Evaluation of the Mechanical and Electromagnetic Shielding Properties of Carbon Fiber Reinforced Thermoplastics Sheet Made of Unidirectional Tape

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Carbon fiber reinforced thermoplastics (CFRTP) made of carbon fiber-polyamide 6 unidirectional (UD) tape with different layer-configuration and tape-length were fabricated using hot compression-molding, and then their mechanical and electromagnetic shielding properties were evaluated. The mechanical property was evaluated using a three-point bending test method. Whereas, electromagnetic interference shielding effectiveness (EMI-SE) was estimated using Simon formalism based on through-thickness electrical conductivity value. In addition, laminate analysis using a laser microscope was conducted to observe inter and intra-laminar of CFRTP. The results showed that maximum load and flexural modulus of CFRTP has a strong relationship with UD tape arrangement. Unidirectional layer configuration is the highest strength and modulus compared with others due to carbon fiber direction.

Furthermore, UD tape length significantly influenced in increasing the modulus for randomly chopped CFRTP. While the total EMI-SE was 29-89 dB in the x-band frequency for all different layer-configuration and tape-length in which quasi-isotropic layer-configuration was the highest electromagnetic shielding performance. Dominant-absorption shielding mechanism was confirmed by higher absorption value rather than reflection, in the range of 21-74 dB from total EMI-SE value. The results revealed an opposite characteristic between mechanical and electromagnetic shielding properties related to UD tape configuration for laminated composite. Also, the intra-laminar analysis showed that electrical volume conductivity strongly influenced by fiber-to-fiber contact in the thickness direction of the composite. It confirmed that quasi-isotropic and bidirectional configuration have higher conductivity resulting in higher electromagnetic shielding performance compared with others. [doi:10.12320/matertrans.MT-ML20190088]

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1. Introduction

Nowadays, electromagnetic (EM) radiation and pollution have been extremely increased in conjunction with the development and application of high-frequency electronic devices or equipment and network like wireless technology. Thus, researchers have developed for decades both technology and material, including polymer-matrix-composite material, to reduce the negative effect of EM radiation through absorption shielding mechanism in order to protect human and other biological species health and their environments.

Carbon fiber reinforced thermoplastics (CFRTP) has been developed for electromagnetic interference shielding application due to its remarkable electrical conductivity, high specific strength and stiffness, broad absorption frequency bandwidth, dominant-absorption shielding mechanism, while presenting low-cost processing, high process-ability for complex shape and recyclability compared with the thermoset-based polymer matrix. Furthermore, the strength and modulus of CFRTP presented remarkable value due to its superior mechanical properties of carbon fiber. CFRTP made of unidirectional tape, carbon fiber reinforced polyamide 6 (CF/PA6), has many advantages such as easy in making laminate configuration, arranging fiber direction and processing a complex-shape product. Consequently, it will make easy to obtain good mechanical properties in multidirectional and electrical properties as well.1-4

While, by using CFRTP, the electromagnetic shielding is dominated by absorption rather than a reflection in order to minimize EM pollution to the environment. Theoretically, electromagnetic interference shielding effectiveness (EMI-SE) of CFRTP is linearly correlated with electrical conductivity. Then, it is strongly influenced by carbon fiber content, orientation and layer configurations resulted in the conductive network in composite.5,6

In this study, an evaluation of the mechanical and electromagnetic shielding properties of laminated CFRTP with three different layer-configuration (unidirectional [0°], bidirectional [0°/90°], and quasi-isotropic [0°/90°/45°/−45°]4, and randomly chopped tape CFRTP is presented. The microscopy analysis of CFRTP structure using a laser microscope is also discussed.

2. Experimental Procedure

2.1 Materials and fabrication method

2.1.1 Materials

Basic specification of unidirectional carbon fiber (UD) tape in this paper are listed in Table 1. Carbon fiber is PAN based T700SC continuous CF produced by Toray Industries Inc. Japan. Whereas, thermoplastic TB-1000, polyamide-6, is

<table>
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<th>Table 1 Unidirectional tape specification.</th>
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<td><strong>Carbon fiber</strong></td>
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<td><strong>Matrix</strong></td>
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<td><strong>Volume fraction, V_f (%)</strong></td>
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<tr>
<td><strong>Width [mm]</strong></td>
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<td><strong>Thickness [μm]</strong></td>
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produced by Idemitsu Unitech Co. Ltd., Japan. Therefore, UD tape was developed by Adwelds Co. Ltd. and Society of Hamamatsu CFRP business R&D using ultrasonic wave and heating method. Then, the UD tape was prepared to make layer arrangement in 0°, 90°, and ±45° directions and also chopped tape as shown in Fig. 1(a).

2.1.2 Fabrication method

Figure 1(b) shows a fabrication method of CFRTP sheet using a hot-compression molding. Firstly, prepared UD tape arranged on the mold according to the layer configuration (unidirectional [0°28], bidirectional [0°14/90°14]s, quasi-isotropic [0°/90°/45°/-45°]4s) or randomly chopped tape). Then, UD tape was molded by hot-compression molding with the temperature and pressure were 260 °C and 0.77 MPa, respectively. The detailed description of the fabricated sample is shown in Table 2.

2.2 Characterization method

CFRTP sheet samples were cut using a diamond cutting machine to prepare flexural test specimens. Table 3 shows the condition of flexural test. Universal testing machine (AG-X/R-100KND, Shimadzu, Japan) was used to evaluate the flexural strength and modulus refers to JIS K7074. The two-wire direct current resistance test using a multimeter (DMM6500 6 1/2 digit multimeter, Keithley, Tektronix company) was used to measure through-thickness resistivity and then was converted to through-thickness conductivity.

To collect the two-dimensional optical images and interlaminar interface, a cross-section of the specimens was polished by waterproof abrasive paper (#600, #800, #1200, #1500 and #2000) and buffed with diamond paste (3 and 1 µm). Then, the polished cross-section surface was observed using a laser microscope (VK-X100 series, Keyence, Japan).
3. Results and Discussions

3.1 Flexural property

It is well established that the strength of CFRTP is strongly affected by fiber-reinforcing direction. Furthermore, in case of using UD tape as raw material, the mechanical performance (strength and stiffness) is also influenced by UD tape quality such as carbon fiber distribution homogeneity, matrix-fiber adhesiveness, and lower void content.

Figure 2(a) shows the comparison of the flexural property between 43% and 55% \( V_f \) — laminated CFRTP. It can be seen that the unidirectional ([0°]) configuration was the highest strength and modulus because of fiber direction as reinforcement represented by UD tape layer-arrangement. Whereas, for the randomly chopped CFRTP, the longer tape-length has a higher modulus while the strength shows a slight increase with increasing tape-length. For instance, the CFRTP with 20 mm-length tape has higher modulus \( (E = 59.6 \text{ GPa}) \) than that with 10 mm-length tape \( (E = 35 \text{ GPa}) \), see Fig. 2(b).

3.2 Electrical property

Electrical conductivity \( \sigma \) is the most important parameter to achieve good electromagnetic shielding property of electrically conductive material like CFRTP. Figure 3 shows the through-thickness electrical conductivity data plot of CFRTP. It well depicted that the quasi-isotropic sample has the highest electric conductivity \( (\sigma = 280 \text{ S/m and } 167 \text{ S/m}) \) compared to other due to the much fiber-to-fiber contact resulted in the conductive path in the through-thickness direction of CFRTP.7)

Therefore, for conductive plastic material like CFRTP, the EM shielding property can be estimated using Simon formalism,\(^8\)\(^-\)\(^10\) and the shielding contribution of reflection and absorption can be calculated by the following equations:

\[
SE = 39.5 + 10 \log_{10} \left( \frac{\sigma}{2\pi f \mu_0} \right) + 8.686 \sqrt{\pi f \mu_0 \sigma}
\]

where \( \sigma \) [S/m] is the electrical conductivity, \( f \) [Hz] is the frequency, \( \mu \) [H/m] is magnetic permeability, \( \mu_0 \) is permeability in a vacuum; \( 4\pi \times 10^{-7} \text{ H/m} \) and \( \mu_r \) is specific permeability of material, and \( t \) [m] is the thickness of shielding material. Also, because the CFRTP composites are non-magnetic material, then \( \mu_r = 1 \). The first two terms estimate the shielding effect by reflection, and the third term predicts the shielding through absorption mechanism. In this theoretical equation, the effect of multiple reflections has been neglected, because the absorption value is greater than \( 10 \text{ dB} \).\(^{11}\)

According to the equation, it can be seen that the reflection decreases with increasing the frequency while the absorption increases. Furthermore, both reflection and absorption increase with increasing the conductivity of shielding material. The shielding through reflection is a surface phenomenon, and so is independent of thickness, while absorption is absorbed by the shielding material and increases with increasing the thickness.

Figure 4(a) confirmed that the shielding is dominated by absorption mechanism rather than reflection. Whereas, Fig. 4(b) revealed that the laminated CFRTP has higher EMI-SE than the randomly chopped CFRTP and it is clearly depicted that the laminated CFRTP has excellent EMI-SE that exceeds 43 dB \( (\text{attenuation more than } 99.995\%) \). Therefore, the laminated CFRTP can be applied as lightweight and high-efficiency EMI shielding material in many fields, such as communication, military, aerospace, automobile, and medicine industries. In addition, for the randomly chopped CFRTP, the length of UD tape does not significantly affect the increase of the shielding property.

3.3 Microscopy structure

Figures 5 and 6 show the microscopy images of the CFRTP to elucidate the interlaminar interface area and resin-rich region that influence the interlaminar strength, fracture behavior, and electrical properties as well.\(^{12,13}\)
4. Conclusion

The flexural properties and predicted EMI-SE of CFRTP made of laminated and randomly chopped carbon fiber tape reinforced thermoplastic have been investigated in the present study.

It can be summarized that, for the laminated CFRTP, the flexural strength and modulus of unidirectional layer configuration was superior to the bidirectional and quasi-isotropic configurations due to fiber direction as reinforcement. Whereas, the chopped-tape CFRTP shows the significant effect in increasing the modulus with increasing tape-length while the strength does not significantly affect.

Furthermore, the electromagnetic shielding property of the laminated CFRTP, whether the layer configuration is unidirectional or cross-ply (bidirectional and quasi-isotropic), the shielding effectiveness is much dominated by absorption rather than reflection. Moreover, the degree of absorption dominance is greater for the cross-ply layer configuration than the unidirectional one. Whereas, the randomly chopped CFRTP has the lower EMI-SE compared to the laminated one for all different tape-length.

In conclusion, the laminated CFRTP has excellent property trade-off between the strength and EM shielding properties so that suitable for both structural and functional applications.
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REFERENCES