Crack Control in Titanium Nickel Fiber Reinforced Polycarbonate Composites

Cheong-Cheon Lee* and Akira Shimamoto

Saitama Institute of Technology, Okabe, Saitama 369-0293, Japan

Titanium nickel fiber reinforced composites have great potential as intelligent materials. In this paper, titanium nickel fiber reinforced polycarbonate composites are developed with different prestrains of the embedded titanium nickel fiber. The effect of reducing the stress concentration, the enhancement of mechanical properties and the resistance to deformation of the titanium nickel fiber reinforced polycarbonate composites were investigated. The stress intensity factor, $K_I$, was determined using photoelasticity and digital image processing to examine the crack closure effect in the titanium nickel fiber reinforced polycarbonate composites. The result shows that the crack closure effect is dramatically improved. The shape memory effect and the thermal expansion behavior of the matrix, caused by temperature increases, improve the resistance to fracture by decreasing the stress intensity factor, $K_I$. The effect of crack closure is attributed to the compressive stress field in the matrix due to the shrinkage of the titanium nickel fibers above the austenitic finishing temperature ($A_f$).

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1. Introduction

Research and development into improving the mechanical properties of composite materials, reducing the material degradation of machines and ensuring the durability of the structures is important in terms of safety for industrial applications. Therefore, the development of material systems with artificial self-enhancement, such as intelligent materials, is indispensable.

There are several research studies that have been carried out into intelligent composite systems that actively suppress fracture damage. For example, Rogers et al.\(^1\) reported the possibility of controlling the stress intensity factor at the crack tip based on the current-carrying shrinkage phenomenon of a shape memory alloy of titanium nickel wire that was implanted in the bottom of a notch. However, a systematic study for this proposal has yet to be performed. In previous papers, Shimamoto, Furuya and Taya et al.\(^2\) proposed a design concept for composite materials that enhanced mechanical properties with a shape memory alloy, and also revealed the crack closure action of the composite materials.\(^2\)\(^-\)\(^7\)

In this study, shape memory titanium nickel fiber reinforced polycarbonate matrix composite is developed as a photoelastic model material with the shape memory effect. The stress reducing effect above the reverse transformation temperature $A_f$ was examined and the value of the stress intensity factor, $K_I$ (fracture toughness) in the vicinity of the notch tip was calculated by photoelasticity.

2. Experimental Procedure

2.1 Product of titanium nickel fiber reinforced polycarbonate composite

Shape memory alloy Ti-50.2 at%Ni fiber of 0.4 mm in diameter was used. The titanium nickel fiber was maintained for two minutes at an atmospheric temperature of 470°C and then quenched into ice water. Polycarbonate resin (Lexan 121 pellet, GE plastics Co., Ltd.) was used for the matrix. The schematic diagram shown in Fig. 1 is the fabrication process of the titanium nickel fiber reinforced polycarbonate composite. We produced four kinds of specimens which were differentiated by their prestrain in the embedded titanium nickel fibers as 0, 1, 3 and 5%. In order to produce the specimen, the titanium nickel fibers (3 fibers) were fixed by a tensile prestrain device. Then, the fibers were put between the polycarbonate pellets. After that, the pressure and temperature on the specimen were gradually changed, as shown in Figs. 2 and 3. After the molding device was taken out of the hot press, the specimen in the molding device was cooled down to room temperature naturally. The titanium nickel fiber was separated from the tensile prestrain device and the specimen was extracted from a shaping die.

To obtain the experimental results on the stress intensity factor calculation, an edge notch was created in the specimen of 4.5 mm in length and 0.3 mm in width, with a notch tip angle of 60° created using a milling cutter, and the center...
Notch was developed in the specimen of 10.0 mm in length and 0.5 mm in diameter using an end mill and a cut saw with a saw tooth angle of 60° where the processing center notch is not a cut of the titanium nickel fiber.

Figure 4 and Table 1 show the geometry of the specimen and the mechanical properties of the materials where the volume fraction of the titanium nickel fiber embedded in the matrix is 0.42%.

2.2 Adhesive strength between the matrix and the fiber

The basic mechanism of the load transfer between the matrix and the fiber can be explained by considering a bar of a single fiber in a matrix material (see the Fig. 5). The load transfer between the matrix and the fiber takes place through the shear stress at the interface. When the applied load is tensile, the shear stress, τ, can be developed on the outer surface of the fiber. Its magnitude decreases from a high value at the end of the fiber to zero at a certain distance from the end. The tensile stress, σ, in the fiber cross section has the opposite trend, starting from a value of zero at the end of the fiber to its maximum at a certain distance from the end. The two stresses are balanced with the applied load P. The distance from the free end to the point denotes the characteristic distance where the normal stress attains its maximum and the shear stress becomes zero. The pure tensile state continues along the rest of the fiber.

2.3 Evaluation of the stress intensity factor by the photoelasticity

The tester for this experiment is a Tensiron/RTM-1T tensile device with an isothermal bath and a photoelastic device which is schematically shown in Fig. 6. The stress concentrated at the crack tip is where the 4th or 5th photoelastic fringe order appeared. Thus, the entire specimen was heated in eight steps in the isothermal bath. The stages of temperature are 293, 303, 313, 323, 333, 343, 353, and 363 K. Shape memory reverse transformation above the austenitic finishing temperature, A_f, occurred. The change in the value of the stress intensity factor, K_I, at the crack tip due to the heating shrinkage of the titanium nickel fiber was observed from the changing photoelastic fringe pattern in the vicinity of the notch-tip.
of the crack tip. Sequentially, series pictures of the photoelastic fringe pattern were taken using a CCD (charge-coupled device) camera. They were analyzed using a personal computer according to the change in temperature. One of the problems with this method is that the photoelastic fringe pattern were taken using a CCD camera according to the change in temperature. To minimize the error, the stress intensity factor, \( K \), was calculated, the distance, \( r \), and the angle, \( \theta \), from the crack tip to the furthest point on the fringe are measured as shown in Fig. 7. Then, the stress intensity factor \( K \) value was determined using eq. (1).\(^{12}\)

\[
K = \frac{N_{m} \sqrt{2\pi r_{m}}}{a \sin \theta_{m}} \left[ 1 + \left( \frac{2}{3 \tan \theta_{m}} \right)^{2} \right]^{-0.5}
\]

where \( N_{m} \) is the fringe order, \( a \) is the specimen thickness, and \( \alpha \) is the photoelastic light intensity. To minimize the error, the range of \( \theta_{m} \) of \( 73.5^\circ < \theta_{m} < 134^\circ \) is chosen and for the stress intensity factor, \( K \), values from 2 or 3 fringe loops\(^3\)
were calculated. Then, we estimated the crack closure by means of the value of the stress intensity factor, \( K \).

3. Theoretical Evaluation Methods

3.1 Longitudinal Young’s modulus

Under a uniaxial load (\( F_{c} \)) on the composite, the load is shared by a fiber (\( F_{f} \)) and a matrix (\( F_{m} \)) as follows:

\[
F_{c} = F_{f} + F_{m}
\]

The loads taken by the fiber, the matrix and the composite can be written using stresses and cross sectional areas of these components as follows:

\[
\begin{align*}
F_{c} &= \sigma_{c}A_{c} \\
F_{f} &= \sigma_{f}A_{f} \\
F_{m} &= \sigma_{m}A_{m}
\end{align*}
\]

where \( \sigma_{c} \), \( \sigma_{f} \) and \( \sigma_{m} \) are the stresses in the composite, fiber, and matrix, respectively, and \( A_{c} \), \( A_{f} \) and \( A_{m} \) are the areas of the composite, fiber, and matrix, respectively.

Assuming that the stresses of the fiber, the matrix and the composite follow Hooke’s law, and the fibers and the matrix are isotropic, the stress-strain relationships for each component can be described as follows:

\[
\begin{align*}
\sigma_{c} &= E_{c}\varepsilon_{c} \\
\sigma_{f} &= E_{f}\varepsilon_{f} \\
\sigma_{m} &= E_{m}\varepsilon_{m}
\end{align*}
\]

where \( \varepsilon_{c} \), \( \varepsilon_{f} \) and \( \varepsilon_{m} \) are the strain in the composite, the fiber, and the matrix, respectively, and \( E_{c} \), \( E_{f} \) and \( E_{m} \) are the Young’s moduli of the composite, fiber, and matrix, respectively.

Substituting eqs. (3) and (4) into eq. (2), equaling the strain (\( \varepsilon_{c} = \varepsilon_{f} = \varepsilon_{m} \)) in the composite, fiber, and matrix, and using the volume fractions, the following equation is obtained.

\[
E_{c} = E_{f}V_{f} + E_{m}V_{m}
\]

where \( V_{f} (= A_{f}/A_{c}) \) is the fiber volume fraction and \( V_{m} (= A_{m}/A_{c}) \) is the matrix volume fraction.

3.2 Recovery force of the specimen with the prestrain

As shown in Fig. 8, under the unloading tensile prestrain (\( \varepsilon_{p} \)) of the titanium nickel fiber in the composite, the load between the fiber (\( F_{f} \)) and the matrix (\( F_{m} \)) are in equilibrium as follows:

\[
\Delta L/2 = \frac{\varepsilon_{p}}{2}
\]

Fig. 8 Concept diagram of contraction deformation by the prestrain.
$F_i + F_m = 0 \quad (6)$

Substituting eqs. (3) and (4) into eq. (6), the following equation can be obtained.

$E_i\varepsilon_i A_i + E_m\varepsilon_m A_m = 0 \quad (7)$

The contraction strain due to the prestrain is described by the following equation.

$\varepsilon_i = (L - L_0 - \Delta L)/L_0 = \varepsilon_{ps} - \Delta L/L_0$

$\varepsilon_m = -\Delta L/L \quad (8)$

where $L$ is the initial length of the specimen, $L_0$ is the initial length of the fiber and $\Delta L$ is the contraction deformation length.

Substituting eq. (8) into eq. (7), the contraction deformation length by the prestrain is calculated using the following equation.

$\Delta L = \frac{E_i A_i \varepsilon_{ps}}{E_i A_i L_0^{-1} + E_m A_m L^{-1}} \quad (9)$

### 3.3 Theoretical stress intensity factor

One of the most important parameters in fracture mechanics is the plane-strain fracture toughness, $K_{ic}$. This is the critical value of the stress intensity factor, $K_i$ at which fracture takes place. This situation can be compared with the case of conventional stress analysis where the working stress reaches the yield point of the material.

In general, the theoretical calculation of the stress intensity factor, $K_i^{th}$, under tension was done using the applied stress, $\sigma$, the crack length, $a$, and the specimen width, $w$. The theoretical stress intensity factor, $K_i^{th}$, is obtained using the following formula:

$K_i^{th} = Y \sigma \sqrt{a} = Y K_0 \quad (10)$

where $\sigma$ is the applied stress calculated assuming that no crack is present, and $Y$ is the finite width compensation coefficient for the side-crack specimen, $Y_{side}$, and the center crack specimen, $Y_{center}$, which are determined from the following equations:

$Y_{side} = 1.12 - 0.23(a/w) + 10.56(a/w)^2 - 21.74(a/w)^3 + 30.42(a/w)^4 \quad (11)$

$Y_{center} = \frac{1 - 0.5(a/w) + 0.326(a/w)^2}{\sqrt{1 - (a/w)}}$

### 4. Results and Discussion

#### 4.1 Mechanical properties of materials

The measured reverse transformation temperature of the titanium nickel fibers with a differential scanning calorimeter (Shimadzu DSC-60) is shown in Fig. 9. The transformation temperatures of the titanium nickel fiber are the martensitic starting temperature, $M_s = 318.16$ K, martensitic finishing temperature, $M_f = 309.19$ K, austenitic starting temperature, $A_s = 315.59$ K, and austenitic finishing temperature, $A_f = 323.88$ K.

Figure 10 shows the stress-strain curve of the titanium nickel fiber as a function of temperature. Young’s modulus and the yield strength increase as the temperature increases. The ultimate strength is 1.55 GPa at temperatures from 293 to 373 K.

Figure 11 presents the results of the Young’s moduli of the titanium nickel fiber and polycarbonate under different temperatures. As shown in Fig. 11, the Young’s modulus of the titanium nickel fiber rapidly increases at more than the austenitic finishing temperature, but Young’s modulus of the polycarbonate decreases as the temperature rises.

Figure 12 shows the recovery force of the titanium nickel fiber due to the heating shrinkage. The recovery force was measured after the residual strain was at room temperature. As shown in Fig. 12, the recovery force increases with increasing temperature, in which the rate of increase in temperature was 5 K/min. Interestingly, the recovery force of the initial strain of 9% was lower than that of the initial strain of 8%. This suggests that the initial strain of 8% is the threshold level. Above this threshold, a complete recovery of the material by heating is not achieved.

Figure 13 shows the results of the tensile test of the polycarbonate, and the titanium nickel fiber reinforced polycarbonate composite (prestrain=0%) was done with a
strain rate of $2.0 \times 10^{-4} \text{s}^{-1}$ at room temperature (293 K). As a result, the Young’s modulus and the tensile strength of the composite increases by 17.7% and 6.3% more than those of the polycarbonate, respectively. From eq. (5), the theoretical Young’s modulus of the composite increases 16.2% more than those of the polycarbonate.

Figure 14 shows the tensile test of the adhesive strength between the matrix and fiber with a strain rate of $2.0 \times 10^{-4} \text{s}^{-1}$ at room temperature. From Figs. 5 and 14, the maximum adhesive strengths (that is, the shear stress, $\tau$) of the specimens with prestrains of 0, 1, 3, and 5%, are 138 MPa, 151 MPa, 252 MPa, and 271 MPa, respectively.

4.2 Estimation of the crack closure effect with the stress intensity factor

Figure 15 shows an example of the photoelastic fringe pattern of the specimens (titanium nickel fiber prestrain and crack location) at each ambient temperature level under a constant tensile load of 196 N (applied stress of 2.2 MPa). As the temperature in the isothermal bath increases, the distance $r_m$ from the crack tip to the furthest point of the each isochromatic fringe loop decreases rapidly below an austenitic finishing temperature of 323.88 K. The stress in the vicinity of the crack tip decreases as the titanium nickel fiber prestrain increases due to the shape memory effect of the titanium nickel fiber, the compressive force according to the titanium nickel fiber prestrain, and the different thermal expansion coefficients between the polycarbonate matrix and the titanium nickel fiber. It can be seen in Fig. 16 that the compressive force exists in the unloading state of the specimen (that is, the load = 0 N) at a temperature of 363 K. This is caused by the shape memory shrinkage effect of the titanium nickel fiber, which generates the compressive force.

Figure 17 shows an example of a digital image processing image of photoelastic stripes. We measured accurately the distance $r_m$ and the angle $\theta_m$ from the image to the furthest point.

The relationships between the temperature in the isothermal bath and the stress intensity factor $K_I$ value for the titanium nickel fiber with prestrains of 0, 1, 3, and 5%, respectively are shown in Figs. 18 and 19.

Figure 18(a) shows that the $K_I$ values decrease by 29.6% at 293 K, 31.9% at 303 K, 34.8% at 313 K, 37.6% at 323 K,
69.8% at 333 K, 73.2% at 343 K, 75.5% at 353 K and 77.5% at 363 K for specimens with an edge notch and a prestrain of 5%, compared with those with only a polycarbonate matrix at 293 K. It can be seen from Fig. 18(b) that the $K_I$ values decreased by 23.2% at 293 K, 25.9% at 303 K, 30.0% at 313 K, 31.6% at 323 K, 2.3% at 333 K, 78.5% at 343 K, 82.8% at 353 K and 86.2% at 363 K for specimens with center notches and a prestrain of 5% compared with those with only a polycarbonate matrix at 293 K. It was difficult to evaluate the $K_I$ values when the ambient temperature was above 353 K since the photoelastic fringes around the vicinity of the crack tip decreased rapidly. It is noted that the stress in the vicinity of the crack tip decreases due to the shape recovery of the titanium nickel fiber at 323.88 K which is the reverse transformation temperature of the titanium nickel fiber. On the other hand, in the case of only polycarbonate, the stress intensity factor, $K_I$, increases with temperature because of the polycarbonate which is a thermoplastic resin softened due to the thermal influence.

Figure 19 shows the relationship between the stress intensity factor $K_I$ and the prestrain of the titanium nickel fiber for gradual temperature changes. For the stress intensity factor, $K_I$, the value decreased as the prestrain increased. From Fig. 19(a), in the case of the specimen with an edge notch at a temperature of 363 K, the $K_I$ value decreased by 75.7% as the prestrain increased from 0% to 5%. Moreover,
Fig. 17 Picture of image processing of isochromatic fringe sharpening.

Fig. 18 Stress intensity factors for various cases of temperature under tension. (a) Edge notch (b) Center notch.

Fig. 19 Stress intensity factors for various cases of prestrains under tension. (a) Edge notch (b) Center notch.
from Fig. 19(b), in the case of the specimen with a center notch at a temperature of 363 K, the $K_I$ value decreased by 85.5% as the prestrain increased from 0% to 5%.

From these results, it can be seen that, under the same tensile load at 293 K, the $K_I$ value of the composite with a prestrain of 0% is lower than that in pure polycarbonate. This is because the polycarbonate of the composite matrix shows a smaller deformation and a greater elastic modulus compared with only the polycarbonate, as shown in the eq. (5) and Fig. 13. On the other hand, in the case of the composite with a prestrain, the $K_I$ value decreases with increasing contraction of the matrix due to the increasing prestrain of the titanium nickel fiber, as shown in the eq. (9). In addition, the titanium nickel fiber prestrain at the elastic limit was generally less than 8%. When the temperature increases, the Young’s modulus of the titanium nickel fiber increases, and when the temperature of the titanium nickel fiber becomes higher than the austenitic finishing temperature, super-elasticity appears and a rapid shape recovery develops by the properties of the shape memory alloy.

From the above results, it is suggested that the proposed intelligent composites in this study can contribute to the establishment of long lasting and safe structures and machines.

5. Conclusion

The effectiveness of the titanium nickel fiber polycarbonate composite that has self-reinforcement behavior on the high temperature side was examined. The following results were obtained:

1. The fracture resistance improvement is caused by the shape memory effect of the titanium nickel fiber, regardless of the crack location. The value of the stress intensity factor, $K_I$, decreases with a rising ambient temperature in the titanium nickel fiber reinforced polycarbonate composites.
2. The effect of the crack closure is attributed to the compressive stress field in the matrix due to the rapid shrinkage of the titanium nickel fibers above the austenitic finishing temperature.
3. The value of the stress intensity factor, $K_I$, decreases as the amount of prestrain increases.

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