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Instant electrode fabrication on carbon-fiber-reinforced plastic structures using metal nano-ink via flash light sintering for smart sensing

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The electrical-resistance-change method (ERCM) is a potential smart-sensing technique for carbon-fiber-reinforced plastic (CFRP) structures. However, a practical way to fabricate electrodes on CFRP structures, such as ink-jet printing with metal nano-inks, is necessary to reduce the time required for the process. As metal nano-inks can be sintered in a few milliseconds under ambient conditions using white-flash-light irradiation from a xenon lamp, the parameters of flash-light sintering such as light energy, duration, and number of pulses were investigated. The light intensity, which is the light energy divided by duration, was found to be an indicator of whether low electrical resistance was attained along with strong adhesion to the CFRP plate. The contact resistance between the electrode and CFRP plate was also examined in a tensile test to confirm the durability. The electrode sintered by flash light with the properly selected parameters exhibited high quality and strain monitoring capability.

1. Introduction

There has been much interest in the electrical-resistance-change method (ERCM) as a sensing technique for carbon-fiber-reinforced plastic (CFRP) structures. It utilizes an electrical network of conductive carbon fibers as a distributed sensor network by properly locating electrodes on structures [1–9]. For example, the changes in electrical resistance due to structural deformation enable strain monitoring [2–5], and those due to interruption in the electric current flow allow the detection of structural damages [6–9]. Furthermore, it may also be applicable to composites with thermally mendable polymers for resistive heating [9–12].

One advantage of ERCM over other monitoring methods is the simple installation required, which is applicable to existing structures without major structural modification or additional expensive equipment [13–15]. The electrodes can be formed on the structural surface using conventional methods. For example, at the laboratory level, commercially available silver pastes can be painted on polished surfaces with exposed carbon fibers. Electrodes prepared by electroplating are qualitatively more uniform, and they are feasible for mass production. These methods are not efficient in terms of time and labor, however, which prevent the application of ERCM to large-scale structures such as aircrafts and space structures. Simpler and faster ways of making a number of electrodes are necessary to maximize the advantages of ERCM.

In recent years, printed electronics has made remarkable progress as an alternative to standard techniques for the production of electronic devices. In particular, metal nano-inks have been widely used for electronic components since they can be simply transferred by ink-jet printing onto a substrate and then sintered by heating [16,17]. Metal nano-inks usually consist of typical conductive metals such as Au, Ag, and Cu nanoparticles, which require high temperatures (150–300 °C) over long periods (30–60 min) for the thermal-sintering process. The use of metal nano-inks was thought to be limited to thermally durable substrates, but a new remarkable sintering method has been proposed for polymer substrates, where metal nano-inks can be sintered in a few milliseconds at room temperature under ambient conditions using white-flash-light irradiation from a xenon lamp. There have been a number of

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reports regarding successful use of flash-light sintering to prepare electrodes on flexible polymer substrates [18–21].

The simple and fast process of flash-light sintering would be ideal for meeting the requirements of ERCM. However, its application to a CFRP laminate has been thought to be difficult because flash-light sintering results in low interfacial strength between the electrodes and the CFRP substrate. Although parametric studies of flash-light sintering have been conducted on flexible polymer substrates, the calculated effects would not be directly applicable to a CFRP substrate because of the high electrical and thermal conductivities of carbon fibers. On the other hand, our recent work showed that silver nano-ink can be used for electrodes on CFRP substrates when it is gradually sintered in an electric furnace [22]. Compared to conventional silver paint electrodes, silver nano-ink electrodes show comparable conductivity accompanied by superior bonding with the CFRP substrate. This result strongly suggests that flash-light sintering should be investigated for possible application to CFRP plates.

In the study reported here, flash-light sintering of silver nano-ink was used to form electrodes on a CFRP substrate for sensing by ERCM. The quality of the electrodes was first investigated by electrical-resistance measurements and SEM observations. The interfacial strength between the electrode and CFRP substrate, which is related to contact resistance, was also evaluated by a cross-cut tape test. Finally, the feasibility of using the electrode to monitor the structural health of the CFRP structure was examined by observing the changes in electrical resistance during a tensile test.

2. Flash-light sintering of silver-nano ink on CFRP laminate

2.1. Specimen preparation

A CFRP plate was prepared from prepreg sheets (PYROFIL #380, Mitsubishi Rayon Co. Ltd) that were unidirectionally laminated with a stacking sequence of $[0_8]_T$. It was fabricated by vacuum-bag molding, with a pressure of 0.65 MPa applied by clamps. The thickness of the laminate was 1.6 mm, and it was cut into 190 mm × 20 mm pieces with the carbon fibers directed longitudinally. The surface of each piece was polished by #400-grit coarse sandpaper to remove enough resin near the surface to expose the carbon fibers. It was then gradually smoothened by #800-grit and #2000-grit sandpapers for better contact with electrodes—our previous work showed that lower contact resistance and stronger interfacial strength were obtained on a smoother surface [22]. The electrodes created on the top surface had dimensions of 5 mm × 20 mm with a spacing of 10 mm, as shown in Fig. 1.

The silver nano-ink (DGP-OS (12000), Advanced Nano Products (ANP) Co., Ltd.) used for flash-light sintering had the same composition as that used in our previous work [22]. The polished surface was covered with masking tape except for the electrode area, where a few drops of silver nano-ink were uniformly spread using a spatula. After the nano-ink was dried for 30 min at 70 °C in an electric furnace, it was sintered via arc-plasma generation in the in-house system of a xenon flash lamp (PerkinElmer Co.). The lamp produced instant white light with a continuous light spectrum for a wide range of wavelengths from 160 nm to 2.5 μm. The silver nano-ink was placed underneath the flash lamp at a distance of 3 mm, and it was irradiated by high-intensity light in a projection area of 150 mm × 10 mm. The energy of the light pulses was controlled by an applied voltage released from a charged capacitor.

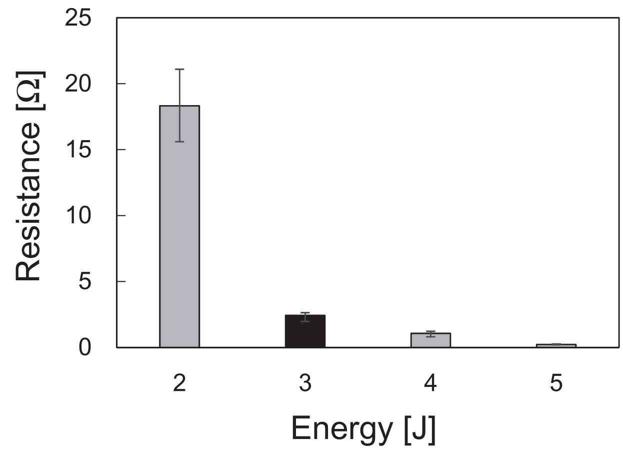

Fig. 2. Electrical resistance measured on electrode sintered by flash light at various levels of light energy.

2.2. Electrical resistance and interfacial strength

The flash light in the experimental setup was generated by controlling three parameters: light energy, pulse duration, and the number of pulses. Based on our earlier experience, the system was first set to a light energy of 3 J and a pulse duration of 5 ms. An electrical resistance of 2.4 Ω was measured on the sintered electrode by two probes; this is defined as the reference value. Fig. 2 shows the electrical resistance obtained at different light energies with fixed durations of 5 ms. The electrical resistance was much higher when the lower energy of 2 J was applied because it was insufficient for sintering; the higher light energy of 5 J resulted in the lower electrical resistance of 220 mΩ. In addition, the electrode became brighter when higher energy was applied, as shown in Fig. 3, indicating the progress of sintering. Owing to the excess light energy, most of the electrode that was sintered by the 5-J flash light delaminated from the CFRP substrate and peeled off easily [21,23]. The weak bonding of the electrode to the CFRP substrate might have been caused by evaporation of the epoxy resin.

The SEM images shown in Fig. 4 were taken (a) before and (b) after flash-light irradiation on the polished surface without silver nano-ink. Before the irradiation, the carbon fibers were partially

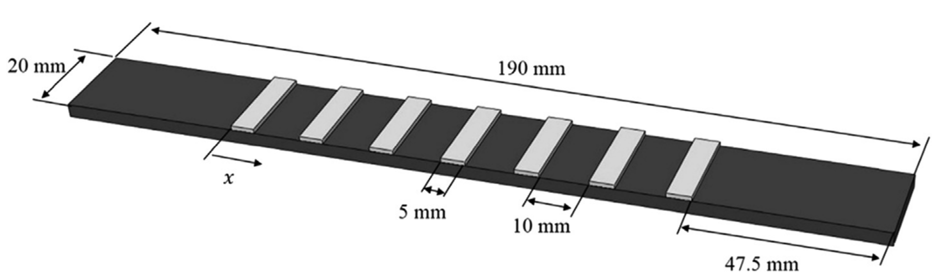

Fig. 1. Specimen dimensions.