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Polymeric carbon nanotube nanocomposite-based force sensors

S.S. Park (2)*, K. Parmar, S. Shajari, M. Sanati

Department of Mechanical and Manufacturing Engineering, University of Calgary, Calgary, Alberta, Canada

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A B S T R A C T

Accurate measurement of cutting forces is important for monitoring and optimization of machining processes. In this study, we fabricated highly sensitive force sensors using polymeric nanocomposites. The sensors consisted of polyvinylidene difluoride (PVDF) polymer reinforced with multi-walled carbon nanotubes (MWCNTs) using a spray coating method. The spray-coated sensors were electrically poled to generate piezoelectric phases. Both the piezoresistive and piezoelectric characteristics of the nanocomposite were utilized for improved performance of the sensors. A Monte Carlo based electro-mechanical model is proposed and was used to investigate the behavior of the nanocomposite sensor. Experimental cutting tests were also performed for comparison with a conventional table dynamometer.

1. Introduction

The emergence of intelligent machining introduces requirements for sensors that are capable of measuring cutting forces with precision, in order to monitor the integrity of machining components and provide adaptive control capabilities in the manufacturing of high-quality, complex components. Real-time information of machining forces provides an indirect indication of the energy usage, chip removal mechanisms, forced vibrations, chatter, and machinability of the workpiece. They are also an indicator of tool breakage and wear. Therefore, accurate measurements of the cutting forces are essential [1].

Sensor systems based on piezoelectricity, strain gauges and capacitance/lasers have traditionally been used to measure cutting forces. These sensors are often expensive and require additional setup and complex signal processing. The piezoelectric dynamometer also poses certain operational limitations, such as the inability to measure static forces due to charge leakages. Moreover, strain gauges suffer from drifts over long periods of time. To overcome these challenges, a novel, low-cost force sensor system using polyvinylidene difluoride (PVDF) and carbon nanotube (CNT) nanocomposites has been developed.

Any force applied to the CNT nanocomposites contributes to the breakup of the conductive network between CNTs, thereby affecting electron transportation and varying the electrical resistivity of the nanocomposites. This piezoresistive behavior of the CNT/polymer can be utilized for in situ health monitoring of structures (mechanical stress or strain) and forces [2].

Apart from the piezoresistive effect, the incorporation of CNTs into piezoelectric polymers, such as PVDF, improves their piezoelectric response. The CNTs also allow the PVDF material to become polarized at lower voltages [3].

The main objective of this study was the investigation of the use of both CNT/PVDF nanocomposites' piezoresistive and piezoelectric properties in the context of force measurement. To understand the overall sensing behavior of CNT/PVDF nanocomposites, a constitutive equation for its electro-mechanical behavior was derived. A Monte Carlo simulation with a random walk method was used to determine the piezoresistive coefficient. The piezoelectric coefficient was evaluated using Monte Carlo finite element discretization techniques.

The simulation results were compared experimentally by fabricating multi-walled carbon nanotube (MWCNT) reinforced PVDF nanocomposites using a spray-coating technique. The fabricated specimens were electrically polarized and used as sensing element in the development of a multi-axial table dynamometer system. The system was verified by conducting orthogonal and dynamic cutting tests.

2. Nanocomposite sensor preparations

The MWCNT used to reinforce PVDF had an aspect ratio close to 1000 and a tube diameter of 15–20 nm. The PVDF resins and MWCNTs were dissolved in a solvent (N,N-dimethylformamide) and placed in an ultrasonic bath for an hour to achieve homogeneous dispersion of the nanoparticles. The nanocomposite ink was then deposited using a spray coating process with an air-compressed atomizer system.

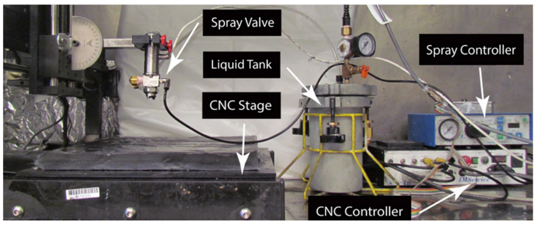

Fig. 1. Spray coating system.

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* Corresponding author.
E-mail address: simon.park@ucalgary.ca (S.S. Park).

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The atomizer spray system consisted of a spray valve, liquid tank and 3-axis computer numerical control (CNC) stage. The system was connected to a supply of compressed air. The ink in the liquid tank was connected to the air-spray valve with a flexible delivery tube. When triggered, the ink mixed with the compressed air, atomizing the ink into fine droplets, which were released through the nozzle of spray valve onto the substrate. Fig. 1 shows the components of the spray deposition system.

After spraying, the nanocomposite-coated substrate was heat treated at 90 °C. To convert the PVDF into a piezoelectric state, the spray-coated samples were polarized at potential of 100 V for 3 h.

The novel nanocomposite materials were also studied through electromechanical modeling and simulated using Monte Carlo methods. Finally, the poled nanocomposite material was used to fabricate the force sensor.

3. Electromechanical modeling

The electromechanical properties of any material involve the relationship among the electrical field (E_i), the electrical current density (J_j), and the mechanical stress (T_{kl}). The change in the electric field (dE_i) with current and stress is expanded in a McLaurin's series in a tensor form, which is as follows [4]:

$$dE_i = \underbrace{\left(\frac{E_i}{J_j}\right)}_{\substack{\textit{Electrical}\\ \textit{resistivity}}} dJ_j + \underbrace{\left(\frac{E_i}{T_{kl}}\right)}_{\substack{\textit{Piezoelectric}\\ \textit{coefficient}}} dT_{kl} + \frac{1}{2}\underbrace{\left(\frac{{}^2E_i}{J_jJ_m}\right)}_{\substack{\textit{Nonlinear}\\ \textit{resistivity}}} dJ_jdJ_j + \frac{1}{2}\underbrace{\left(\frac{{}^2E_i}{T_{kl}T_{no}}\right)}_{\substack{\textit{Nonlinear}\\ \textit{piezoelectric}\\ \textit{tensor}}} dT_{kl}dT_{no} + \underbrace{\left(\frac{{}^2E_i}{J_jT_{kl}}\right)}_{\substack{\textit{Piezoresistive}\\ \textit{coefficient}}} dJ_jdT_{kl} + \cdots \tag{1}$$

In the above expansion, each term represents different physical properties as indicated the equation. The first term is electrical resistivity (ρ_{ij}), the second term represents the piezoelectric voltage coefficient (g_{ikl}), and the fifth term is the piezoresistive coefficient (π_{ijkl}). By ignoring the nonlinear and higher order terms, Eq. (1) can be reduced to the following equation:

$$E_i \cong \rho_{ij}J_j + g_{ikl}T_{kl} + \pi_{ijkl}J_jT_{kl} \tag{2}$$

Eq. (2) represents the generalized relationship between the electrical field and the applied stress. The electrical resistivity change can be determined [4]:

$$\Delta\rho_{ij} = \frac{E_i - \rho_{ij}J_j}{J_j} \tag{3}$$

To determine the electrical resistivity change of the material, with respect to the piezoelectric and piezoresistive coefficients, the following equation is derived by combining Eqs. (2) and (3):

$$\Delta\rho_{ij} = \left(\frac{g_{ikl}}{J_j} + \pi_{ijkl}\right)T_{kl} \tag{4}$$

For nanocomposite materials such as CNT–PVDF nanocomposites, it can be inferred that, the polymer matrix exhibits a piezoelectric property and the CNT conductive network imparts a piezoresistivity, the overall electromechanical property would be related to the addition of the piezoresistive and piezoelectric coefficients, as shown in Eq. (4). This is similar to the mixture postulation rule based on the continuum micro-mechanical principles. Assuming perfect bonding between the CNTs and the polymer matrix, the properties of nanocomposite materials can be related to the similar properties of its constituents, i.e., the polymer matrix and CNTs [5].

To obtain these coefficients through simulations, the CNT network inside the polymer matrix was replicated using Monte Carlo simulations. In this technique CNT–nanocomposites were modeled through the use of discrete microstructures called representative volume elements (RVEs).

3.1. Piezoresistive simulation

The equivalent resistance of the CNT network is measured based on the random walk method. In this method, the random walker is simulated by a particle in the electrical network [6].

In the model, particles are imported from the highest potential nodes (sources). These particles move through the network to the lowest potential points (sinks), as shown in Fig. 2. The pathway used by the particles depends upon the probability of each possible path from one node to another.

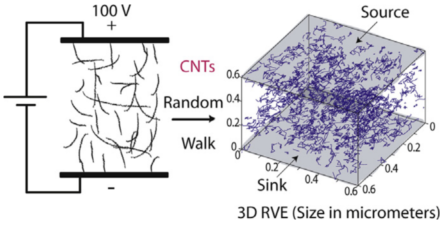

Fig. 2. Random walk piezoresistive model.

The model counts the number of particles and calculates the corresponding current and voltage of each node, considering the total number of particles. With the calculated electrical current, the resistivity of the CNT network can be determined. Changes in the geometry of nanocomposites due to applied forces may result in the contraction or expansion of the CNT network. As a result, the electrical conductivity of network varies.

The electric conductivity values of the RVE, with and without application of stress, are calculated. Following the determination of the resistance values, a conductance matrix describing the CNT network is generated. By using random walks simulations, the electrical resistivity of the RVE can be ascertained.

By applying different stress values to the RVE, different conductivity values are achieved. Fig. 3 presents the effects on conductivity from changes in the geometry of the RVE under normal stress. The electrical resistivity of a nanocomposite specimen is linearly related to the applied stress. This property is used to sense the applied force.

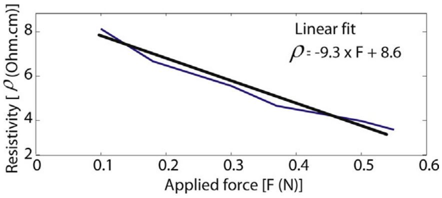

Fig. 3. Electric resistivity of RVE versus applied stress.

3.2. Piezoelectric simulation

As the piezoresistivity and piezoelectricity are two independent phenomena, a separate Monte Carlo Finite Element Method (MCFEM) based simulation is carried out to obtain the piezoelectric coefficient [7]. The MCFEM model is based on the method developed by Spanos and Kontsos [8] which is capable of predicting physical properties of the CNT nanocomposite including piezoelectric property.

For any piezoelectric materials, electromechanical behavior can be described by the constitutive equation [9]:

$$\begin{aligned} T &= cS - e^T E \\ D &= eS + \epsilon E \end{aligned} \tag{5}$$

where T is mechanical stress, c is the elastic stiffness tensor, S is the strain tensor, e incorporates the piezoelectric coupling constants, E is the electric field, D is the electric displacement and ε contains the dielectric constants.

To obtain the piezoelectric property of CNT nanocomposites, the following equation is solved using traditional finite element