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Detection of in-plane and out-of-plane fiber waviness in unidirectional carbon fiber reinforced composites using eddy current testing

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ABSTRACT

In this paper, we propose a specialized probe to detect in-plane and out-of-plane fiber waviness in unidirectional carbon fiber-reinforced plastics and to characterize fiber orientations by an eddy current-based nondestructive technique. Experimental studies show that the proposed probe can detect in-plane fiber waviness with amplitude of 1.1 mm and length of 15.9 mm in a thin unidirectional carbon fiber reinforced plastic at sufficiently high drive frequency. The validity of the proposed method is verified through three-dimensional finite element method analysis. Variation in amplitude and phase of output signal obtained in numerical analyses qualitatively agreed with experimental results. Out-of-plane fiber waviness induced in a thick unidirectional carbon fiber-reinforced plastic can also be detected using the proposed probe. It is found that output signals in complex plane obtained during scanning a material with out-of-plane waviness become ring-shaped plots. Those plots in complex plane are used to identify the presence and location of out-of-plane fiber waviness.

1. Introduction

Because of developments in molding methods such as resin transfer molding and filament winding, carbon fiber-reinforced plastics (CFRPs) have been used increasingly as structural materials in aerospace and automobile industries. When CFRP parts are molded, defects can be produced inside the CFRP. Fiber waviness refers to fiber deformation in CFRPs, and is one of the process-induced defects in molded CFRP. Waviness is induced by axial loading of carbon fibers because of residual thermal stresses [1]. Process parameters that affect the development of fiber waviness most were investigated by Kugler and Moon [2,3]. They showed experimentally that large differences in the coefficient of thermal expansion (CTE) between the mold and the CFRP, and a large temperature gradient caused during cooling are significant process parameters for the development of waviness [2]. It has also been reported that in the filament winding of hoop-shaped CFRPs, not only the CTE mismatch but also insufficient tow tension can induce fiber waviness [3]. In-plane and out-of-plane fiber waviness can occur during CFRP manufacture. In thin laminates, because out-of-plane motion of carbon fibers is restricted, in-plane waviness is more likely to occur [2]. However, because thick laminates easily experience large temperature gradients through the thickness [1], out-of-plane waviness can be induced. Because fiber waviness causes significant degradation of compressive strength of CFRP structures [4,5], it should be detected by nondestructive testing.

X-ray computed tomography (CT) is considered to be an effective nondestructive technique for waviness detection because of its excellent detectability. Sutcliffe et al. used multiple field image analysis to extract local fiber orientation from micro CT X-ray images [6] and confirmed that results obtained from the method agreed well with data from micrographs of a polished sample. Although X-ray CT has excellent detectability of fiber waviness, which has not been achieved by other nondestructive testing methods, this method is limited by test material geometry and hence is not suited for on-site inspection. Ultrasonic testing (UT) has also been studied for the detection of fiber waviness in CFRPs. Smith et al. mapped the distribution of in-plane fiber orientation by choosing a small group of waveforms and a short time window [7]. In addition, Smith et al. quantified the out-of-plane ply angle using a focused probe [7]. Zardan et al. studied ultrasonic beam deviations induced by an oblique interface of out-of-plane waviness, and detected experimentally the perturbed acoustic

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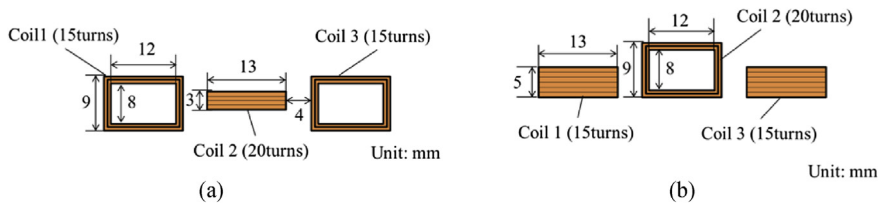

Fig. 1. Schematics of the probe for waviness detection: (a) top view, (b) front view.

field [8]. Pain and Drinkwater applied a total focusing method (TFM) to an ultrasonic array technique [9]. They found experimentally that out-of-plane waviness could be visualized more clearly in a TFM phase image than in an amplitude image. Although the ultrasonic methods described above are effective to detect waviness, the test materials must be immersed in water, or couplant is required for incidence of ultrasonic waves onto the test material. Thermal nondestructive techniques have been developed in recent years to detect waviness. Elhajjar et al. investigated the application of thermoelastic stress analysis to detect out-of-plane waviness in carbon fiber composites [10]. They measured surface temperature of the specimen with out-of-plane waviness under cyclic loading. It was shown that the distribution of waviness can be visible in the obtained thermal image. Although this approach can be used to visualize the location of fiber waviness, it is difficult to inspect the inside of the test material [10]. Moreover, this approach can be limited by component geometries because of the use of cyclic loading. Eddy current testing (ET) is a nondestructive testing method for electrically conductive materials. Because ET uses electromagnetic induction, it has an advantage of non-contact testing. ET has been applied recently to defect detection in CFRPs because carbon fiber is electrically conductive [11–15]. Heuer et al. obtained an eddy current image of fiber waviness in carbon fiber bundles [15]. They used a half transmission probe with high spatial resolution, and higher drive frequencies were chosen to increase its sensitivity.

In this study, a new ET approach is proposed to detect fiber waviness in CFRPs. A new ET probe that is specialized for detection of in-plane and out-of-plane waviness is developed. First, the probe is used to detect in-plane waviness in a unidirectional CFRP with simulated fiber waviness. To investigate the signal change obtained in the experiments, eddy current and magnetic field distributions around in-plane waviness are calculated using finite element method (FEM) analysis. Second, detectability of out-of-plane waviness is investigated experimentally. Complex plane analysis to identify the vertex location of out-of-plane waviness is discussed.

2. Eddy current testing probe

A new eddy current testing probe specialized for waviness detection was developed. Fig. 1 shows schematics of the probe, which consists of three rectangular coils 1–3. Three coils were fabricated with 0.3 mm diameter enameled copper wires, and coils 1, 2 and 3 have 15, 20 and 15 turns, respectively. Coils 1 and 3 have the same dimensions and number of turns. Coil 2 is placed between and is orthogonal to coils 1 and 3 as shown in Fig. 1. The proposed probe in Fig. 1 has three functions: in-plane waviness detection, out-of-plane waviness detection and characterization of fiber orientations.

Fig. 2 shows the physical principle of in-plane waviness detection. Coils 1 and 2 are used during in-plane waviness detection. Coil

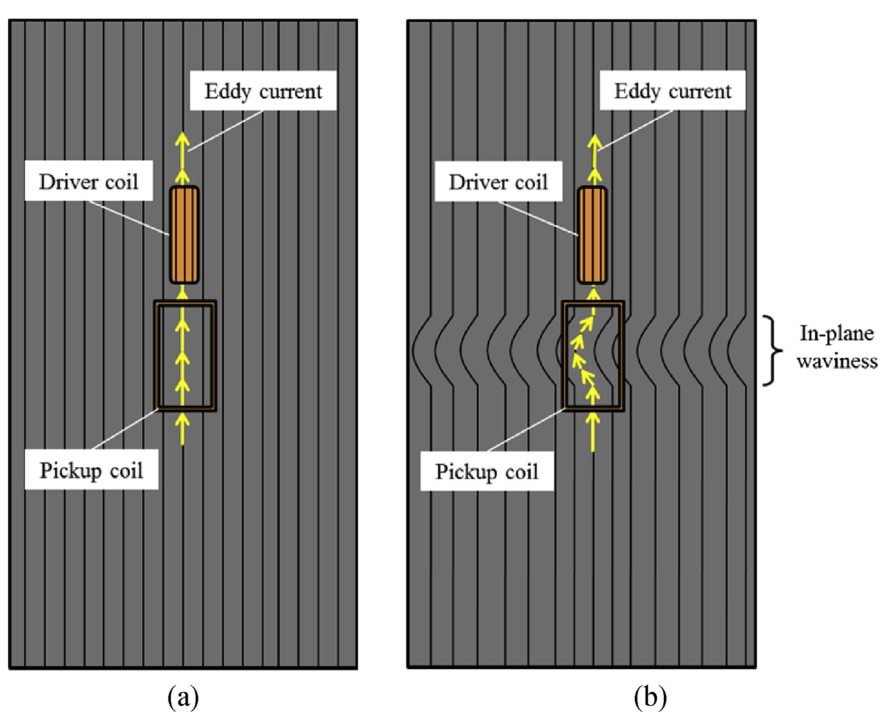

Fig. 2. Schematics of eddy currents in unidirectional CFRP: (a) with no fiber waviness, (b) with in-plane waviness.