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Strain sensing of printed carbon nanotube sensors on polyurethane substrate with spray deposition modeling

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ABSTRACT

The unique mechanical and electrical properties of carbon nanotubes represent a potential for developing a piezo-resistive strain sensor for smart structures. This study demonstrated a new processing technique of multi-walled carbon nanotube strain sensors with tunable strain gauge factors. A digital-controlled spraying-evaporation deposition process that uses a 12-array bubble jet nozzle attached to a digital x-y plotter combined with a heated substrate which induces evaporation of the solvent was developed. The demonstrated fabrication technique has advantages such as high efficiency, low cost and scalability. The experimental results showed that the prepared carbon nanotube strain sensors are capable of measuring strains through highly linear electrical resistance change. The gauge factors of the fabricated strain sensors could be easily tuned by controlling the number of printed layers of carbon nanotubes. In this work, strain sensors were fabricated with printed carbon nanotube layers ranging from 10 to 50 layers and strain gauge factors were measured in a range of 0.61–6.42. Moreover, the dynamic loading test results revealed that the printed carbon-nanotube strain sensors exhibited excellent durability and stability at cyclic strain. These superior sensing capabilities of the fabricated CNT sensors make them a promising candidate for wearable smart electronics and structural health monitoring applications.

1. Introduction

Carbon nanotubes (CNTs) have attracted extensive attentions in the research community due to their unique electrical and mechanical properties [1–3]. The electrical resistance of CNTs is interestingly correlated to their mechanical deformation, which is called piezo-resistive effect [4]. This electrical characteristic of CNTs coupled with their high mechanical strength makes them a promising material for strain sensors. Piezo-resistive strain sensors are an interesting area of industrial and academic research due to the growing demand for flexible and wearable electronics [5–8], smart textiles [9] and structural health monitoring [10].

To create CNT based strain sensors with desired properties, various fabrication techniques have been employed to date, including compression molding [11], solution casting [12], contact film transfer [13,14], screen printing [15,16] and spray coating [17,18]. Liu et al. [11] prepared a carbon nanotube/graphene/polyurethane strain sensor by compression molding method. The strain gauge factors were calculated to be 5.1 and 152.93 at 5% and 30% strain, respectively. A higher strain sensitivity was obtained at a larger strain. Michelis et al. [19] employed inkjet printing technique to fabricate a carbon nanotube based strain sensor. The gauge factor was found to be 0.9, which is comparable to the gauge factor of commercially available metallic foil strain gauges.

While these techniques are able to create sensors, some challenges in fabrication have prevented their widespread industrial applications. For instance, although the contact film transfer technique is able to produce CNT strain sensors with good sensitivity, transferring film to substrate is time-consuming and complex, often requiring a surface treatment of the substrate and multiple fabrication steps, which increase the overall cost and limit the manufacturing scalability of this technique. Conventional spray deposition processes often use an airbrush with a large spray area to fabricate strain sensors, but they are not able to deliver CNT materials to desired locations, thus the materials cost increases during the fabrication process. Additionally, these techniques such as film transfer and solution casting lack the ability to produce strain sensors with controlled strain gauge factors.

To address some of the above-mentioned problems, this study reports a scalable and low-cost method, known as spray deposition modeling (SDM), for fabricating carbon nanotube strain sensors with desired gauge factors. SDM is a digital-controlled additive manufactur-

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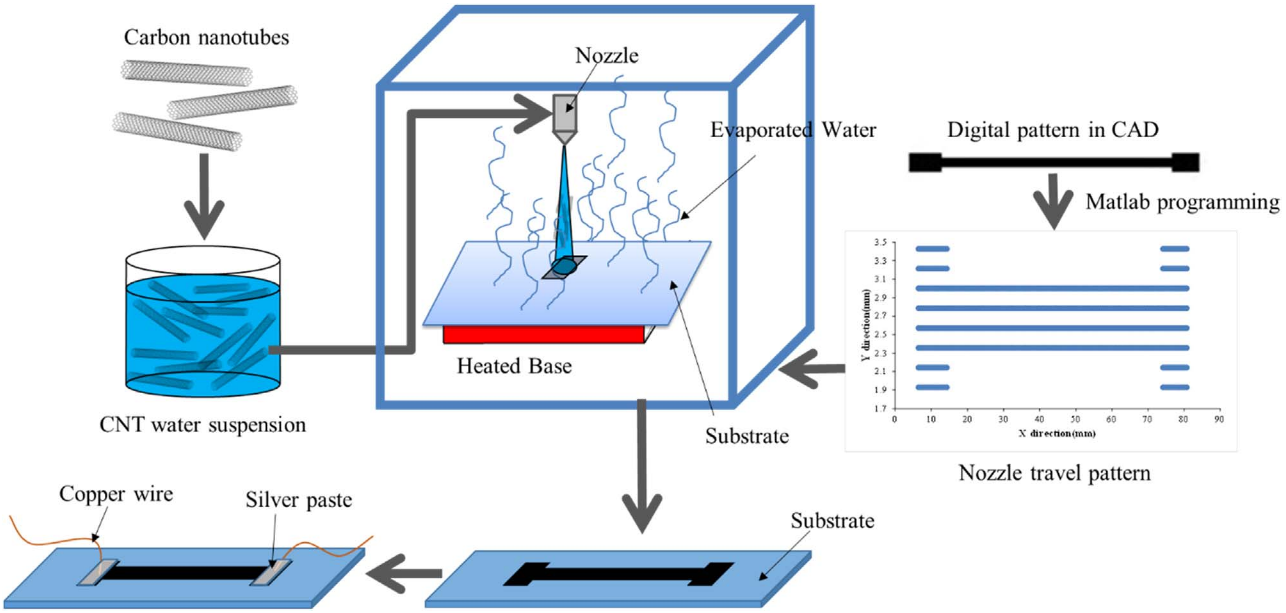


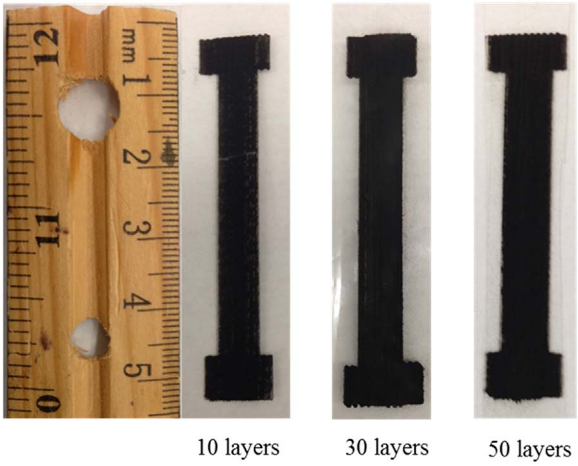
Fig. 1. Schematic of the digital fabrication of CNT strain sensors through the SDM technique.

ing process in which the CNT ink droplets are supplied in the form of a stream to any desired location through an x-y axis movable nozzle. Thus, as nozzle moves, the CNT patterns could be printed continuously at different locations. The highest resolution of SDM is 96 dots per inch, which enables the CNT patterns to be printed over the same area with precision and accuracy. The SDM is also an additive manufacturing process, which enables the strain sensor to be built layer by layer and has a minimum loss of the supplied material. Conventional film transfer, spray deposition or solution casting technique do not have the layer-by-layer additive characteristics and manufacturing accuracy, thus SDM is a more efficient method to produce CNT patterns. In this study, CNT strain sensors on polyurethane substrate with high sensitivity were fabricated through the SDM technique and the resulting sensing performance was examined.

2. Experimental methods

The digital fabrication of CNT strain sensors is achieved by the process shown in Fig. 1. The sensor design was first done in a CAD software. To simplify the process only black and white images were used. A MATLab code was used to bring in 2D images and generate G-code that controls the motion of nozzle. The fabrication process began with CNT/water suspensions. Multi-walled carbon nanotubes (MWCNT) (Chengdu Organic Chemical) with an average outer diameter of 30 nm was used in this study. The desired amount of MWCNT materials was initially dispersed into water using a sonication tip. A surfactant (Triton-X100, Fisher BioReagents) was used to de-agglomerate the nanotubes to enhance their dispersion. The CNT ink with good dispersion of carbon nanotubes was achieved by sonication for 1 h. The prepared CNT ink can remain stable for one week.

The CNT ink was then loaded into the cartridge to be sprayed on to a polyurethane (SMP Technologies Inc.) substrate that developed by solution casting. While the substrate was heated, 12-array bubble jet nozzles sprayed the ink material in the order given by the G-code. During the spraying process, water evaporated and CNTs were deposited on the substrate. The samples shown in Fig. 2 were printed at the speed of 15 mm/s using a nozzle set with 12 nozzle outlets to increase the productivity. Each droplet has the diameter of 235 µm. For simplicity, unidirectional strain sensors were fabricated with different numbers of printed layers from 10 to 50 layers with an interval of 10 layers. The length and width of each sample are 5 cm and 1 cm, respectively. Large contact pads were designed at the ends to reduce the contact electrical resistance.



10 layers 30 layers 50 layers

Fig. 2. Physical images of 10, 30, 50 CNT layers (dog-bone shaped) printed on a transparent polyurethane thin film substrate.

The electrical sheet resistance of printed strain sensors was measured at room temperature with a four-point probe apparatus (Signatone Quadpro system). In order to investigate the effect of applied strain on the electrical resistance of the fabricated strain sensors, three types of experiments were performed using a MTS hydraulic 100kN test system including: (1) monotonic tensile test; printed CNT strain sensors were stretched at a constant velocity of 2 mm/min (2) monotonic compression test; Compression specimen was a 12.7 by 12.7 by 25.4 mm prism. The strain sensor was bonded by adhesives to one face of this prism and aligned with the loading direction. The compression specimens were compressed at a constant velocity of 2 mm/min (3) cyclic tensile test; specimens were stretched/released at a constant displacement speed of 0.48 mm/min. Each cycle