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Hybrid fabrication process of additive manufacturing and direct writing for a 4×4 mm matrix flexible tactile sensor[†]

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Abstract

Various machines require data from their external environments for safety and/or accuracy. In this respect, many sensors that mimic the human sensory system have been investigated. Among these, tactile sensors may be useful for obtaining data on the roughness of, and external forces acting upon, an object. Several tactile sensors have been developed; however, these are typically fabricated via a series of complex processes, and hence are unsuitable for volume manufacturing. In this paper, we report a fabrication process for a 4×4 mm matrix flexible sensor element using layered manufacturing and direct-write technology. A composite composed of photocurable resin and Multi-walled carbon nanotubes (MWCNTs) was used as the sensing material. The MWCNTs were mixed with the photocurable resin using ultrasonic dispersion, and the liquid mixture exhibited excellent piezoresistive properties following curing using ultraviolet light. The used photocurable resin is flexible and elastic after curing. Therefore, the composite material can be bent and deformed. To use this composite material with the flexible sensor, dispensing characteristics were examined using direct-write technology. For the acquisition of sensor data, a commercial pin-header was inserted and photocurable resin was filled up to the height of pin-header and cured . Then, the composite material was dispensed onto the pin-header as a sensing material. Using this process, a flexible sensor with piezoresistive properties was formed.

Keywords: Additive manufacturing; Direct writing; Multi-walled carbon nanotubes; Tactile sensor

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1. Introduction

Robots may be able to obtain data on the texture, weight, and size of objects, as well as on external forces, through physical contact via the use of tactile sensors. Tactile sensors are therefore a desirable component of future robotic systems. To improve the precision of these sensors, they should be attached to a curved surface. However, common tactile sensors use a strain gauge and a thin-film as sensor materials, and are sensitive only to the displacement of the strain gauge. Tactile sensor technology involves complex fabrication processes, and devices are typically not flexible. In addition, they are not typically suitable for large-scale production [1-4].

A flexible tactile sensor based on the PDMS and copper that detects pressure through the capacitance between copper electrodes was proposed [5]. However, detecting the capacitance is difficult because of parasitic capacitance. A flexible tactile sensor based on the metal array and pressure-sensitive material by the MEMS process was proposed [6]. However, it was made not stretchable by the metal array wiring.

Here, we report the use of a pressure-sensitive material to form a flexible tactile sensor. A composite material consisting of Multi-walled carbon nanotubes (MWCNTs) and a photocurable resin, which exhibits flexibility following curing, is used. We describe a fabrication process to create flexible tactile sensors based on this composite material.

2. Experiments

2.1 Experimental system

Fig. 1 shows a composed direct-write system that was used to dispense the MWCNTs pressure-sensitive material. The MWCNTs pressure-sensitive material was contained in a barrel, which was fixed to a *z*-axis stage. The nozzle was connected to the edge of the barrel, and could be translated using three axis linear stages (LPK Inc.). The flow from the pneumatic dispenser (ACCURA8-DX, Iwashita Engineering Inc.) can be controlled by adjusting the air pressure. The three translation stages and the pneumatic dispenser were placed on the optical table (DVIO-B-1812M-300T, Daeil systems Co.).

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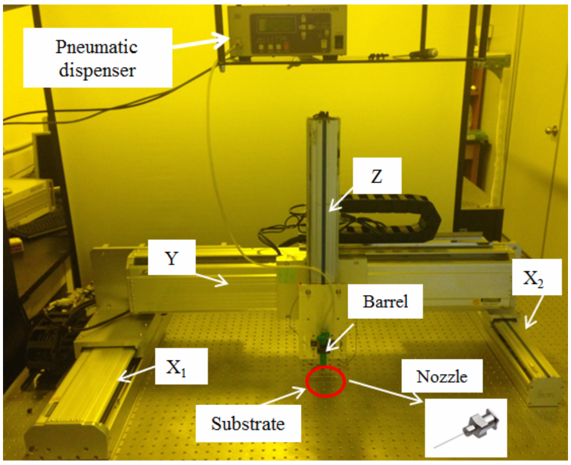


Fig. 1. Photograph of the direct-write system.

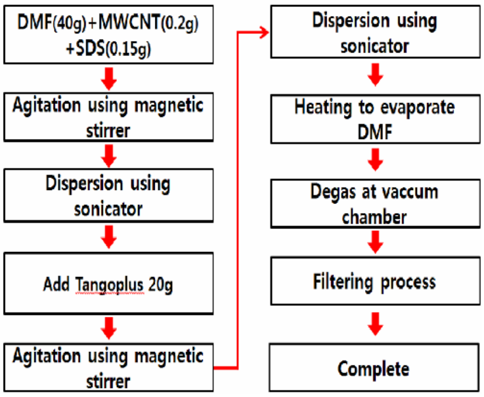


Fig. 2. Sensor material fabrication process.

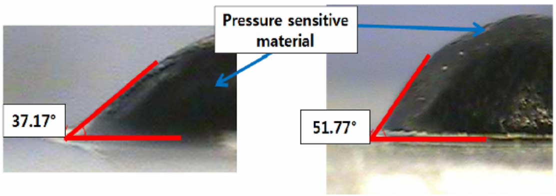
2.2 Sensor material

The MWCNTs pressure-sensitive material exhibits piezoresistivity; when the pressure-sensitive material is deformed, electrical resistance increases [7]. For these reasons, this material was applied as the flexible tactile sensor. To dispense the pressure-sensitive material using the direct-write system, it should be in a liquid state. In this regard, the MWCNTs (IGN, Nanolab) were dispersed into Tango-plus FLX 930 resin using a sonicator (Q700, Qsonica) [8, 9]. The Tango-plus FLX930 is a photocurable resin that reveals flexibility when cured by a UV ray. Fig. 2 shows the steps of the process of fabricating the MWCNTs pressure-sensitive material.

MWCNTs 0.2 g, SDS (Sodium dodecyl sulfate, ≥ 99.0%, Sigma-Aldrich) 0.15 g, and solvent (Dimethylformamide, ≥ 99.8%, Sigma-Aldrich) 40 g were blended using a magnetic stirrer for 5 minutes. Then, the sonicator dispersed the blended material, with the following conditions: amplitude 50 µm, 10-second run, and 2-second pause. Total operating time was 5 minutes. Here, SDS prevents the cohesion of the dispersed MWCNTs particle because they have a cohesive force.

Then, the Tangoplus FLX 930 was added into the dispersed material, and the sonicator dispersed the mixture using the same setup. For the elimination of the solvent, the mixture was heated on a hot plate at 100°C for 48 hr. If the mixture is heated over 100°C, it undergoes a phase change and reaches a solid state.

To remove bubbles created through blending and dispersing steps, the mixture should undergo a degassing process using a vacuum tool. Finally, the mixture was filtered using syringe filter with a pore size of 150 µm (Whatman). Using this process, MWCNTs pressure-sensitive material was fabricated, which has flexibility following curing and is liquid.



(a) (b)

Fig. 3. Contact angle on the substrate in response to MWCNTs pressure-sensitive material: (a) on a slide of glass; (b) on the cured Tangoplus FLX 930.

The contact angle is dependent upon the material properties of both the substrate and the dispensed material. A large contact angle is desirable for achieving a narrow line width, and a high areal density of sensitive lines. Fig. 3 shows the contact angle of the MWCNTs pressure-sensitive material on different substrates; Fig. 3(a) shows the contact angle on glass and (37.17°) and Fig. 3(b) shows the contact angle on a cured Tangoplus FLX 930 (Stratasys Inc.) (51.77°).

Tangoplus FLX 930 is a more suitable substrate for the generation of a narrow line width than glass is. In addition, the Tangoplus FLX 930 exhibits elasticity and flexibility following curing. For these reasons, the Tangoplus FLX 930 was selected as the sensor body material.

2.3 Fabrication methodology of the flexible tactile sensor

Fig. 4 shows a schematic of the fabrication process of the flexible tactile sensor [10]. The mold was a polymer material (VeroGray RGD850, Stratasys), which was formed using a rapid prototyping machine (EDEN-250, Stratasys). To detach the fabricated flexible tactile sensor from the mold, the mold was coated with polydimethylsiloxane (PDMS, Dowcorning-Sylgard®184). This material prevents the sensor from adhering to the mold.

The Tangoplus FLX 930 was poured into the mold to depth of 1 mm and was cured using ultraviolet light. Then, the MWCNTs pressure-sensitive material was dispensed. A pin header was then inserted into the mold to create electrical contacts between the measurement equipment and dispensed MWCNTs pressure-sensitive material. Then, the Tangoplus FLX 930 was poured again to a depth of 1 mm and was cured using ultraviolet light. In addition, the MWCNTs pressure-sensitive material was dispensed on it followed by the pin

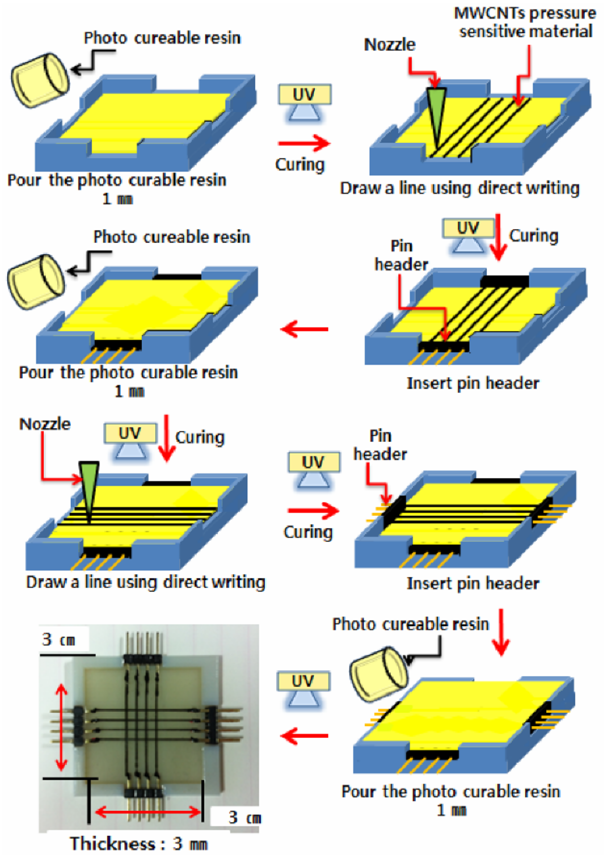


Fig. 4. Flexible tactile sensor fabrication process.

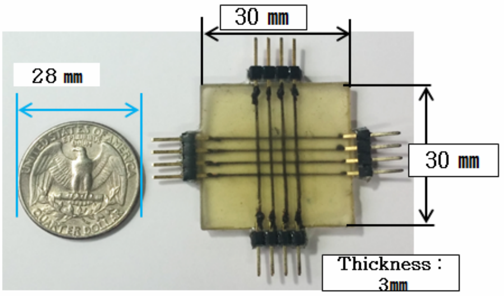


Fig. 5. Fabricated flexible tactile sensor.

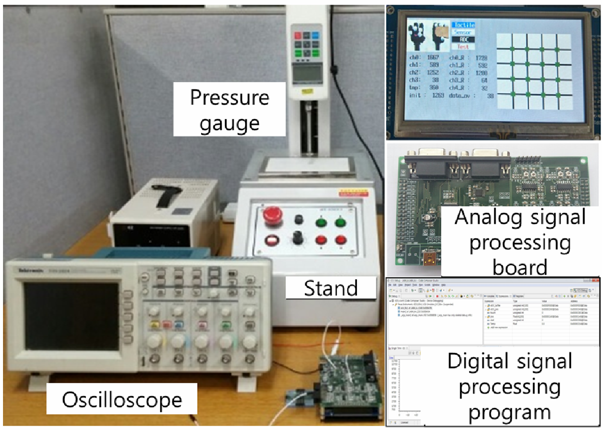


Fig. 6. Flexible tactile sensor test-bed system.

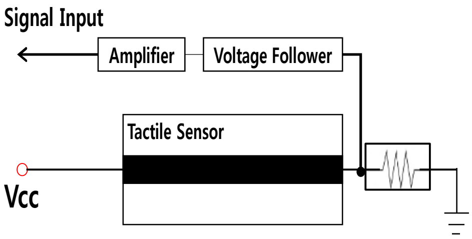


Fig. 7. Wiring diagram for sensing experiments.

header insertion. Finally, the Tangoplus FLX 930 was poured to cover the sensor. Then the sensor was removed from the mold.

The Tangoplus FLX 930 was used to form a protective and insulating layer that can be deformed in response to a pressure, allowing the MWCNTs pressure-sensitive material to provide a signal, and can be cured using ultraviolet light, which simplifies the manufacturing process. The lines of the sensor were arranged in a grid to enable the determination of the location of the pressure when the flexible sensor is affected by pressure.

Fig. 5 shows a fabricated flexible tactile sensor. The dimensions of the device were 30 × 30 × 3 mm. The MWCNTs pressure-sensitive material and the Tangoplus FLX 930 were cured using a 2000 mW/cm^2 intensity UV lamp for 10 minutes. The translation speed of the nozzle and the dispensing pressure were 10 mm/sec.

The flexible tactile sensor in Fig. 5 has a 4 × 4 matrix of detecting MWCNTs pressure-sensitive material lines. Therefore, there are 16 points of intersection. When a force is applied upon the intersection, its electrical resistance is changed. The changing range of the electrical resistance depends on the applied force [11, 12].

2.4 Sensor test set-up

In the fabricated flexible tactile sensor, the output signal includes noise because of the usage of materials that enhances the flexibility of the sensor. Fig. 6 presents the sensor-measurement system that assesses the performance of the sensor. The sensor-measurement system comprises three parts, including a signal-processing unit that measures sensor signal, a monitoring system, and a pressure gauge system. The signal-processing unit includes a filter for amplifying small signals, I/V converting, and noise reduction, as well as an ADC (Analog digital converter) system that digitally processes analogue signals arising from the sensor. Next, the monitoring system comprises a PC and embedded LCD that visualize the input signal from the sensor. Finally, the pressure gauge system comprises a proven pressure gauge and an automotive stand for constant external forces [13, 14].

The signal-processing unit is composed of a signal distribution resistance and amplifying circuit, as shown in Fig. 7. The signal amplification was set to five-times the sensor output in

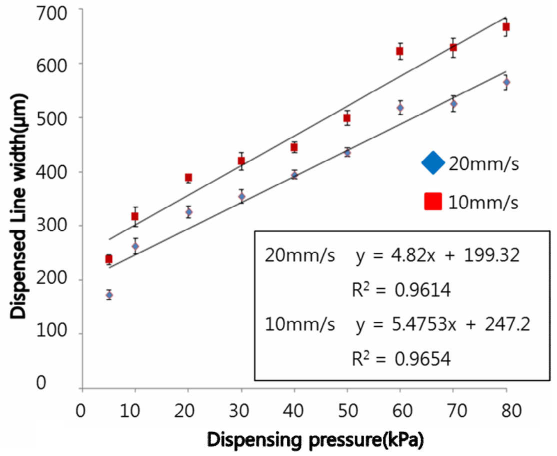


Fig. 8. Cured line width of the MWCNTs mixture at various dispensing pressures.

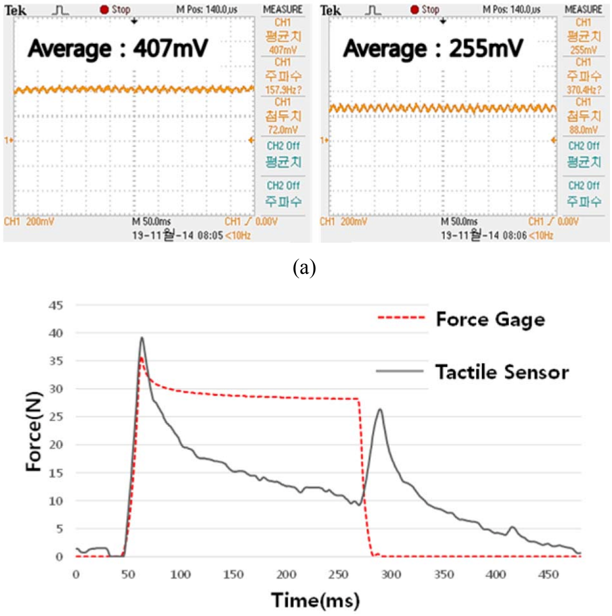
this study. According to the signal properties of the sensor output, an I/V convert or non-convert circuit was designed and a differential amplifier circuit was applied to compliment the constant signal level. The I/V circuit converts the resistance of the sensor into a usable voltage that can be read by the analog to digital converters, therefore reducing noise arising from the sensor. The differential amplifier circuit and low-pass filter designed in the signal processing unit were set at 1 MΩ after measuring the resistance of the sensing device, and the cut off frequency of the low-pass filter was set at 10 kHz. The controller in the signal-processing unit consists of a dsPIC33EP from Microchip Inc. that analyzes the output signal of the sensor and noise-filters the analog signal into the sampling frequency 15 kHz by designing an IIR filter at a 12 bit ADC signal.

3. Results and discussions

3.1 Fabrication characteristics of the MWCNTs pressure-sensitive material

To fabricate a precise tactile sensor, generating a high areal density of MWCNTs pressure-sensitive lines is desirable. The dispensing conditions, including dispensing pressure, nozzle size, and speed of the nozzle, are important parameters for achieving a small line width as well as contact angle.

The experimental system in Fig. 1 was used to examine the dispensing characteristics of the MWCNTs pressure-sensitive material. The diameter inside the nozzle was 180 μm (MN-28G-13, Iwashita Engineering Inc.), and the gap between the nozzle and substrate was 50 μm. The dispensing pressure was in the range from 10 kPa to 80 kPa, and varied in 10 kPa steps. Two translation speeds of the nozzle were investigated: 10 mm/s and 20 mm/s. The dispensed line widths were measured from images acquired using an optical microscope (OSM-U, Dong-won), and an image processing application (ITPlus-4.0, Alpha Systec). The line widths were measured 30 times and the average was calculated.



(a)

(b)

Fig. 9. Sensing performance of the fabricated sensor.

Fig. 8 shows the dispensed line width achieved using the direct-write system as a function of the pressure and translation speed of the nozzle. As shown in Fig. 8, line width increased approximately linearly as a function of the dispensing pressure at the same moving speed. However, the line width was smaller at higher translation speeds of the nozzle.

3.2 Performance of the fabricated sensor

Signal detecting experiments on the flexible tactile sensors using Tangoplus FLX 930 and MWCNTs were conducted. Fig. 9 presents the experiment results of the output signal on the external force (N) maintained on the sensor.

Fig. 9(a) presents an oscilloscope-measured value of sensor change upon the 10-N force exerted on the sensor, which shows a small change of around 152 mV. The graph in Fig. 9(b) implies that the output signal of the sensor can obtain responses on external forces and therefore capture the property of changing output value according to the force on the sensor. That is, the output value of the sensor responds to the changing force exerted upon the sensor and therefore is not constantly maintained in contrast to constant external forces. In particular, the increasing or decreasing status of an external force can be measured through comparison exercise of sensor outputs, which requires a standby time of approximately 160 ms until the restoration of the sensor to normal status.

4. Conclusions

We have described the fabrication of a tactile sensor formed from MWCNTs and a photocurable resin (Tangoplus FLX

930). The material was fabricated using ultrasonication dispersion, and exhibited piezoresistivity. This material was fabricated into a 4 × 4 mm array using a dispensing direct-write and additive manufacturing process, and the pressure, gap between the nozzle and substrate, and moving velocity were optimized to achieve a narrow line width. The resulting sensor had a dimension of 30 × 30 × 3 mm. In addition, the sensor`s signaling properties were assessed through experiment. To minimize noise arising from the sensor, the study designed a system composition and digital filter, and could find sensor characteristics of those made materials.

Acknowledgments

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