Fiber Waviness Detection by Electromagnetic Testing in Carbon Fiber Reinforced Plastics

Akinori TSUDA 1, Hiroki KAWAI 1, Yuichi YAMAGUCHI 2, Koichi INAGAKI 2, Hiroaki HATANAKA 1, Minoru TAGAMI 1
1 IHI Corporation, Yokohama, Kanagawa, Japan
2 IHI Corporation, Nishitama-gun, Tokyo, Japan

Contact e-mail: akinori_tsuda@ihi.co.jp

Abstract. Carbon fiber reinforced plastics (CFRPs) are used in various products such as aerospace components to accomplish the weight saving. CFRPs consist of the carbon fibers as the reinforcement and the resin as the matrix. The fiber waviness causes a reduction in the mechanical properties of CFRPs. However, detecting in-plane waviness has been less well-established. This paper reports on the feasibility of two types of electromagnetic methods which detect in-plane waviness using high sensitive magnetic sensors. In the magnetic flux leakage (MFL), the electric current is passed directly through carbon fibers between electrodes attached to the specimen's edges, and the magnetic variation appear around the waviness due to a detour of the current flow. As another method, we developed the electric current perturbation (ECP) for the targeted in-plane waviness detection. The pancake coil is set upright on the specimen and the magnetic sensor is placed immediately beneath the coil with its sensitive axis parallel to the fibers. Experimental test data were obtained from the specimens that have both of artificial and naturally-induced waviness and the test results clearly show the indications around the waviness.

1. Introduction

CFRPs have been attractive structural materials for aerospace components because of their light weight and superior mechanical properties. In the manufacturing process, the prepregs that consist of thin fiber bundles and the resin are prepared first, and they are laminated in the pressing machine to be fabricated into the thicker components. During the cooling after pressing in high temperature, the occurrence of the fiber waviness due to the unexpected shrinkage has been a concern. Since carbon fibers ensure the strength to CFRPs, the waviness would lead to degradation of the mechanical properties [1]. Therefore the inspections focusing on the fiber waviness detection should be needed during the manufacturing.

The two types of waviness will occur; the out-of-plane waviness and the in-plane waviness as shown in Fig. 1 (a) and (b) respectively. In case of the out-of-plane waviness, the ultrasound scatterings from the carbon fiber waviness can be detected [2]. However, the detection of the in-plane waviness by the ultrasound is difficult because the in-plane waviness causes less scattering and the detection methods have not been well-established.

This paper reports on the feasibility of the detection for the in-plane waviness by applying the magnetic flux leakage (MFL) and the electric current perturbation (ECP). The carbon fibers have high conductivity so that electric current flows along fiber direction and...
we developed two types of electromagnetic methods to detect in-plane waviness in CFRPs using high sensitive magnetic sensors. The CFRP plates with naturally and artificially-induced in-plane waviness were prepared as the specimens. In both methods, the indications due to the magnetic field change around the fiber waviness were able to be detected.

![Fig. 1. Fiber waviness of CFRPs](image)

2. Fiber waviness detection by MFL

2.1 Principle

Fig. 2 shows the principle of the fiber waviness detection by the MFL. The electric current is applied to the specimen with two electrodes attached to the edges. If the specimen does not include fiber waviness, the uniform current flows between the electrodes, so the uniform magnetic field, which is orthogonal to the current direction, appears on the surface of the specimen. Thus, the magnetic sensor does not respond when the sensitive axis of the sensors is set along the direction of the target fiber. Conversely, if the specimen includes the waviness, the electric current curves and the direction of the magnetic field varies around the waviness. Then the sensor responds around the waviness due to the occurrence of the magnetic field change parallel to its sensitive axis.

Based on this principle, the waviness areas could be detected by scanning the sensor on the surface of the specimen.

![Fig. 2. Principle of fiber waviness detection by MFL](image)

2.2 Experimental procedure and setup

2.2.1 Specimen

Fig. 3 shows the specimen with naturally-induced in-plane waviness. Fig. 3 (a) shows the schematic illustration of the specimen. Prepregs with 0° and 90° were laminated alternately, and the total thickness of the specimen was 2 mm. Fig. 3 (b) shows an example of the
waviness detected by the X-ray CT. The severe waviness areas, which include the fibers with high wave amplitude, appear in the specimen. Fig. 3 (c) shows the waviness areas in the prepregs for 0° detected by the X-ray CT. The dashed lines show the waviness areas and the solid lines show the severe waviness areas and it was found that the waviness areas concentrate near the side B.

2.2.2 Experimental procedure

Fig. 4 shows the schematic illustration of the MFL experimentation. The electrodes were attached to the top and the bottom edges on the specimen and the electric current was applied to the specimen along 0° fiber direction. The magnetic field on the both sides A and B of the specimen were measured by the sensor. Magneto-Impedance (MI) sensor was employed as the sensor in this experiment [3]. MI effect consists in an abrupt variation in the impedance of amorphous wire when applying high-frequency current to the wires under the small magnetic field [4-5]. The lock-in amplifier extracted the amplitude and the phase components from the sensor signals when the AC current with a frequency of 10 MHz was applied to the specimen by the power amplifier. The scan speed in the Y direction was 33 mm/s and the pitch in the X direction was 1 mm as shown in Fig. 4(a). The bandpass filter with a frequency from 3 to 30 Hz was applied to the acquired signals as the scan-directional space filter.
2.3 Experimental test results

The scanned results of the specimen with naturally-induced waviness are shown in Fig. 5. The indications appeared on the both sides around the waviness areas. The striped indications appeared, because waviness has multiple curves as shown in Fig. 3 (b). The signal amplitudes from the side B are larger than those from the side A because of the concentrating waviness near the side B. As shown in these results, the MFL can detect the in-plane waviness clearly.

3. Fiber waviness detection by ECP

3.1 Principle

In the MFL, the applying electric current depends on the shape, the size and the fiber direction of components. Besides, to detect the subsurface waviness by attaching electrodes on the surfaces of components is not effective because of the low conductivity in lamination axis. To solve this issue, we have developed the method of electric current perturbation (ECP). The excitation coil is made use instead of the electrodes for applying the electric current to the specimen. Fig. 6 shows the principle of the fiber waviness detection by the ECP. The path of the induced eddy current locally by the pancake coil has a butterfly-shaped loop. Then, the sublinear eddy current appears in the specimen beneath the coil. To induce the eddy current along the target fiber direction, the coil is placed on the specimen and the magnetic sensor is placed beneath the coil.

The eddy current flows straightly beneath the coil if the specimen does not include fiber waviness. Conversely, the eddy current curves if the specimen includes the waviness. Thus the direction of the magnetic field also varies beneath the coil if the probe is set around the waviness. Therefore, the waviness areas can be detected by scanning the probe on the surface of the specimen.
3.2 Experimental procedure and setup

3.2.1 Specimen

Fig. 7 (a) and 7 (b) show the picture of the specimen and the illustration of the waviness areas, respectively. The specimen was made of prepregs including four artificial waviness areas in the different layer. The fiber directions were 0° and 90°. The total thickness of the specimen was 4 mm. The waviness areas were placed toward the side B.

3.2.2 Experimental procedure

Fig. 8 shows the schematic illustration of the ECP experimentation. Fig. 8 (a) shows the ECP probe. The MI sensor is made use as the magnetic sensor in this experiment. Fig. 8 (b) shows the experimental setup, which was almost the same as the MFL. The excitation coil induces the eddy current locally on the specimen. The difference of experimental setup from Section 2.2.2 was as follows. The AC current with a frequency of 3 MHz was applied to the coil. The scan speed was 50 mm/s and the frequency range of the bandpass filter was set from 1.5 to 30 Hz.

3.3 Experimental test results

The scanned result of the specimen with the artificial waviness is shown in Fig. 9. The indications appeared around the waviness areas. The result shows that the ECP can detect in-plane waviness. The indication was not clear around 2 mm-deep waviness area because of the skin effect based on the driven frequency.
4. Conclusions

This paper presented the application of two types of electromagnetic methods to detect in-plane waviness in CFRPs using high sensitive magnetic sensors. The MFL was applied to the 2 mm-thick specimen including the naturally-induced waviness, and the indications appeared around the waviness areas.

The other ECP was also applied to the 4 mm-thick specimen including the artificially-induced waviness in the different layer. The indications appeared around the waviness areas, thus the results indicated that the ECP detects in-plane waviness. As the further study, we will optimize the configurations of the ECP to improve signal-to-noise ratio of the signals from the in-plane waviness.

References