUSIONS

Thus, despite the obvious advantages of strain gauges based on polymers modified with dispersed conductive structures, there are problems in creating effective strain gauges capable of operating under large deformations with improved sensitivity and measurement accuracy (implementation of the strain gauge self-compensation effect

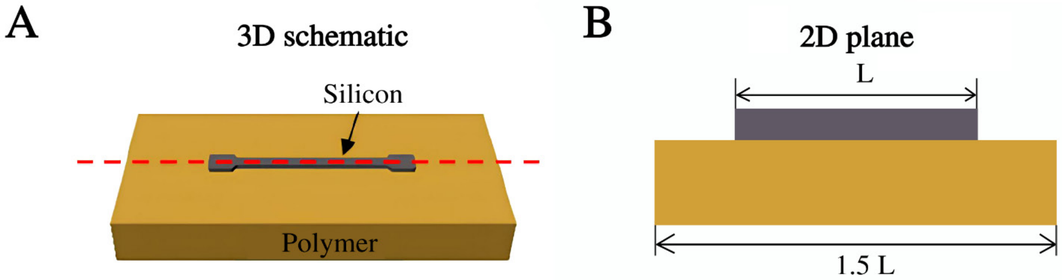

Fig. 4. Schematic of a thin silicon strip supported by a polymer substrate. (A) 3D schematic of a unit cell. (B) 2D plane. Adapted from Ref. [36].

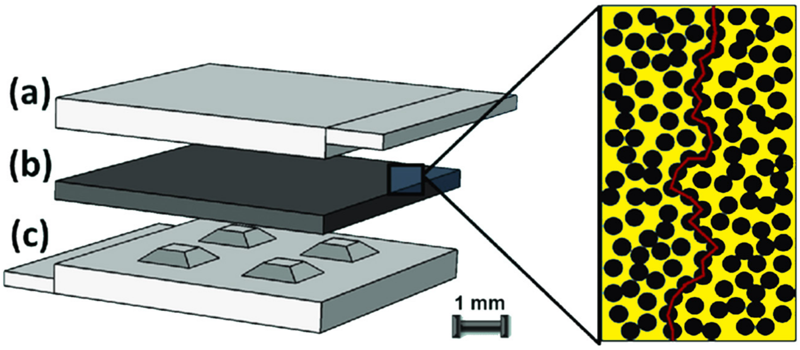

Fig. 5. Piezoresistive pressure sensor for detecting low compressive stresses. (a,c) aluminium electrodes; (b) piezoresistive filler composite. Adapted from Ref. [37].

when combining a semiconductor material with a negative TCR and a high calibration coefficient and metal with a positive TCR), as well as improved resource characteristics allowing for long-term operation with multiple compression/decompression modes. Carbon nanotubes play an important role in the technologies for creating polymer composites for strain measurement tasks. It is also possible to change the properties of composites by varying the type of polymer matrix. The analysis of strain gauge modeling methods is carried out, and their design for measuring various types of mechanical pressure is presented.

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Полимерные композиты с наноразмерными добавками для задач тензометрии: краткий обзор

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Аннотация. В статье рассмотрены различные типы полимерных композитов с наноматериалами, которые предназначены для задач тензометрии. Несмотря на явные преимущества тензорезисторов на основе полимеров, модифицированных дисперсными проводящими структурами, существуют проблемы создания эффективных тензодатчиков, обладающих возможностью работы в условиях больших деформаций с улучшенной чувствительностью и точностью измерений. Данная проблема эффективно решается при реализации эффекта самокомпенсации тензорезисторов в случае наполнителей из полупроводникового материала (с отрицательным температурным коэффициентом сопротивления) и металла (с положительным температурным коэффициентом сопротивления), что также улучшает ресурсные характеристики позволяя реализовать длительную эксплуатацию с многократными режимами компрессии/декомпрессии. Важное значение в таких технологиях играет использование углеродных нанотрубок. Кроме того, свойства композитов изменяются варьированием типа полимерной матрицы. В данной работе представлен обзор и проведен анализ конструкций для измерения различных типов механического давления и методов моделирования тензодатчиков.

Ключевые слова: нанокомпозиты; полимеры; углеродные нанотрубки; УНТ; тензометрия