Recent Progress in Screen-Printed Smart Skin for Real-Time Load Detection in Structures

YU-JIN JUNG, HYE-KYOUNG JEON and SUNG-HWAN JANG

ABSTRACT

Civil engineering is constantly seeking innovative solutions to enhance the monitoring and maintenance of infrastructure. This is because traditional monitoring methods are often costly and time-consuming due to the use of multiple devices and manual inspections. Carbon nanotube (CNT)-polymer based self-sensing composites provide an innovative approach for structural health monitoring. Among these, composites fabricated using screen-printing techniques also offer the advantages of being cost-effective and suitable for mass production. In this study, we will manufacture a smart skin as a novel detection material for structural health monitoring by screen-printing CNT/polyurethane (PU) ink. The authors report on the optimized screen-printing design for the smart skin based on electrical characteristics and optical microscopy analysis for different mesh counts. Moreover, we investigate the electro-mechanical response of carbon nanotube-reinforced composite materials under impact loadings. Finally, we will present a new sensing system by applying the smart skin in a grid pattern to the structure, enabling the detection of various impacts. This innovative approach allows for the development of a versatile sensing system that can monitor and identify different types of impacts on the structure.

INTRODUCTION

In civil engineering, the monitoring and maintenance of infrastructure play crucial roles in ensuring safety and sustainability. Traditional structural health monitoring methods involve labor-intensive and expensive procedures, such as using multiple specialized devices and manual inspections. So, there is a growing demand for innovative solutions that can provide efficient and low-cost monitoring techniques [1-3].

Yu-Jin Jung, Ph.D. candidate, Department of Smart City Engineering, Hanyang University ERICA, Ansan, Gyeonggi-do 15588, South Korea
Hye-Kyoung Jeon, Ph.D. candidate, Department of Smart City Engineering, Hanyang University ERICA, Ansan, Gyeonggi-do 15588, South Korea
Sung-Hwan Jang, Associate Professor, Corresponding author, Department of Civil and Environmental Engineering, Hanyang University ERICA, Ansan, Gyeonggi-do 15588, South Korea

CNT-polymer composites have been proposed for many applications, such as self-sensing materials for structural health monitoring, damage detection in aerospace structures, and wearable electronics for healthcare monitoring [4-7]. These composites can detect and respond to various mechanical stimuli, allowing for real-time structural integrity monitoring. Additionally, screen-printing techniques for fabricating these composites offer significant advantages such as cost-effectiveness and scalability, making them suitable for large-scale production. Screen-printing technology has been extensively studied for various applications, including self-sensing materials for structural health monitoring. Xiaowu Tang and Kaibin Wu (2022) demonstrated the feasibility and potential for applying screen-printing technology using Ag paste and carbon nanotube composite ink [8]. Go et al. (2021) investigated strain sensors based on carbon black/CNT composite materials using a screen-printing technique and demonstrated that the samples could serve as flexible strain sensors [9]. However, there needs to be more research specifically focused on the influence of mesh count in screen-printing. Further investigations on the relationship between mesh count and the properties of printed materials are needed to enhance our understanding of the printing process and optimize the performance of printed composites.

This study focuses on developing a smart skin as a novel detection material for structural health monitoring in civil engineering applications. The smart skin is fabricated by screen-printing CNT/PU ink, providing a flexible and integrated sensing platform. The authors present optimized screen-printing designs for smart skin by analyzing electrical properties and optical microscopy images for different mesh counts. Furthermore, the electro-mechanical response of carbon nanotube-reinforced composite materials under impact loadings is investigated. Understanding the behavior and performance of the smart skin under several times loading conditions is essential to ensure its reliability and effectiveness in real-world applications.

Finally, we applied it to the structure as a grid-patterned multi-channel sensor. This approach offers the potential for a new large-area sensor system capable of detecting impacts acting on the structure. Additionally, applying a multi-channel sensor-based smart skin enables monitoring of the overall electrical property changes, facilitating the identification of the location and magnitude of impact loads. This functionality provides the potential for expanding structure health monitoring applications.

EXPERIMENTAL

Materials

CNT was purchased from Nanolab (MA, USA). CNT has an average diameter of 15µm, a length of 5-20µm, and a purity higher than 85wt%. A medium flexible PU casting resin (PX60 part A) and a hardener (PX60 part B) were obtained from Easy Composite (Stoke, UK). The viscosity of the matrix resin was from 450 to 650mPa.s, and the cure time was 1–2hr at room temperature. The solvent used for the dispersion of CNT was a high purity of acetone with 99.7% supplied by Samchun Chemical (Gyeonggi-do, South Korea).

Fabrication of smart skin using a screen-printing technique

The smart skin was fabricated by uniformly dispersing CNT in a PU matrix, according to previous studies [10, 11]. About 50 milliliters of acetone was used as a solvent for the dispersion of CNTs. Acetone readily dissolved the high-viscosity PU and enabled high-quality dispersion of CNT. An ultrasonicator of Qsonica (CT, USA) distributed the CNT in the matrix. In this study, the ultrasonicator was operated in pulsed mode (15sec on and 15sec off) for 40min in an ice bath to minimize the effect of overheating. The dispersed mixture was then placed on a hot plate at 60°C for 24h to evaporate the acetone. The PU hardener was added at a mix ratio of 1:1 and uniformly mixed using a three-roll mill of Trilos (CA, USA).

A smart skin sensor was fabricated by designing CNT/PU ink printing and top/bottom electrodes. The CNT concentration in the CNT/PU ink, which can be screen-printed, was fixed at approximately 3wt%. Theoretically, the fabricated CNT polymer ink can be printed on substrates such as paper, fabric, plastic, and glass. In this study, we report on the smart skin printed on an inkjet label sheet. The fabrication process of the smart skin using the screen-printing technique is shown in Figure 1. Firstly, conductive silver paint was printed on the inkjet label sheet to create the bottom electrode, which was then dried at room temperature for one day to solidify the electrode. Next, the CNT/PU ink was printed onto 30, 110, and 300 mesh screens at an appropriate speed and dried at room temperature for one day. Finally, a conductive silver paste was overprinted to create the top electrode, which was then dried at room temperature for one day to solidify the electrode. For comparison, all smart skin sensors were fabricated using the same procedure.

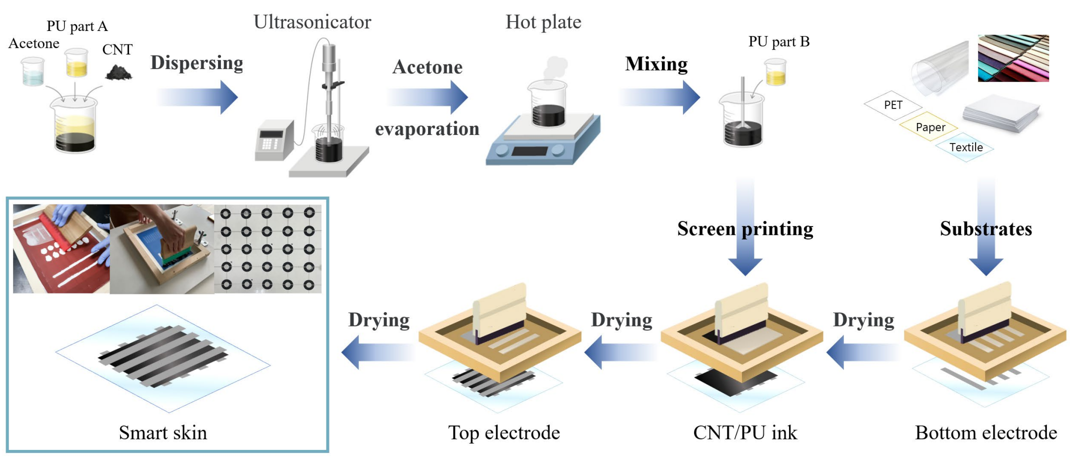


Figure 1. Fabrication process of smart skin applied with screen-printing technique

Characterization and measurement

The resistance of the smart skin was measured using a two-point probe resistivity measurement system of Keithley (OH, USA). Each data point was obtained by averaging five measurements taken from different samples. Additionally, optical microscope images of the screen-printed smart skin sensor were obtained using an electron optical microscope of Dino-Lite (Seoul, South Korea).

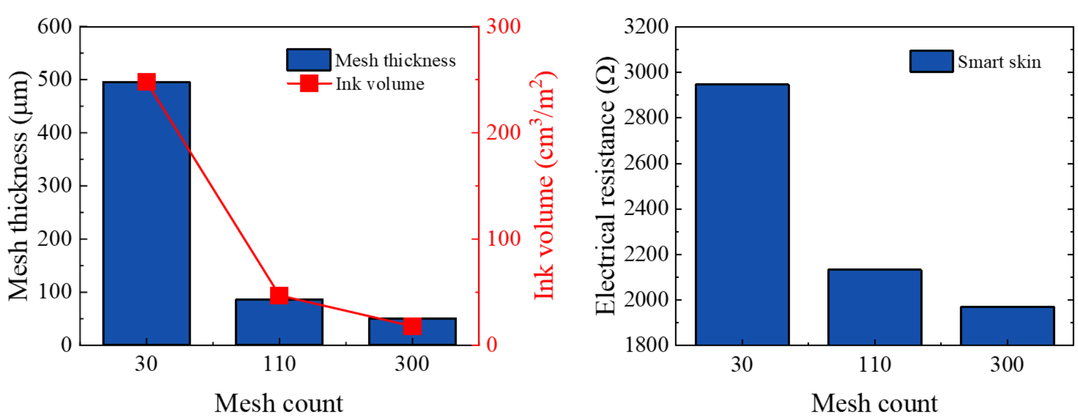
The electro-mechanical response of the smart skin was investigated under impact loading. During the mechanical testing, the electrical resistance of the samples was measured using a DAQ system. A drop impact tester of Instron (MA, USA) equipped with a 16 mm diameter hemispherical head was used for impact testing. The impact mass was kept constant for all samples while utilizing different impact heights to apply various impact loads. To ensure the accuracy of the measurement system, we conducted tests on five samples at each load condition.

RESULTS AND DISCUSSIONS

Printing and electrical characteristics of CNT/PU by mesh count

The printing and electrical characteristics of the smart skin sensor for different mesh counts of the screen are shown in Figure 2. As the mesh count increased, the thickness and the volume of ink passing through the mesh decreased. This is because the mesh becomes thinner and more tightly woven as the mesh count increases. Also, the printed CNT/PU ink showed a decrease in electrical resistance as the mesh count increased. This phenomenon can be attributed to an increased mesh count leading to a more closely packed and finer mesh structure, allowing for a larger contact area between the electrodes and a shorter path for the electrical current to travel. Consequently, the overall resistance of the CNT/PU ink decreased as the mesh count increased, indicating improved electrical properties.

The printing characteristics for each mesh count can be observed through the optical microscope images in Figure 3. At mesh count 30, it is evident that the printing was done with wide spacing, resulting in significant gaps between the printed areas. Furthermore, the thickness of the printing could have been more uniform due to the relatively thicker mesh. On the other hand, at mesh count 110, it can be observed that the printing was done without any noticeable gaps, and the printed areas exhibited a uniform thickness. At mesh count 300, an observation can be made that the printing was uneven and showed waviness. This can be attributed to the dense and extremely thin mesh, which resulted in an excessively thin printing thickness. As a result, 110 emerges as the appropriate printing mesh count for CNT/PU ink with a CNT content of 3wt%. It demonstrates a uniform and consistent printing quality, ensuring optimal performance for the smart skin sensor.



(a) (b)

Figure 2. (a) Printing and (b) electrical characteristics by mesh count of screen

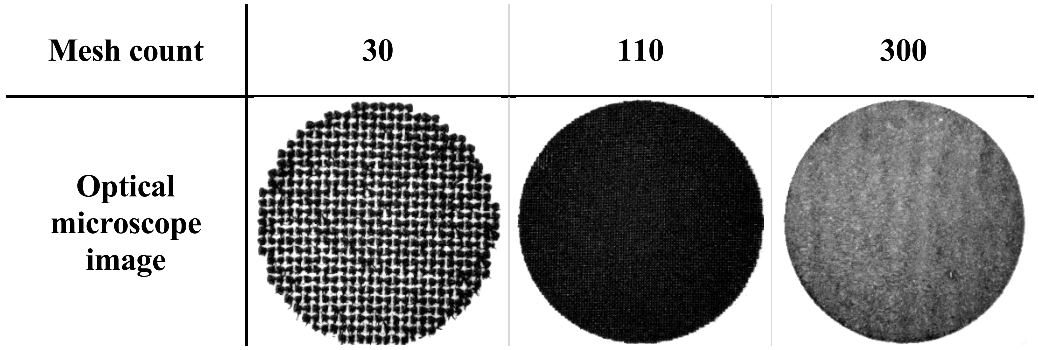
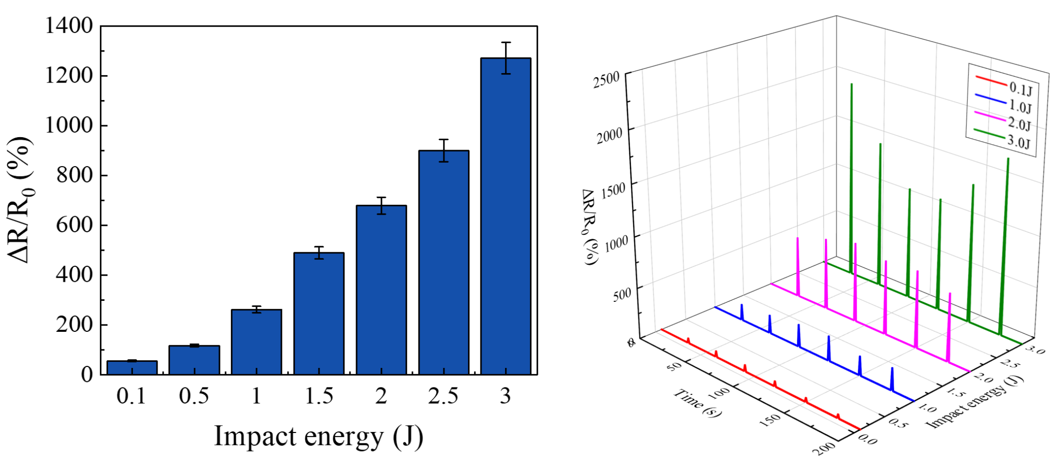


Figure 3. Optical micrographs image of screen-printed smart skins by mesh count

Electro-mechanical characteristics of smart skin by impact loads

Figure 4 shows a comprehensive depiction of the electro-mechanical behavior of the smart skin sensor when subjected to various impact loads. The results reveal a significant relationship between the impact energy and the rate of change of electrical resistance in the smart skin sample. As the impact energy increases, the magnitude of the electrical resistance variation in the smart skin also increases [12, 13]. These rapid changes in resistance effectively demonstrate the characteristic of smart skin to quantify and assess the magnitude of impact. One notable observation is the trend in electrical resistance of the smart skin when subjected to impact loads, as illustrated in Figure 4(b). During five repeated impact loads, the resistance of the smart skin reacts and returns in real time, highlighting its electrical change characteristics. By continuously monitoring the rate of change in electrical resistance, the smart skin sensor can also detect and analyze several times impact events immediately.



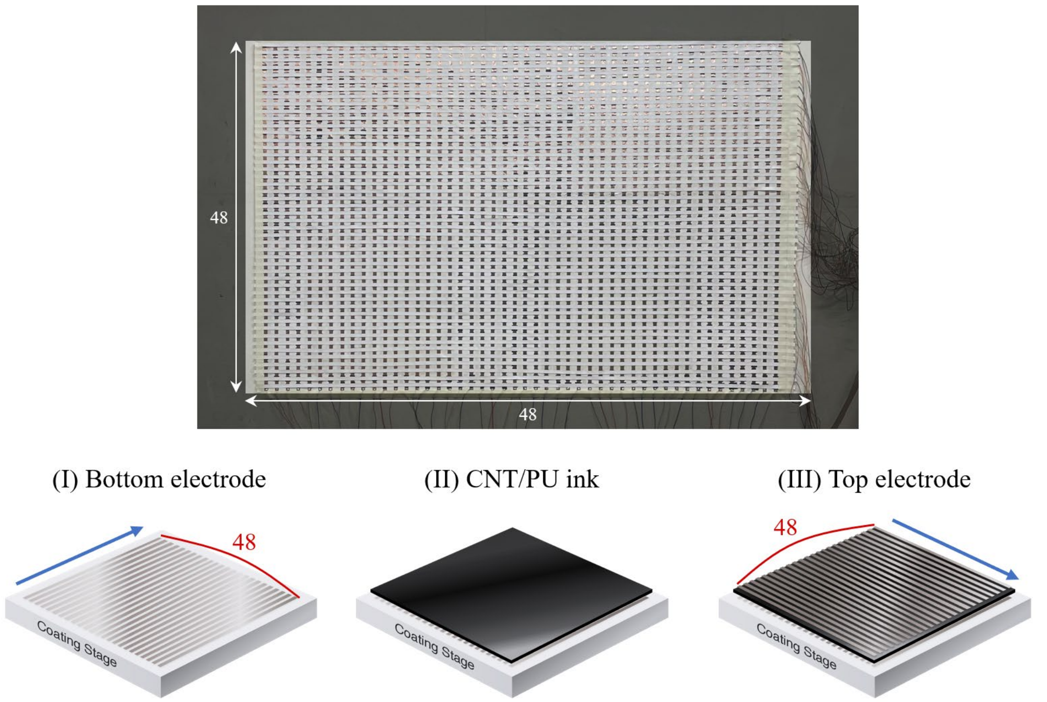
(a) (b)

Figure 4. Electro-mechanical characteristics of smart skin under various impact loads

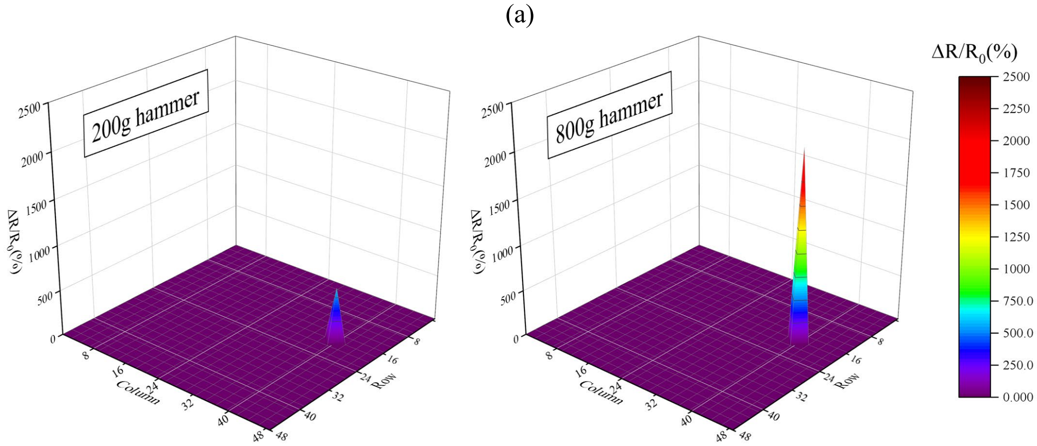
Application of smart skin to structure

The smart skin applied to the structure was fabricated in a grid format consisting of 48 horizontal and 48 vertical electrodes, as shown in Figures 5 and 6. To investigate the electrical-mechanical response of the multi-channel smart skin, impacts were applied using hammers of various weights.

As a result, pronounced electrical changes in the smart skin were observed due to impacts applied with different weights, as depicted in Figure 7. Additionally, no electrical signal was detected in areas of the smart skin where no impact load was applied. These findings highlight the real-time monitoring capability of the multi-channel sensor-based smart skin, easily identifying the location and magnitude of the impact load.



(a)



(b)

Figure 5. (a)Application process and (b)electro-mechanical characteristics of multi-channel smart skin under impact load

CONCLUSION

This study reports on the recent advancements of smart skin as a monitoring sensor for impact loads, utilizing screen-printing techniques. The smart skin exhibited different printing and electrical characteristics based on the mesh count. Optimal printing conditions were determined for CNT/PU ink. The electrical-mechanical properties of the smart skin were investigated under several times impact loads. The smart skin demonstrated excellent sensing capabilities in response to impact loads. Furthermore, it was successfully applied to large areas of structures and showed remarkable performance in detecting impact loads. The proposed smart skin can be utilized as a self-sensing infrastructure material, particularly suitable for civil infrastructure monitoring, leading to significant cost savings in maintenance. In the future, the author plan to expand their research to encompass various structural health monitoring aspects and develop a multi-sensor system to construct a comprehensive structural health monitoring system.

ACKNOWLDGEMENT

This work was supported by the Technology Innovation Program (20014127, Development of a smart monitoring system integrating 3D printed battery-free antenna sensor technology with AI optimization) funded by the Ministry of Trade, Industry & Energy (MOTIE, Korea) and the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2020R1C1C1005273).

REFERENCES

1. Gong, X., Huang, K., Wu, Y. H. 2022. “Recent progress on screen-printed flexible sensors for human health monitoring,” Sensors and Actuators A: Physical 345, 245, 113821.
2. Siahkouhi, M., Razaqpur, G., Hoult, N.A. 2021. “Utilization of carbon nanotubes (CNTs) in concrete for structural health monitoring (SHM) purposes: A review,” Construction and Building Materials, 309, 125137.
3. Nisha, M.S., Singh, D. 2016. "Manufacturing of Smart Nanomaterials for Structural Health Monitoring (SHM) in Aerospace Application Using CNT and CNF,” Nano Research, 37, pp. 42–50.
4. Jang, S.H., Yin, H.M. 2015. “Effect of aligned ferromagnetic particles on strain sensitivity of multi-walled carbon nanotube/polydimethylsiloxane sensors,” Applied Physics Letters, 106(14), 141903.
5. Jang, S.H., Yin, H.M. 2015. "Effective electrical conductivity of carbon nanotube-polymer composites: a simplified model and its validation," Materials Research Express, 2(4), 045602.
6. Raghavan, A., Kessler, S.S., Dunn, C.T. 2023. “Structural health monitoring using carbon nanotube (CNT) enhanced composites,” IWSHM-2009, 1, pp.1034-1041.
7. Du, J., Wang, L., Shi, Y. 2020. “Optimized CNT-PDMS Flexible Composite for Attachable Health-Care Device,” Sensors, 20(16), 4523, pp.1-13.
8. Tang, X., Wu, K., Wang, R. 2022. “Screen Printing of Silver and Carbon Nanotube Composite Inks for Flexible and Reliable Organic Integrated Devices,” ACS Applied Nano Materials, 5(4), pp.4801-4811.
9. Fang, Y., Li, L.Y., Jang S.H. 2021. “Piezoresistive modelling of CNTs reinforced composites under mechanical loadings,” Composites Science and Technology, 208, 108757.
10. Jang, S.H., Yin, H.M. 2017. "Characterization and modeling of the effective electrical conductivity of a carbon nanotube/polymer composite containing chain-structured ferromagnetic particles," Journal of Composite Materials, 51(2), pp. 171-178.
11. Jang, S.H., Li, L.Y. 2020. "Self-Sensing Carbon Nanotube Composites Exposed to Glass Transition Temperature," Materials, 13(2), 259.
12. Jang, S.H. 2020. “Self-Sensing Carbon Nanotube Reinforced Composites for Smart Cities. 5th International Conference on Smart Monitoring,” Assessment and Rehabilitation of Civil Structures, 25(1), pp.1-7.
13. Kim S.Y., Choi B.G., Baek W.K. 2019. “Impact paint sensor based on polymer/multi-dimension carbon nano isotopes composites,” Smart Materials and Structures, 28 (3), 035025.