

EFFECT OF THE SMART CURE CYCLE ON MECHANICAL PROPERTY OF CARBON EPOXY COMPOSITE LAMINATE

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Abstract

In general, a thermal residual stress is generated during a curing process of composite laminates due to the difference of coefficient of thermal expansion of each layer. The thermal residual stress during the fabrication process make the mechanical properties of composite laminates weaken such as fatigue life and dimensional accuracy and tensile strength and so on.

In this work, smart cure cycle with carbon epoxy composite symmetrical laminate which stacked $[0_5/90_5]_S$ was used to reduce the fabrication thermal residual stress of the bonding layer between composites laminated different fiber directions. The curing reaction was monitored by using dielectrometry. To evaluate the thermal residual stress, the curvature experiments with a symmetric stacking sequence of $[0_2/90_2]_T$ were performed.

From the study, it was concluded that about 26% of thermal residual stress during fabrication could be reduced in a composite laminate by adjusting cure cycle, which improved its static tensile strength in 16%.

1. Introduction

Since the carbon fiber epoxy composite materials have high specific stiffness, high specific strength and high damping than conventional metal materials, they have been widely used in aircraft, spacecraft, machine tool and infra structures and the armaments industry. However, the fabrication thermal residual stress generated during curing process of the composite due to the difference of coefficients of thermal expansions (CTE) has been a major problem which is deleterious to their mechanical performance and dimensional accuracy. However, the research results about the curing cycle optimization to alleviate this problem are rare. Kim et al. have devised smart curing method for carbon fiber epoxy composite laminate [1, 2, 3]. Hodges et al. and White et al. experimentally investigated the method for the reduction of residual stresses in epoxy curing [4, 5].

In the study, a smart cure cycle was applied to symmetrical composite with the stacking sequence of $[0_5/90_5]_S$. The thermal stress was evaluated the

curvature experiment of asymmetric $[0_2/90_2]_T$ composite strip according to each cure cycle. And to evaluate the mechanical performance of the composite laminate, static tensile test was performed.

2. Experiments

2.1 Smart cure cycle for thermal residual stress reduction

In order to reduce the thermal residual stress, 2 optimal cure cycles was performed as shown in Fig. 1. Smart cure cycle has abrupt cooling operation and polymerization operation and reheating operation which has effect the degree of cure [6]. A conventional curing process is recommended by the prepreg manufacturers as shown in Fig. 1 (a).

2.2 Dielectrometry for cure monitoring

In this study, unidirectional carbon fiber epoxy composite (USN 150, SK chemical) was used for the composite of which properties is shown Table 1.

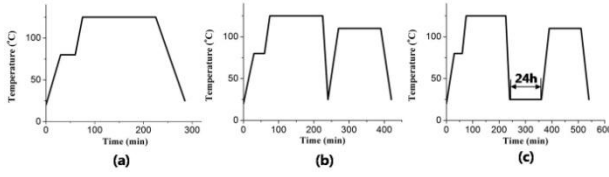


Fig. 1 Various cure cycles: (a) conventional cure cycle; (b) optimal cure cycle 1; (c) optimal cure cycle 2.

Table 1 The mechanical properties of materials(carbon/epoxy USN 150)

E_1 (GPa)	131.6
E_2, E_3 (GPa)	8.20
G_{23} (GPa)	3.5
G_{12}, G_{23} (GPa)	4.5
ν_{12}, ν_{23}	0.281
$\alpha_1 (\times 10^{-6}^\circ\text{C})$	-0.9
$\alpha_2, \alpha_3 (\times 10^{-6}^\circ\text{C})$	27
T_{ply} (mm)	0.146

For cure monitoring, and interdigital dielectric sensor was embedded in the composite following by enclosing them with a vacuum bag as shown in Fig.2 (a). Properties of the composite (USN 150) is shown in Table 1. The dielectric sensor is composed of two very long electrodes with opposite polarity on the same plane as shown Fig.2 (b). Then, the dissipation factor D is measured during the cure cycle using a commercial dielectrometer (U1732B, Agilent, USA) using an alternating current of 1 kHz frequency. The dissipation factor represents the ratio of the energy loss by movements of dipoles and ions to the supplied energy. The dissipation factor is related to the degree of cure as the mobility of dipoles and ions present in the resin to follow the alternating electric field, varies with the state of cure. Employing the equivalent circuit model composed of a parallel circuit of resistance R_m and capacitance C_m as shown in Fig. 3, the dissipation factor D for the equivalent circuit can be obtained as follows

$$D = \left| \frac{I_R \cdot V_R}{I_C \cdot V_m} \right| = \left| \frac{I_R}{I_C} \right| = \left| \frac{Z_C}{Z_R} \right| = \frac{1}{\omega \cdot R_m \cdot C_m} \quad (1)$$

where, I and Z are electric current and equivalent impedance, respectively, V_m is alternating voltage

with angular frequency ω applied to the equivalent circuit and subscripts R and C represent resistance and capacitance of the equivalent circuit model, respectively. A schematic of in situ monitoring is as shown Fig.4.

2.3 Curvature experiment

During the cure operation of carbon epoxy composite laminate, thermal residual stress may be occurred due to difference of CTE's between composites laminated different fiber directions.

To estimate the fabrication thermal residual stress, the actual bonding temperatures of the interface between composite laminates during curing operation were measured with respect to cure cycles using $[0_2/90_2]_T$ composite laminate strips.

A dimension of the $[0_2/90_2]_T$ carbon composite laminate is shown in Fig. 5 (a). Then, the curvature of $[0/90]_T$ strip generated by the difference of CTE's between composites which fiber directions laminated differently was shown in Fig. (b). Temperature difference ΔT between the actual bonding temperature ($T_{bonding}$) of the interface and the room temperature (T_{room}) were calculated using the measured curvature(R) of the $[0/90]_T$ composite laminate strip as follows;

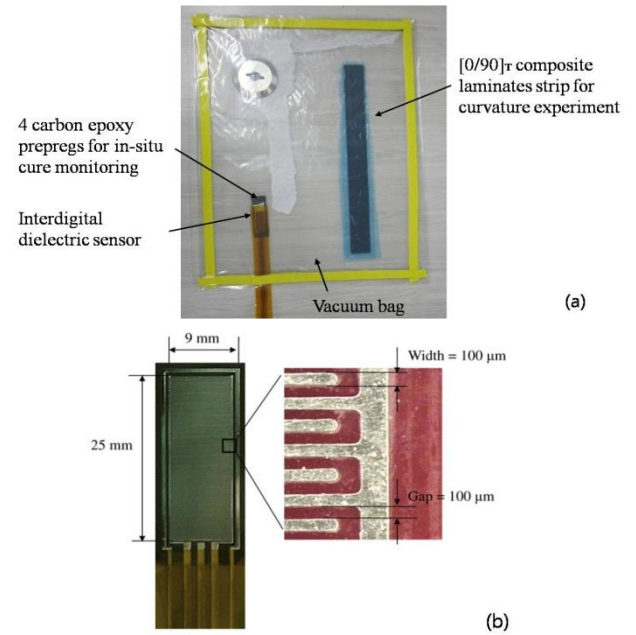


Fig. 2 In situ monitoring of the carbon epoxy composite laminate by dielectrometry: (a) experimental set-up; (b) dielectric sensor for cure monitoring.

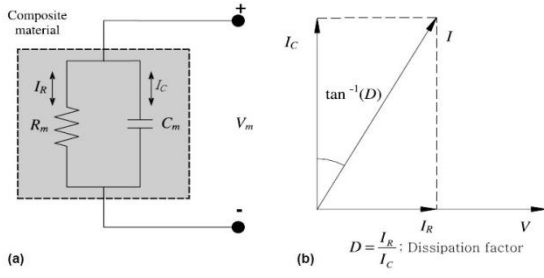


Fig. 3 Principle of the dielectrometry: (a) equivalent electrical circuit model for composite material; (b) electrical current I through the dielectric material whose real and imaginary components are I_R (loss current) and I_C (charging current)

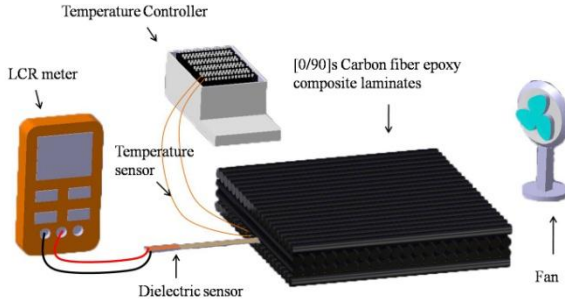


Fig. 4 Cure monitoring of the carbon epoxy composite laminate during heating and cooling by dielectrometry and temperature controller.

$$\Delta T = T_{\text{bonding}} - T_{\text{room}} = \frac{t[3(1+m)^2 + (1+mn)(m^2 + 1/mn)]}{6R(1+m)^2(\alpha_{90^\circ} - \alpha_{0^\circ})} \quad (2)$$

where m is the t_0/t_{90° : thickness ration of the composite laminated 0° to the composite laminated 90° . n is the E_{0°/E_{90° : modulus ration of the composite to the steel. t is the $t_0+t_{90^\circ}$: total thickness of the strip. α_{90° , α_{0° is CTE's of the composite laminated 90° and 0° respectively.

In optimal cycle 2, 3 cases, when dissipation factor (DF) value is the maximum, specimen was cooled down abruptly using an ice water. Then, specimen was reheating at 110°C for 2 hour to accomplish the full curing.

2.4 Static tensile test

In order to characterize the mechanical properties of the composite laminates with respect to cure cycles, the static tensile test was performed with

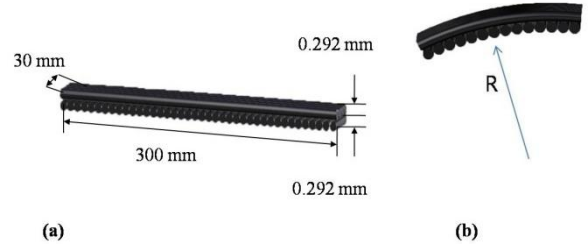


Fig. 5 $[0_2/90_2]_T$ Carbon composite laminate strip : (a) before curing, (b) at room temperature after curing

universal tester (MTS 810, USA). The static tensile test was performed with the speed of 1mm/min.

3. Result and discussion

From the dielectrometry, the dissipation factor was obtained and the phase transformation (liquid to solid) of epoxy resin was monitored. Fig. 6 shows the result of cure monitoring by using dielectric sensor. In optimal cycle 1, when DF was the maximum, specimen was cool down abruptly. Then, specimen was reheated at 110°C for 2h after curing using the cycles with the abrupt cooling to complete the full curing of the specimen. In optimal cycle 2, specimen was reheated at 110°C for 2h after polymerized for 24h. Fig. 7 and Table 2 shows the curvature of $[0_2/90_2]_T$ composite laminate with respect to cure cycles. The T_{bonding} is the bonding temperature of interface between composites plies with the different fiber angle (in this case 0° and 90°). A higher T_{bonding} mean that it has the large thermal residual stress due to the large temperature difference between T_{bonding} and T_{room} .

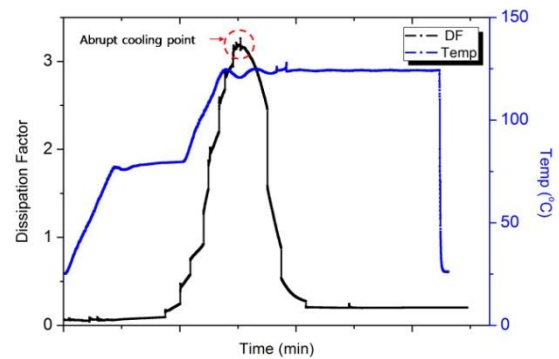


Fig. 6 Dissipation factor and temperature with respect to time by in-situ monitoring using dielectric sensor.



Fig. 7 Experimental results of curvature of $[0/90]_T$ composite laminate.

Table 2 Experimental results of curvature experiment

Cycle	Curvature, R(mm)	$T_{\text{bonding}}(^{\circ}\text{C})$
Conventional cycle	122.4	132.3
Optimal cycle1	157.1	108.6
Optimal cycle2	194	98.7

From the experiments, it was found that the specimens with abrupt cooling and reheating have low bonding temperature. Especially, the specimen polymerized for 24h after abruptly cooled down (optimal cycle 2), has the lower bonding temperature than that of the specimen with cured in optimal cycle 1 (without polymerization). Therefore, it might be concluded that polymerization operation at T_{room} could eliminate the thermal residual stress. From the curvature experiment, we found that an optimal cure cycle 2 with abrupt cooling followed by post curing could reduce 26% of thermal residual stress of carbon epoxy composite laminate.

Fig. 7 shows the static tensile test result of the composite laminate. The specimen cured with the conventional and the optimal cure cycles showed the similar elastic modulus (~ 65 GPa). However, the tensile strength (1028 MPa) of the specimen the tensile strength (1028 MPa) of the specimen cured with the optimal cure cycle 2, shows 16 % of improvement compared to that with conventional cure cycle (936 MPa) due to its reduced thermal residual stress.

4. Conclusion

In this work, a smart cure system using dielectric sensor was performed to reduce the thermal residual stress. From the experimental results, the following conclusions were made.

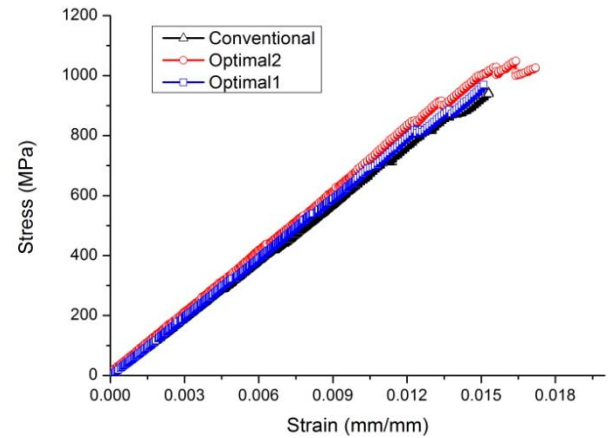


Fig. 7 Stress-strain curve from the static tensile test with respect to cure cycles.

- (1) From the experiments, we found that an optimal smart cure cycle with abrupt cooling followed by post curing could reduce 26% of thermal residual stress of the carbon epoxy composite laminate.
- (2) The result showed the tensile strength of the specimen fabricated under smart cure cycle was 16% higher than that of the specimen fabricated under the conventional cure cycle.

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