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An investigation of contact resistance between carbon fiber/epoxy composite laminate and printed silver electrode for damage monitoring

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An addressable conducting network (ACN) enables the structural condition to be monitored by the electrical resistance between electrodes on surface of CFRP (carbon fiber reinforced polymer) structure. To improve the reliability of ACN for damage detection, the contact resistance between the electrodes and CFRP laminates needs to be minimized. In this paper, the silver nanoparticles electrodes were fabricated via printed electronics techniques on CFRP composite. The contact resistance between the silver electrodes and CFRP was measured with respect to various fabrication conditions such as the sintering temperature of silver nanoink and the surface roughness of CFRP laminates. The interfaces between silver electrode and carbon fibers were observed using scanning electron microscope (SEM). From the study, it was found that the lowest contact resistance of 0.3664 Ω could be achieved when the sintering temperature of the silver nanoink and surface roughness were 120 °C and 230 nm, respectively.

1. Introduction

There have been attempts to use thermally mendable polymers as a matrix of self-healing composites [1,2]. Since the thermally mendable polymers based on Diels–Alder (DA) reaction have ability to heal upon heating and good mechanical properties, they have possibility to be used as structural applications [3–5]. However, thermally mendable polymers literally need certain amount of heat energy to heal damages inside. Takahashi et al. introduced the concept of addressable conducting network (ACN) which is two pairs of metallic electrodes perpendicular to each other on the both surfaces of the thermally mendable composite [6,7]. The ACN uses carbon fibers network as a sensor for damage detection using electrical resistance change method (ERCM) and heat generator using electrical resistive heating. Two long metallic electrodes on both sides of a laminate which are perpendicular to each other make it possible to pin point the damage inside. And once the damage is detected, certain amount of current will be applied to the electrodes to heat up the specific area [8]. Also, ERCM has no expensive instruments comparing to optical fiber sensor and piezoelectric sensor, embedded monitoring system. Therefore, sensitive damage detection using ERCM and heating up the specific area without heating the entire laminate is essential for this type of self-healing composites.

The ACN has a potential application to develop self-healing composites if a thermally mendable polymer is used as the matrix. Subcritical damages in a carbon fiber composite with thermally mendable polymer matrix can be detected and repaired electrically by the ACN, meaning that ACN enables carbon fiber composite to self-heal as well as self-detect. For damage detection and heating using electrical current, the contact resistance between metallic electrode and a composite panel takes a big portion of the entire resistance between two electrodes. Also, the electrical contact resistance plays an important role in various bonding techniques, such as flip-chip bonding [9] and resistance spot welding [10]. The lower contact resistance between metal electrode and CFRP laminates means the better adhesion between the metal electrode and CFRP laminates. Also, it is crucial factor to realize the sensitive damage monitoring and resistive heating system with addressable conductive network. The localized heating around the electrode was occurred by the high contact resistance at electrode [11,12]. Therefore reducing the contact resistance is one of the big tasks to use ERCM. Kwok et al. showed sensitiveness of contact resistance due to surface roughness and heat concentration near electrodes area due to high contact resistance [11]. Electrical properties of silver electrode/CFRP structure such as contact resistance and sheet

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resistance is easily influenced than the mechanical properties by sintering conditions. Therefore, the in-depth study on contact resistance of silver electrode/CFRP structure is needed.

In this work, the silver electrodes were fabricated on the CFRP surfaces via printed electronics technique. The silver nanoparticles ink was printed and sintered varying the sintering temperature on the CFRP which has different surface roughness. Then, the electrical contact resistance between the electrodes were measured, from which the contact resistance was calculated. The surface of the sintered silver electrode was observed using scanning electron microscope (SEM) to characterize the morphology of the sintered silver electrode. Also, the cross-section of silver electrode/CFRP laminates was observed to check the silver electrode/CFRP interfaces. Tensile test for in-situ monitoring of contact resistance change was performed.

2. Experimental

2.1. Analysis of contact resistance

Fig. 1a shows a circuit diagram of electrical resistance between silver electrodes and a composite panel. As shown in Fig. 1a, the resistances are connected serially and the total resistance can be achieved by adding all the resistances. Since the electrical resistance of silver is much lower than the contact resistance and composite resistance, the total resistance $R^1{}_{total}$ can be expressed as shown in Eq. (1).

$$R^1_{total} = 2 \cdot R^{electrode}_{silver} + 2 \cdot R_{contact} + R_{composite} \approx 2 \cdot R_{contact} + R_{composite} \quad \left(\because R^{electrodes}_{silver} << R_{contact}, R_{composite}\right) \tag{1}$$

where R^1_{total}, $R^{electrode}_{silver}$, $R_{contact}$ and $R_{composite}$ are total resistance, resistance of silver electrode, contact resistance and composite resistance between neighboring electrodes, respectively.

Since R^2_{total} has two times longer composite resistance than that of R^1_{total}, it can be expressed as Eq. (2).

$$R^2_{total} \approx 2 \cdot R_{contact} + 2 \cdot R_{composite} \tag{2}$$

General form of the electrical resistance at the location x in Fig. 1b, can be expressed as Eq. (3).

$$R^x_{total} \approx 2 \cdot R_{contact} + x \cdot R_{composite} \tag{3}$$

Supposing that there is no distance between two electrodes, the total resistance is equal to the double of the contact resistance as depicted in Eq. (4). Therefore, if we draw a trend line of the plot of displacement vs. resistance, their intercept will be the double of the contact resistance.

$$\text{When} \quad x = 0, R^0_{total} \approx 2 \cdot R_{contact} \tag{4}$$

Since the resistance of air is much bigger and the resistance of silver electrode is much smaller than that of composite, the contact resistance is majorly dependent on thickness direction composite resistance as shown in Eq. (5).

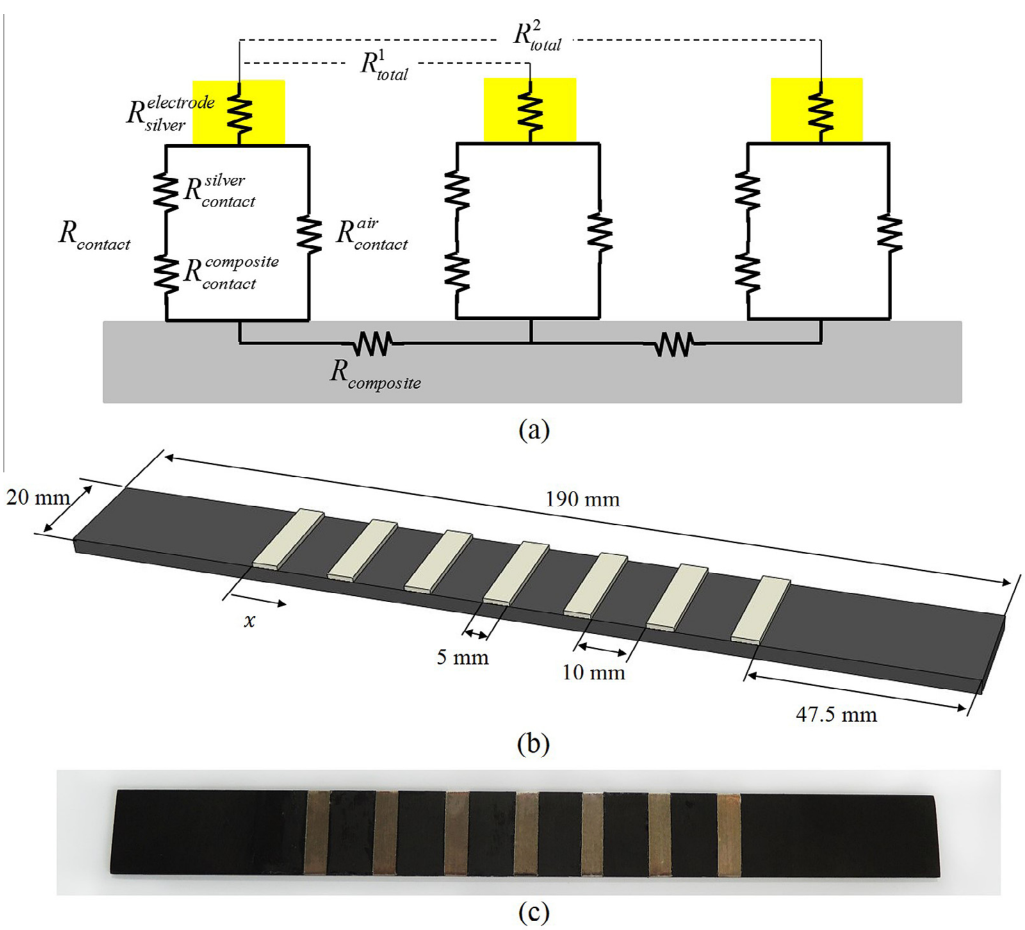

Fig. 1. (a) Circuit diagram of electrical resistance between the silver electrodes and a composite laminate, (b) schematic of the silver electrode/CFRP laminates structure and (c) photograph of the specimen; the silver electrodes were sintered on the CFRP laminates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)