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Defect detection in adhesive joints using the impedance method

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ABSTRACT

Adhesive joints distribute a load over a larger area than mechanical joints, but they are very sensitive to surface treatment, service temperature, humidity and other environmental conditions. The ultrasonic method is well known as a non-destructive approach to evaluate defects in adhesive joints, but it cannot detect joint strength degradation due to surface defects or contaminations.

In this paper, we evaluated the defects of adhesive joints using the impedance method, which measures the electrical impedance of the adhesive joint. To increase the electrical conductivity of aluminum-to-aluminum single lap joints, 2 wt% of carbon nanotubes were dispersed in the adhesive. The impedances of adhesive joints that were modified with artificial defects were measured by using an LCR meter, and the strengths of the joints were evaluated.

1. Introduction

Composite materials have high specific strength and high specific stiffness with excellent damping and impact properties. The joint design of composite materials is a very important consideration because improper design may lead to overweight or defective structures. Compared to mechanical joints, adhesive bonding for composite materials does not require holes and distributes the load over a larger area. However, adhesive bonding is very sensitive to the surface treatment, service temperature, humidity and other environmental conditions [1]. The ultrasonic method is well known as a non-destructive approach for evaluating the defects in adhesive joints. Additionally, methods of on-line health monitoring of adhesive joints using fiber-optics or piezoelectric sensors have been proposed by several researchers [2–4]. However, these methods cannot detect joint strength degradation due to surface defects or contaminations.

Carbon nanotubes (CNTs) have attracted considerable research attention over the past two decades due to their remarkable mechanical and electronic properties [5–7]. It is widely accepted that multi-wall carbon nanotubes (MWCNTs) exhibit metallic electrical conductivity, while single-wall carbon nanotubes (SWCNTs) can exhibit either metallic or semiconductor electrical conductivity, depending on the hexagonal lattice orientation of the nanotube main axis [8]. Ounaies [9] and Thakre [10] demonstrated significant improvement in electrical conductivity of up to 9 or 10 orders of magnitude at a weight concentration of SWCNTs of only 0.1–0.2 wt%.

Vega [11] used single-walled carbon nanotubes (SWCNTs) as a sensor and proved that SWCNTs could be used to monitor internal stresses developing during the curing process of thermoset materials. Thostenson and Chou [12] studied the in situ sensing method to detect localized damage of mechanically fastened joints using 0.5 wt% carbon nanotubes. Kang [13] detected crack initiation and propagation by measuring the variation of the equivalent resistance in the adhesive joint with carbon nanotubes.

In this paper, we evaluated the defects of adhesive joints using the impedance method, which measures the electric impedance of an adhesive joint. The aluminum-to-aluminum single lap joints were formed with 2 wt% of carbon nanotubes dispersed into the adhesive to increase the electrical conductivity. The impedances of the adhesive joints that have artificial defects were measured by using an LCR meter, and the strengths of the adhesive joints were evaluated.

2. Manufacturing process of the adhesive joints with artificial defects

Single lap joints were manufactured according to the ASTM D1002, D5868 standard; their schematic diagrams are shown in Fig. 1. Aluminum alloy 2024 was used for the adhesive joints, and the adhesive length and thickness of the joints were 30 mm and 1 mm, respectively.

An epoxy adhesive (YD-128) and hardener (G-640) from KUKDO Chemical Co. were used to form the adhesive joint. Table 1 presents

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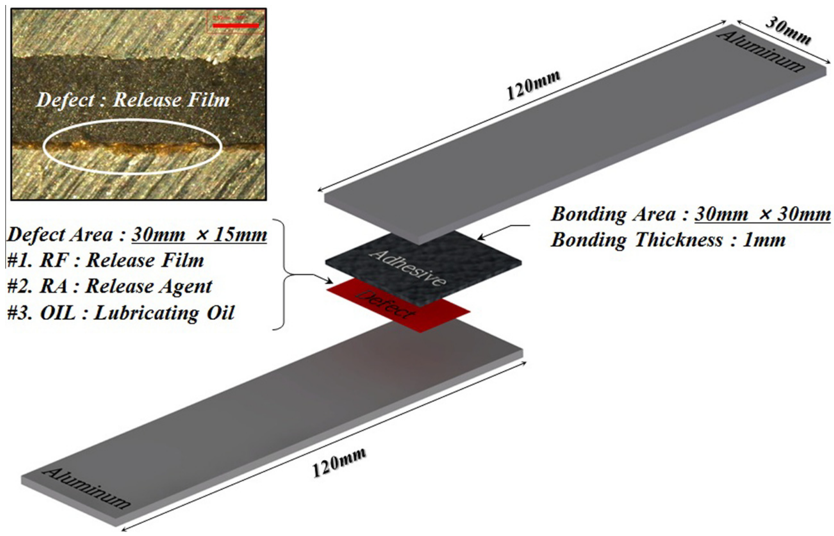

Fig. 1. Schematic diagram of the adhesive single lap joint.

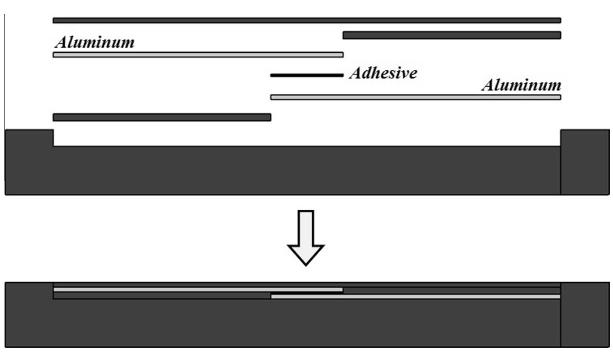

Fig. 2. Schematic diagram of the adhesion fixture.

Table 1
Material properties of the epoxy adhesive.

Item	YD-128
Lap Shear Strength	34.1
Mixing ratio: YD-128/G-640 = 100/59	
Curing condition: 80 °C for 2 h	

the mixing ratio and strength of the adhesives. The carbon nanotubes (NANOSOL-R) of CNT Solution Co. were used, and the ranges of the diameter and length of the CNTs were 10–15 nm and 10–20 μm, respectively.

The 80E three-roll mill of EXAKT Co. was used, and 2 wt% carbon nanotubes were dispersed into the adhesive. The mixing and dispersion of the nanotubes were conducted by the three-roll mill, and the roll gaps were adjusted. The three-roll mill was used one time at the 20 μm gap, one time at the 15 μm gap and five times at the 10 μm gap. The adhesive with dispersed carbon nanotubes was applied to the aluminum specimen, and then, a fixture was used to control the adhesive thickness. Fig. 2 shows the schematic diagram of the adhesive joint fixture. The surface treatment of the aluminum piece to be adhered greatly affects the strength and failure mode of the adhesive joint. In this paper, the surface of the aluminum was polished using 120-mesh sandpaper. After polishing, the aluminum surface was cleaned and dried using acetone. Three types of artificial surface defects (release film, release agent and lubricating oil) were made on half of the adhesive area, as shown in Fig. 2. Release films were attached to the surface of the aluminum, and then, the release agent and lubricating oil were sprayed and their excesses were wiped off. An adhesive thickness of 1.0 mm was set by the adhesion fixture, as shown in Fig. 2. The assembled adhesive joints were cured in an oven at 80 °C for 120 min. The cured adhesive joints were cut using a diamond wheel cutter, and the residuary fillets of the adhesive joints were removed using a razor.

3. Impedance of the adhesive joint

The AC electrical impedances of the adhesive joints with artificial defects were measured and compared with those of the adhesive joint without the defects. A U1733C LCR meter of AGILENT Co. and a HIOKI 3532-50 LCR meter of HIOKI Co. were used for measuring the AC impedances. There are two modes (serial and parallel) of operation of the LCR meter. We used the serial mode for measuring the AC impedances of the adhesive.

Fig. 3 shows the variations of the reactance (L), capacitance (C), resistance (R), and impedance (Z) according to the measuring frequency in the adhesive joint with and without release film. As shown in Fig. 3, every value (L, C, R, Z) was decreased when the measuring frequency was increased. Additionally, the difference of the impedances between the adhesive joints with and without the release film was the largest when the measuring frequency was the smallest. Therefore, the measuring frequency in this paper was set to 100 Hz, and then, the five joint specimens were tested for each condition, with the measured AC impedances averaged.

Fig. 4 shows the reactance of the adhesive joints with and without artificial defects. As shown in Fig. 4, the reactance of the adhesive joint without defects was the smallest and that of the adhesive joint with the release film was the largest. However, the deviation of each value was relatively high.

Fig. 5 shows the capacitance of the adhesive joints with and without artificial defects. As shown in Fig. 5, the capacitance of the adhesive joint without defects was largest and that of the adhesive joint with the release film was the smallest. However, because each of the capacitance values is very small and the