Evaluation of Crack Closure in Intelligent Structure Member with Embedded SMA*

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Crack closure in epoxy resin plates with embedded shape memory (SMA) wires as an actuator in intelligent structure members was investigated as a function of the length of crack, duration of the supply of electric current to the SMA wires and the volume fraction of the SMA wires under tensile loads using photoelastic experiments. The effect of heat generation due to the SMA wires in the plate was also investigated. The crack closure was evaluated by the stress intensity factor obtained from photoelastic fringes generated near the crack tip. The results showed that the closure strongly depended on the crack length and duration of the current supply. The closure was not found in the plate with a crack which did not pass through the SMA wires. A complete cessation of the supply caused the disappearance of the closure with time. Continuous current supply resulted in change in quality of the epoxy matrix and separation of the SMA wires from the matrix. The intermittent current supply prevented the separation and maintained the closure.

Key Words: Intelligent Structures, Intelligent Materials, Shape Memory Alloy, Crack Closure, Stress Intensity Factor, Crack, Photoelasticity

1. Introduction

Intelligent material is defined as material which is equipped with sensor, processor and actuator functions⁽¹⁾⁻⁽³⁾ and is being developed in many fields. In the field of structural materials, there have been several attempts at prevention of crack generation and closure of generated cracks by means of metals and polymers with embedded shape memory alloy (SMA), which is an effective actuator in intelligent materials^{(4),(5)}. These studies have been limited to the production and theoretical propositions of a composite material which yields compressive residual stress in the matrix. In order to obtain practical material having the functions of crack prevention and crack closure, the properties of SMA embedded in materials

and the interactions between the SMA and matrix must be evaluated.

From this standpoint, the relationship between the amount of prestrain in SMA wires embedded in an epoxy resin plate and crack closure has been investigated⁽⁶⁾. However, in order to recover the SMA shape, the total area of the specimen was increased at high temperature. Heat generation due to the supply of electric current to a SMA wire is desirable for actual use.

In this study, crack closure in epoxy resin plates with embedded SMA wires was investigated as a function of the crack length, duration of the supply of electric current to the SMA wires and the volume fraction of the SMA wires under tensile loads, using a method for generating heat via the current supplied. In addition, the effect of heat generation due to the SMA wires in the plates was investigated.

2. Experimental Method

2.1 Epoxy resin plate embedded SMA wire

The SMA used was a TiNi wire 0.5 mm in diameter with 290 MPa maximum recovery stress, 6% shape recovery, and 58°C austenite finishing temperature,

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A_f . The SMA wires with 4.6% prestrain produced by 200 MPa stress were embedded in epoxy resin plates. The epoxy plates were produced from the compound

Fig. 1 Stress-strain curves of SMA wire

Fig. 2 Stress-strain curves of epoxy resin

Fig. 3 Young's modulus of SMA wire

Fig. 4 Young's modulus of epoxy resin

with Araldite-CY230 : hardener-HY956 = 100 : 20 in a weight ratio. Figures 1 and 2 show the stress-strain curves of the SMA wire and epoxy resin under tensile loads, respectively. Figures 3 and 4 show the Young's modulus of the SMA wire and epoxy resin as a function of temperature, respectively.

The SMA wires were fixed during the formation of the plates to prevent recovery of the SMA shape during high heat generation in the initial stage of the molding. A steel plate of 0.15 mm thickness with silicone grease applied to the surface was placed in the mold before adding the mixture of Araldite and hardener, in order to form a notch of about 0.2 mm to simulate a crack.

2.2 Amount of electric current supplied to SMA wire

The recovery of the SMA shape depends on the temperature, and when the temperature exceeds A_f , the shape recovers completely. The temperature depends on the amount of current supplied. In order to determine the amount of current supplied, the temperature on the surface of a SMA wire was measured as a function of the amount and duration of the current supplied using an infrared camera. The results for the SMA wire with about 4.6% prestrain produced by 200 MPa stress are shown in Fig. 5. These results showed that a current supply of more than 1.5 A produced complete shape recovery, that of 2.5 A produced the fastest complete shape recovery, and that the temperature was almost constant after the first 10 s. An abnormal memory property was, however, found for the 2.5 A current supply. Hence a supply of 1.5 A or 2 A current, for which the recovery was complete for the first 7 s or 4 s, respectively, was found to be suitable in this study.

On the basis of a preliminary examination, the amount of electric current supplied to the SMA wire in the matrix was selected to be 1.5 A.

Fig. 5 Relationships between duration of current supplied to SMA wire and temperature on SMA wire surface

2.3 Crack closure function test

Figure 6 shows the specimens used for investigating the effects of the duration of current supply to the SMA wires, the crack length and the volume fraction of the SMA wires on crack closure. Specimen A of a volume fraction of the SMA wire, V_f , of 0.0785% had a crack which did not pass through the SMA wire. Lengths, L , between the SMA wire and the crack tip of 0, 2, 4 and 6 mm were used. Specimen B of $V_f = 0.736\%$, which was about ten times the V_f of specimen A, and $L = 2$ mm had three SMA wires. Specimen C with the same V_f as that of specimen A had a crack which passed through the SMA wire.

An electric current of 1.5 A was supplied for 60 s to the SMA wires in the specimens under a tensile load of 314 N in a photoelastic measuring apparatus, as shown in Fig. 7, and thereafter the current was switched off.

Photoelastic fringes, known as isochromatics,

(a) Specimen A with $V_f = 0.0785\%$

(b) Specimen B with $V_f = 0.736\%$

(c) Specimen C with $V_f = 0.0785\%$

Fig. 6 Shape and dimension of specimens

generated near the crack tip, as shown in Fig. 8, were recorded using an 8 mm video camera, and used to calculate the stress intensity factor, K_I , using the Irwin method⁽⁷⁾ according to the equation

$$K_I = \frac{n\sqrt{2\pi r_m}}{\alpha t \sin \theta_m} \left[1 + \left(\frac{2}{3 \tan \theta_m} \right)^2 \right]^{-0.5} \times \left(1 + \frac{2 \tan (3\theta_m/2)}{3 \tan \theta_m} \right) \quad (1)$$

where n is the fringe order, α is the photoelastic sensitivity, t is the specimen thickness, r_m is the distance from the crack tip to a point on a required fringe and θ_m is the angle along r_m . In order to improve the accuracy of the measurement of K_I , methods for multiplying the original isochromatics and extracting the isochromatics⁽⁸⁾ were used.

In order to evaluate the function of crack closure in the specimens, we used the variation rate of K_I , ΔK_I , defined by

$$\Delta K_I = \frac{K_{I(0)} - K_{I(t)}}{K_{I(0)}} \times 100 \quad (2)$$

where $K_{I(0)}$ is K_I before current supply to the SMA wires, and $K_{I(t)}$ at time t after the supply. The cracks in the specimens are closed when ΔK_I is negative, and open when ΔK_I is positive.

2.4 Observation of change in quality due to heat generation

Heat generation from the SMA wires, which was necessary to recover the SMA wire shape, was

Fig. 7 Experimental setup

Fig. 8 n , r_m and θ_m used for calculating stress intensity factor, K_I , in Irwin's method

assumed to change the quality of epoxy matrix. In order to investigate that change, a specimen 75 mm long, 40 mm wide and 5 mm thick with one embedded SMA wire was used. An electric current of 1.5 A was supplied for 1 h to the SMA wire in the specimen under the no-load condition in the apparatus shown in Fig. 7. Thereafter the current was switched off, and residual isochromatics were observed.

3. Experimental Results

3.1 Effect of crack length on crack closure

Variations in isochromatics near the crack tip among specimen A of $L=2$ mm, and specimens B and C when electric current was switched on are shown in Figs. 9, 10 and 11, respectively. In these figures, the SMA wires are indicated by the black horizontal lines and the cracks by the black segmented lines at the lower center. The fringe order of isochromatics before the current was supplied to specimens A and B,

Fig. 9 Variation in isochromatics in specimen A of $L=2$ mm for current supply duration of 60s

Fig. 10 Variation in isochromatics in specimen B for current supply duration of 60 s

Fig. 11 Variation in isochromatics in specimen C for current supply duration of 60 s

in which the cracks did not pass through the SMA wires, shown in Figs. 9 and 10, increased with time. On the other hand, that in specimen C, in which the crack passed through the SMA wire, shown in Fig. 11, decreased with time.

Figure 12 shows the relationships between the duration of current supply to the SMA wires and the variation rate of the stress intensity factor, ΔK_I . For specimen A of $L=0$ mm, K_I was not obtained because isochromatics near the crack tip were disturbed due to heat generation from the SMA wire. In this figure, the values of ΔK_I in specimen A decreased gradually with time. This decrease implied that crack closure was not obtained. Crack closure in specimen B, of which V_f was about ten times that of specimen A, was also not obtained. The values of ΔK_I in specimen C increased gradually with time.

These results showed that crack closure in the specimens in which the crack did not pass through the SMA wires did not occur independently of the crack length and the volume fraction of the SMA wires, and that closure in the specimen in which the crack passed through the SMA wires occurred. The crack opening was inferred to be due to bending round the crack tip of the matrix between the side with a crack and the SMA wires because only the matrix near the SMA wires was compressed by the shape recovery of the SMA wires, and the matrix outside the compressed matrix elongated due to thermal expansion.

3.2 Time dependence of crack closure

Figure 13 shows ΔK_I in specimen C as a function of time for the current supply duration of 60 s and after electric current was switched off. The value of ΔK_I was restored to that before the current supply for a duration of about 420 s. Hence, the crack closure after the current was switched off also depended on time. This implied that crack closure was maintained when the temperature in SMA was above about A_s , but was lost when the temperature became below about A_s .

Fig. 12 Variations in ΔK_I in specimens A, B and C for current supply duration of 60 s

Fig. 13 Variation in ΔK_I in specimen C for current supply duration of 60 s and after current was switched off

Fig. 14 Effects of heat generation from SMA wire on epoxy matrix around SMA wire for continuous current supply duration of 1 h

3.3 Change in quality of matrix and its prevention

Figure 14 shows residual isochromatics in an epoxy matrix around the SMA wire for a continuous current supply duration of 1 h. In this figure, the SMA wire is shown by the black horizontal line. High-order isochromatics, which imply extensive change in quality due to heat generation, were found around the SMA wire in Fig. 14(a), but did not exit outside the two black triangles which were cracks generated in the epoxy matrix. Parts of the SMA wire on the left and right sides of the left and right triangular cracks separated from the matrix. The separation started at the locations of the cracks for the current supply duration of about 80 s, and proceeded gradually toward the outside from the central cracks.

In order to decrease the changes in quality and the separation, the temperature in the matrix around the SMA wire must be reduced. In order to reduce the temperature, decrease of the amount of current supplied is considered. However, such a decrease may increase the duration necessary to recover the complete shape of the SMA wire, or may prevent complete shape recovery because of low temperature in the SMA wire.

Therefore, the following technique of intermittent current supply was proposed. First the current was

Fig. 15 Cycle of intermittent current supply

(a) Central part (b) Right side

Fig. 16 Effects of heat generation from SMA wire on epoxy matrix around SMA wire for intermittent current supply duration of 1 h

(a) Continuous (b) Intermittent

Fig. 17 Temperature distribution obtained for continuous and intermittent current supply duration of 1 h

supplied to the SMA wires for the duration necessary to close the crack, and then, in order to cool the matrix, switched off for a duration for which closure function was maintained. Whenever the closure function was lost, the current was again supplied just before the loss occurred. Figure 15 shows a cycle for intermittent current supply. This cycle was determined empirically.

In order to investigate the effectiveness of the cycle shown in Fig. 15, residual isochromatics were observed on a specimen similar to that used to obtain the isochromatics shown in Fig. 14. The results are shown in Fig. 16. Change in quality due to heat generation, shown in Fig. 16(a), decreased in comparison with those in Fig. 14(a), and no crack or separation was observed. Around the end of the specimen, no separation was found, except for in a limited zone close to the end.

Figure 17 shows the temperature distributions on the specimen surface for an intermittent current supply of 1 h measured using an infrared camera, and a

Fig. 18 Variation in isochromatics in specimen C for intermittent current supply duration of 24 h

continuous current supply of 1 h. A temperature of about 37°C was obtained for the intermittent supply, and about 61°C for the continuous supply. This indicated that the intermittent supply can be used to control the amount of remaining heat in the matrix. Therefore, the intermittent current supply was found to decrease changes in the quality of the epoxy matrix due to heat generation, and to prevent the separation of the SMA wire from the matrix.

3.4 Maintenance of crack closure for a long duration

Figure 18 shows variation in isochromatics near the crack tip in specimen C for an intermittent current supply of 24 h. Isochromatics for the first 1 h were maintained for about 20 h, and no changes in quality due to heat generation were found. This implied that intermittent supply was effective for maintaining crack closure for a long duration.

4. Conclusions

Crack closure in epoxy plates with embedded SMA wires was investigated as a function of the crack length, duration of the supply of electric current to the SMA wires and the volume fraction of the SMA wires. The results were as follows.

(1) The closure function in the specimens in which the crack did not pass through the SMA wires for a fixed duration of the current supply was not

obtained, regardless of the crack length and the volume fraction of the SMA wires, but the closure in the specimens in which the crack passed through the SMA wire was obtained.

(2) The closure function in the specimens in which the crack passed through the SMA wire after the current supply was switched off decreased with time.

(3) Continuous current supply resulted in changes in the quality of the epoxy matrix and separation of the SMA wire from the matrix. The intermittent current supply prevented the separation and maintained the closure for a long duration.

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