Effects of Fabrication Method, Shape, Strain and Temperature on Conductive Properties of Smart Stress-Memory Patch

Fang Yuan*, Takayuki Shiraiwa and Manabu Enoki

Department of Materials Engineering, School of Engineering, The University of Tokyo, Tokyo 113-8656, Japan

Fatigue is an important factor of failure of structures such as bridges, buildings, etc. To prevent the failure, a sensing method of fatigue damage is desired. In previous studies, it was demonstrated that smart stress-memory patch is a suitable and effective method for fatigue monitoring, because it is possible to evaluate a number of fatigue cycles and stress amplitude of structurewirelessly. However, there are still some problems on the conductive property. For instance, using the conventional shape of conductive film, it was found out that the crack length could not be estimated accurately because sometimes the resistance of the conductive film was unstable and did not increase monotonically as the crack length increased. Moreover, effects of environment factors such as temperature and strain have not been figured out. The objective of this research is to clarify the effects of fabrication method, shape of conductive film and environment factors on conductive property of smart stress-memory patch to improve the sensitivity on the crack length measurement. The sensitivity of the smart patch was evaluated by changing the fabrication procedure and the shape of conductive film under strain-controlled fatigue testing. It was shown that the effects of strain could be ignored under atmosphere environment and the effect of temperature could be ignored until around 65°C.

[doi:10.2320/matertrans.MAW201404]

(Received April 17, 2014; Accepted June 19, 2014; Published July 26, 2014)

Keywords: structural health monitoring, crack length measurement, smart stress-memory patch, conductive film

1. Introduction

At the beginning of the 19th century, civil engineering developed extraordinarily. The development has made life easier and more convenient. However, it was not without problems. Some dramatic collapses took place like the collapse of Silver Bridge. Such accident still happens around the world nowadays, in spite of evolvement of engineering design and materials. These failures of structures may lead to injuries, deaths, or severe economic losses. It has been found out that the main reasons for the destruction of welding structures are related to fatigue.\(^1\) Thus, to prevent the failure of structure, it is important to monitor fatigue loading conditions.

Until now, a lot of methods have been developed for sensing of fatigue. However, there are some problems on the practical use such as necessity of wiring, electrical power supply and complicated measuring devices. Under such background, smart stress-memory patch (hereinafter called “smart patch”) has been developed. The smart patch is a pocket-sized wireless sensing method that realized the qualitative evaluation of fatigue damage.\(^2\)\(^–\)\(^9\) The sensor in the smart patch is composed of an ion-sputtered metal film deposited on a thin copper specimen with a pre-crack. After attaching the sensor to structure, a fatigue crack develops in the sensor, and the fatigue damage parameters such as number of cycles and stress amplitude of the structures are evaluated by measuring the crack length of the sensor. The crack length can be estimated by monitoring the electrical resistance change of the ion-sputtered metal film via wireless transmission. Then, the residual fatigue life of structures can be evaluated from the cyclic number and the stress amplitude. Although the smart patch is a very effective and convenient tool of monitoring fatigue, some problems exist on the practical use. One is a large-scale scattering in the relationship between the electrical resistance change and the crack length of the conductive film on copper specimen. As a result, the crack length cannot be estimated correctly from resistance change. The other is that the influences of environmental factors such as temperature and strain amplitude on the relationship between the electrical resistance change and the crack length are not clear.

In this research, the relationship between the electrical resistance change and the crack length of smart patch was evaluated by changing the fabrication procedure and the shape of conductive film in order to improve the sensitivity of crack length measurement. Furthermore, the influences of environmental factors such as strain and temperature on the smart patch were investigated.

2. Principles of Smart Patch

There are several basic principles of smart patch. Based on these principles, the estimation of crack length, cyclic number and stress amplitude, even residual fatigue life have been realized respectively.\(^5\)\(^–\)\(^7\)

Firstly, to realize a wireless sensing of fatigue by smart patch, it is essential to understand its crack length wirelessly. Once the relationship between electric resistance change of conductive film and the crack length is understood, it will never needed to set microscope upon smart patch for monitoring the crack length. Two calibration formulae have been reported. One is proposed by Ogawa et al. and the other one is derived by Deng et al. Ogawa et al. developed a carbon deposit technique, using electric resistance of a rectangle carbon film for crack length measurement of nonconductive materials. They have shown that the normalized resistance \(R/R_0\) could be expressed as,\(^10\)

\[
\frac{R}{R_0} = \frac{f}{(1 - a_f/W_f)} + (1 - f) \tag{1}
\]
Here, $W$ means the width of carbon film, $a$ shows the crack length and $R_0$ is the electric resistance when $a$ equals to zero, $f$ is a geometrical function determined by finite element analysis (FEA) of electric field distribution. The normalized crack length, $\alpha$, can be expressed as $a/W$. Moreover, the research by Ogawa et al., FEA of electric field distribution on ion-sputtered metal film was also conducted by Deng et al. to evaluate the change in electric current flow during the crack growth. The following expression is used to express the relationship between electric resistance and crack length:\(^{11}\)

$$R = R_0 + ca^b. \quad (2)$$

Here, $b$ and $c$ are constants. This equation can be transformed as following, if $\alpha$ expresses the normalized crack length, and $d$ equals the number obtained by dividing $c$ by $R_0$ and multiplying width of crack length to the power of $b$,

$$\frac{R}{R_0} = d\alpha^b + 1. \quad (3)$$

However, the physical meaning of expression has not been figured out, since feature of electron flow around crack tip is complicated.

Secondly, in order to judge fatigue damage to structures, cyclic number and stress amplitude are derived after obtaining the crack length data from the conductive film. It is well known that fatigue crack propagation can be divided into three stages and stable crack growth is observed where is represented as the Paris’ law. Using this Paris equation, the cyclic number, $N$, can be represented as the function of the normalized crack length, $\alpha$, and the stress amplitude, $\sigma$. Furthermore, if two sensors with distinct properties are employed to structure, two equations on the cyclic number $N$ can be obtained, respectively. From these equations, stress amplitude and cyclic number are derived respectively. Finally, it has been proved that residual life of structures can be estimated by smart patch in previous research. By knowing calculated fatigue cycles, stress amplitude, and material constants, the residual fatigue life can be evaluated.

3. Analytical Approach

3.1 FEA of electric field distribution

To investigate the relationship between resistance change and crack length in the conductive film, software Abaqus was used to perform the calculation of the electrical field distribution of the conductive film. Figure 1 showed an example of the FEA models. Since the shape of the conductive film was symmetrical up and down, only half of the shape was used in the simulation. Here, mesh size is 0.05 mm, $\Phi_0$ is the constant electrical potential of 1 V, $a_c$ is 0–1.9 mm, $W_c$ is 1.9 mm, $L$ is 8 mm (example) and $W$ is 1.05 mm (example). Insulating boundary conditions are applied on the notch surfaces and both side edges of the specimen. The material was designed to be platinum, which is the same as the experiments. The density, electrical conductivity, and thickness of conductive film were 21.37 kg/mm$^3$, 0.34 (Ω mm)$^{-1}$ and 8 mm, respectively. The normalized crack length, $\alpha$, equals $a_c/W_c$.  

Fig. 1 Boundary conditions in FEA and definition of $L$, $W$, $a_c$ and $W_c$ of conductive film.

3.2 Different patterns of conductive film

In order to improve the sensitivity of smart patch, four different shapes of conductive film were compared. The patterns were shown as Fig. 2. First, a typical rectangle shape was set as Shape 0, which is similar to an previous study.\(^6\) Then, the area near the crack was enlarged to increase influence of crack development (Shape 1). Furthermore, the path around the crack tip was narrowed in attend to control the route of the electric current (Shape 2). Finally, the area of conductive film away from crack path was minimized in order to reduce the absolute value of the initial resistance.
If the initial resistance is reduced, the change of electrical resistance during crack growth can be emphasized.

4. Experimental Approach

4.1 Fabrication method of smart patch

To realize wireless transmission, smart patch consists of five parts: copper specimen, insulating layer, conductive layer, electrical cables and connects between conductive film and electrical cables. The copper specimen is the most basic part of smart patch. Electrodeposited copper (ED-Cu) was chosen as the material of smart patch, because its crack grows stably in fatigue environment. Then, the insulating and conductive layers exist in order to measure the crack length. Finally, the electrical cable is connected between smart patch and measuring device. Here, two distinct ways of creating smart patch, shown as Fig. 3, were tried to improve the sensitivity since it was considered that making procedure influences the electrical properties of conductive film. The differences between methods 1 and 2 are as following: compared to method 1, the surface of sensor specimen was polished to a mirror finish in method 2. For method 2, the specimen was insulated by insulating vanish, instead of insulating spray, and smart patch was connected to electrical resistance meter through conductive epoxy, instead of conductive copper tape.

4.2 Fatigue experiment

To compare the sensitivity of smart patch under different conditions, fatigue experiments were conducted. ED-Cu sheet with a thickness of 0.1 mm was cut to rectangular coupons with a dimension of 40 mm × 5 mm. A single notch with a length of 2.5 mm and a width of 0.3 mm was induced at the center from one side of the coupon. The notch tip was round-shaped with a radius of approximately 150 µm. Additionally, the notch tip was sharpened to curvature radius of about 30 µm by a razor blade (High-stainless 100 µm, Feather Safety Razor Co., Ltd.). Then, the conductive film was fabricated according to method 1 and 2, and the fatigue tests were carried out under strain-controlled condition. During the experiments, the crack length was caught by CCD camera. Simultaneously, the electrical resistance of the conductive film on smart patch was measured by an electrical resistance meter. Both of the data were saved in the computer. Fatigue tests were carried out under constant strain amplitude with strain ratio of 0.5, frequency of 19 Hz, sinusoidal curve type. The maximum strain was changed to $2 \times 10^{-3}$, $3 \times 10^{-3}$, $4 \times 10^{-3}$ respectively. Three samples were used for each condition to verify the reproducibility.

4.3 Temperature experiment

Experimental setup was shown as Fig. 4. Temperature was monitored by thermocouple on real time and data was recorded through data logger and computer. At the same time, resistance of conductive film was recorded continuously by resistance meter and computer. During experiments, smart patch was heated up by electric stove and cooled up in atmosphere. After it returned to the room temperature, smart patch was observed by laser microscope. Five experiments were conducted. The maximum temperature were controlled as 33°C, 45°C, 55°C, 75°C and 100°C respectively.

5. Results and Discussion

5.1 Effects of fabrication method

The effect of making procedures on the electrical property of smart patch was investigated. Figure 5 showed the relationships between resistance change and normalized crack length, when using smart patches made by methods 1
and 2. The results showed that the sensitivity of electrical resistance change to crack growth were almost the same for both the method 1 and 2. Overall, the resistance rose as crack development. Near the beginning of crack growth, the resistance did not change a lot. However, for method 1, the resistance was not stable and the resistance did not increase monotonically as the crack length increased, when normalized crack length was less than 0.4. This large scattering problem did not appear in case of using method 2. To clarify the reason of this difference, these conductive layers were observed by optical microscope. The results were shown in Fig. 6. From these pictures, it was figured out that conductive film made by method 2 was smoother than method 1. This is considered as the main reason for the difference of experimental results’ difference.

There may be two main reasons why the conductive layer surfaces made by different making procedure were distinct. The first one was that surface of sensor specimen was polished first in method 2. The second one was that insulating layer made by vanish was smoother than that of spray. Besides, connecting the sensor to electrical resistance meter through conductive epoxy instead of copper tape may contribute to this difference as well, because the epoxy conducting part is steadier than tape.

5.2 Effects of shape of conductive film

The sensitivity was evaluated by FEA and fatigue testing with four types of conductive film. Figure 7(a) shows the results of FEA about the relationship between resistance change and normalized crack length when changing the shape of the conductive film. To make smart patch more sensitive, for the same normalized crack length, the larger resistance change is the better. Thus, from above results, it was understood that the sensitivity of smart patch was improved by changing shape of conductive film from shape 0 to 1, 2, 3, and shape 3 was the best shape among them. Furthermore, calibration curves (presented by Ogawa and Deng respectively), which may represent the relationship between resistance’s change of conductive film and crack length, were applied to the results in this research. Calibration curve in Deng’s work agreed with the results in this research more than Ogawa’s. The reason was considered that the shape of conductive film was quite different from Ogawa’s, which was a regularly rectangle shape.

![Fig. 5 Relationship between resistance change and normalized crack length when using Methods 1 and 2.](image)

![Fig. 6 Surface of conductive film when using methods 1 and 2.](image)

![Fig. 7 (a) Relationship between resistance change and normalized crack length when using Methods 1 and 2; (b) surface of conductive film.](image)
Although the simulation results showed shape 3 is the most sensitive on crack length measurement, this numerical model neglects several factors such as microcrack around the main crack, electron mean free path in thin conductive layer, thickness variations and surface roughness. These factors can be affected the electrical properties in conductive film. To verify the results of simulation, fatigue experiments under same conditions were conducted for four shapes of conductive films. Deng’s calibration curve was also applied to all results (Fig. 7(b)). The results of fatigue experiments agreed with what was presumed by FEA, both of which showed that shape 3 was the most suitable shape for conductive film of smart patch. Here, range of normalized crack length was set to be from 0 to 0.8, because crack development was stable in this range.

The scattering in electrical resistance change was also evaluated. The estimation error of fatigue crack length for shape 1, 2 and 3 was calculated to be 258 µm, 432 µm, and 259 µm respectively. The error for shape 1 was small as a result that resistance did not scatter much as crack growth. The value of error range of shape 3 was less than shape 2. It verified that shape 3 was the best shape among them.

Moreover, it was understood from Fig. 7 that, to the same normalized crack length, the absolute values of resistance change in fatigue tests were smaller than FEA. There were several reasons. The main one was considered that conductive film created for experiments was not exactly in the same condition as what was calculated in FEA. As shown in Fig. 8, the crack did not grow in the right center of conductive film vertically because of the accidental errors. Thus, at the beginning of crack development, the resistance did not change much as crack growth, as a result that conductive film did not break in the right center of conductive film vertically as expected. Except this, other reasons could also be considered. For instance, surface of conductive film was not perfectly smooth or thickness of conductive film was not uniform.

5.3 Effects of strain

The influence of strain on smart patch was also investigated. Figure 9(a) showed relationships between resistance change and normalized crack length under different strains, derived from data of fatigue experiments. Under different strain conditions, the relationship did not change over all. Moreover, Deng’s calibration curve was applied to these relationships as well. The coefficients $b$ and $d$ were calculated for each experiment and results were plotted in Fig. 9(b). The average values of coefficients $b$ and $d$ under same experiment conditions, derived based on results, were connected by dotted lines. From which, it was known that coefficients did not change much under different strains. Thus, effects of strain on smart patch could be ignored.

Besides, the scattering of results was a little large as Fig. 9 showed. The large scattering of results was considered because of differences in making procedure for different smart patches. The main possible reasons were considered as following: surface of smart patch was not perfectly polished to every smart patch; thinning proportion of vanish differs as time passes; the effects of temperature on conductive film.

5.4 Effects of temperature

In order to figure out the effects of temperature on smart patch, relationships between temperature and resistance change were obtained based on the data from temperature experiments. They were shown in Fig. 10. The results showed that in static condition, the effect of temperature on resistance could be ignored until around 65°C, above that,
resistance dropped down. When heating up from 20°C to 65°C, all layers expanded, and the resistance rose due to the reduction of the cross-section area of conductive film. After the temperature exceeded 65°C, the insulating layer became flexible due to the heat, and the resistance dropped down even when temperature was raised above 65°C. Then, when cooling down from 100°C to 65°C, the conductive film continued contracting and the resistance got down.

Fig. 10 Relationships between resistance change and temperature under different temperature experiments. The maximum temperature was (a) 33°C, (b) 55°C, (c) 75°C, (d) 100°C.

Fig. 11 Pictures caught by optical microscopy. Areas of both insulating (left half of picture) and conductive (right half of picture) were shown. The maximum temperature was (a) 55°C, (b) 75°C.

Pictures caught by optical microscope were compared in Fig. 11. Area of both insulating (left half of picture) and conductive (right half of picture) was shown. It could be understood from the results that, as temperature was raised, the roughness of insulating layer did not change much. However, that of conductive film became higher as temperature rose. The data of arithmetic average of the 3D roughness, \( S_a \), obtained from laser microscope also verified
that. The value of $S_a$ was 0.86 µm and 1.15 µm when maximum temperature was 55°C and 75°C respectively.

6. Conclusion

(1) The measurement accuracy of smart patch was improved by changing fabrication procedure. Two fabrication methods were compared through fatigue experiments to find the suitable one. The results showed that for both methods, relationship between resistance change and crack length was almost the same. Nevertheless, for method 1, large scattering problem appeared when the normalized crack length was less than 0.4. Thus, method 2 was a more suitable method to create smart patch. It was because method 2 created smoother conductive layer.

(2) To make conductive film more sensitive to crack growth, the influence of shape of conductive film on smart patch was investigated. Different patterns of conductive film were compared through simulation and fatigue experiments. Both results showed that the sensitivity of smart patch was improved by changing shape of conductive film and shape 3 was the best among three shapes.

(3) Effects of strain amplitude on smart patch were also figured out. Performances of smart patch under different strain environments were recorded. The results showed that effects of strain could be ignored under atmosphere environment.

(4) In order to figure out effects of temperature on smart patch, resistance change under different temperatures was monitored. The results showed that effect of temperature could be ignored until around 65°C, in static condition. Above that, resistance dropped down. It might be because of the change of resistance film under a high temperature.

REFERENCES