EXPERIMENTAL AND THEORETICAL STUDY ABOUT ELECTRICAL AND THERMAL PROPERTIES OF CARBON FIBER MAT REINFORCED THERMOPLASTICS

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Abstract
In order to clarify the fundamental electrical and thermal properties of developed CF/PP (carbon fiber reinforced polypropylene) which has different fiber orientation from conventional CFRP (carbon fiber reinforced plastics), electrical conductivity, EMI SE (electromagnetic interference shielding effectiveness) and thermal conductivity were evaluated. In addition, a theoretical study was done about electrical conductivity of CMT (carbon fiber mat reinforced thermoplastics). As a result, it was found that electrical conductivity of CMT was much higher than that of CTT (chopped carbon fiber tape reinforced thermoplastics). There was the same tendency about EMI shielding. Also, electrical conductivity of CMT can be expressed by percolation theory. In addition, thermal conductivity of thickness direction was not improved very well.

1. Introduction

Novel CFRTPs (carbon fiber reinforced thermoplastics) was successfully developed in Japanese national project (2008-2012fy) [1]. These CFRTPs have not only high mechanical properties, but also high cycle moldability and high recyclability. They are advantages of CFRTPs, of course, but in order to expand their application field, it is necessary to reveal many functional properties, such as electrical and thermal properties. Concerning electrical property of CFRP, a lot of studies have been performed. The subject was not only about fundamental electrical property [2], but also about its application, such as damage detection by electrical resistance change method [3], EMI SE [4], lightning resistance [5], and so on. Also, some studies about thermal property of CFRP were performed [6]. However, the materials used in these studies were continuous CFRP or discontinuous CFRP with fiber length of 1 mm or less. So, there was almost no study about discontinuous CFRP with high mechanical properties.

Hence in order to reveal the fundamental electrical and thermal properties of CFRTPs developed in the Japanese national project, some measurements and theoretical study were performed. In this study, CMT which is expected to have high functional properties was mainly used and compared with another materials, such as CTT or UD (uni-directional) materials.

2. Experiments

2.1. Materials

The material mainly used in this study was CF/PP CMT. CMT can be regarded as isotropic material which consists of carbon fiber, T700S, randomly oriented in-plane direction. The fiber length is 6 mm and V_f (fiber volume fraction) are 30%, 20% and 12%. These materials were provided by Toray Industries, Inc. For comparison, another two types of CF/PP were used. One was CF/PP UD material and the other was CF/PP CTT material. UD material is a laminate of CF/PP UD tape with V_f of 47% the width of which is 15 mm. CTT material is an isotropic material and consists of the same UD tape as UD material. The size of chopped tape is 35×15 [mm]. These two materials were provided by Mitsubishi Rayon Co., Ltd. and Toyobo Co., Ltd. The illustrations of these materials are shown in Figure 1.

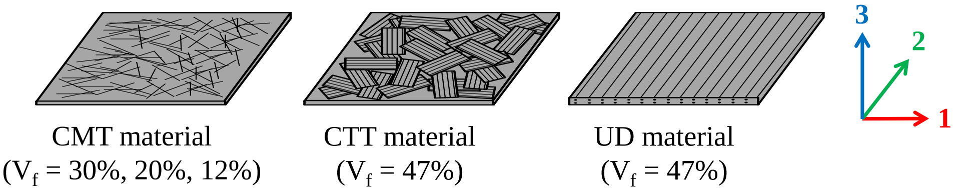

Figure 1. Illustrations of three types of CF/PP used in this study.

2.2. Measurement of electrical conductivity

In the measurement of electrical conductivity of CFRP, four terminals method is sometimes applied from the viewpoint of contact resistance at the edge of specimen. However, in this study, we set a high value on the simplicity of the measurement and decided to use two terminals method. The validity of the result is verified in the next chapter. If direction 1 is the direction of *L:* length of specimen [m], 2 is the direction of *B*: width of specimen [m] and 3 is the direction of *H:* thickness of specimen [m], the following equations (1), (2) and (3) are satisfied about electrical conductivity of three directions, σ_1, σ_2 and σ_3.

$$\sigma_1 = \frac{1}{\rho_1} = \frac{L}{RA} = \frac{1}{R}\frac{L}{BH} \tag{1}$$

$$\sigma_2 = \frac{1}{\rho_2} = \frac{B}{RA} = \frac{1}{R}\frac{B}{HL} \tag{2}$$

$$\sigma_3 = \frac{1}{\rho_3} = \frac{B}{RA} = \frac{1}{R}\frac{H}{LB} \tag{3}$$

Where, σ is electrical conductivity [S/m], ρ is volume resistivity [$\Omega \cdot$m], *R*: resistance between two terminals, *A*: area of cross section [m^2], *L*: length of specimen [m], *B*: width of specimen [m] and *H*: thickness of specimen [m]. In addition, due to the characteristics of the fiber orientation of each material, the following relationship (4) is satisfied.

$$\sigma_{1CMT} = \sigma_{2CMT} \, , \sigma_{1CTT} = \sigma_{2CTT} \, , \sigma_{2UD} = \sigma_{3UD} \tag{4}$$

The size of specimens was shown in Table 1. First, the surfaces where the electrical terminals are attached were polished with five levels, #240, #400, #800, #1,200, and diamond paste of 3μm. The objective of this polishing was to expose carbon fiber on the surfaces and to solve the problems of contact resistance. The surfaces of CMT before and after polishing were shown in Figure 2 and Figure 3. Before polishing, there was too much resin to perform accurate measurement, but after polishing, the resin was removed. Then, electrical terminals were attached to the polished surface by conductive silver paste like Figure 4 and measure the resistance between two terminals. Finally, from the results and equations (1)–(4), the electrical conductivity was calculated.

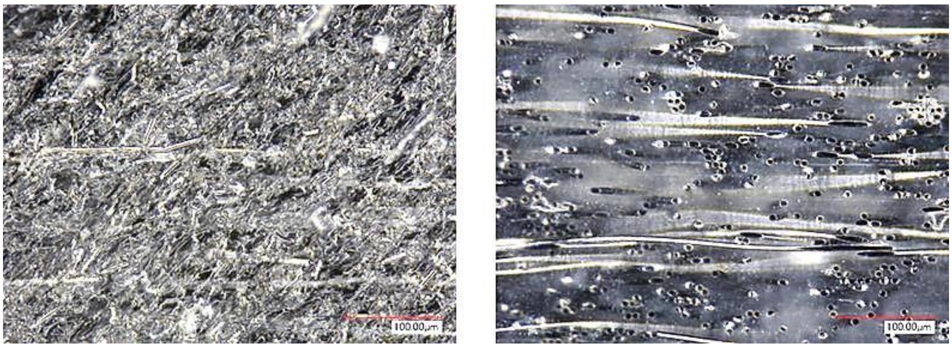

Figure 2. The edge of CMT specimen (V_f = 12%) for the measurement of electrical conductivity of in-plane direction (left: before polishing, right: after polishing).

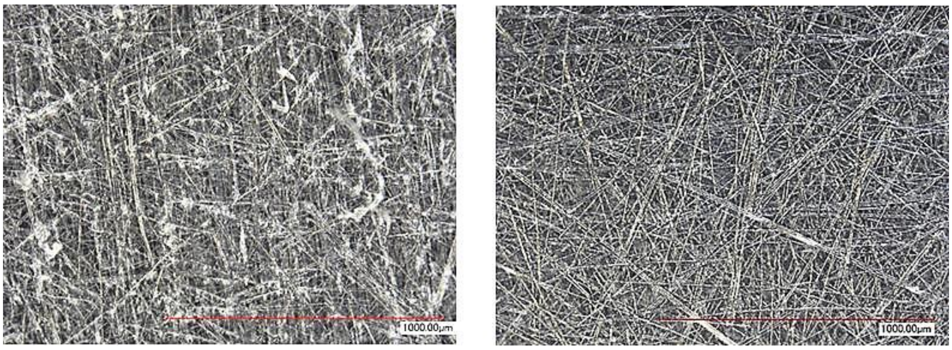

Figure 3. The edge of CMT specimen (V_f = 12%) for the measurement of electrical conductivity of thickness direction (left: before polishing, right: after polishing).

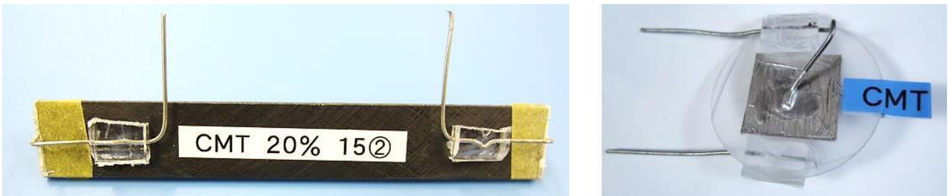

Figure 4. CF/PP specimen for measurement of electrical conductivity (left: in-plane direction, right: thickness direction).

Table 1. Size of specimens used for the measurement of electrical conductivity of each direction.

Material	V_f [%]	In-plane direction			Thickness direction	
		H [mm]	B [mm]	L [mm]	B [mm]	L [mm]
CMT	30	1.6				
CMT	20	2.1				
CMT	12	1.8	6, 10, 15	100	15	15
CTT	47	2.1				
UD	47	1.8				

2.3 Measurement of EMI SE

EMI SE which is one of the applications of electrical property was evaluated by KEC method. The testing device and illustration of KEC method were shown in Figure 5 and Figure 6 respectively. SE is generally expressed by following equation (1).

$$SE = 20\log_{10}\left(E_1/E_2\right) \tag{5}$$

Where, E_1 [V/m] and E_2 [V/m] are incident and transmission electric field, respectively. Specimen size was 150 × 150 [mm]. To evaluate the difference caused by V_f of CMT, CMT with V_f of 30% and 20% were used. Also, to evaluate the effect of thickness, three kinds of thickness were prepared about CMT, that is, 0.8 mm, 1.6 mm and 2.5 mm. Moreover, to evaluate the difference caused by fiber orientation, CTT was also used for comparison. The specimens used in this measurement were shown in Table 2.

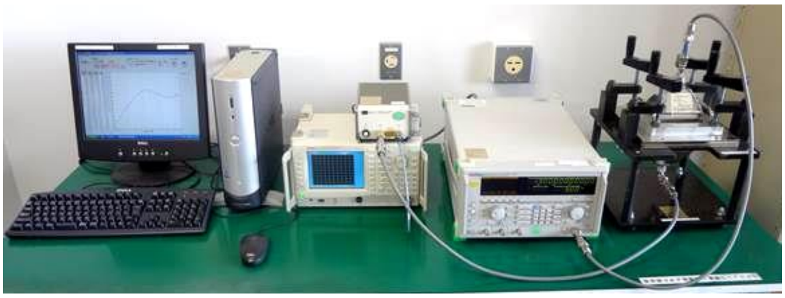

Figure 5. Testing device for the measurement of EMI shielding effectiveness.

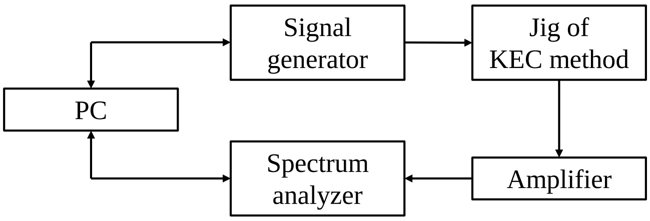

Figure 6. Illustration of testing circuit for the measurement of EMI SE.

Table 2. Specimens used for the measurement of EMI SE.

Material	V_f [%]	Thickness [mm]
CMT20	20	2.1
CMT30_1	30	0.8
CMT30_2	30	1.6
CMT30_3	30	2.5
CTT47	47	2.0

2.4 Measurement of thermal conductivity

In this study, heat flux meter method was applied for the measurement. The picture and illustration of this method were shown in Figure 7. Specimen was inserted between hot plate and cold plate and temperature of each plate was kept to be constant and heat flux was measured by heat flux meter. Thermal conductivity can be calculated by the following equation (6).

$$\lambda = \frac{Q_h + Q_c}{2} \cdot \frac{L}{T_h - T_c} \tag{6}$$

Where, λ is thermal conductivity [W/(m・K)], Q_h and Q_c are heat flux detected at hot and cold plate respectively [W/m^2], T_h and T_c are temperature of hot and cold plates respectively [K], and L is thickness of specimen [m].

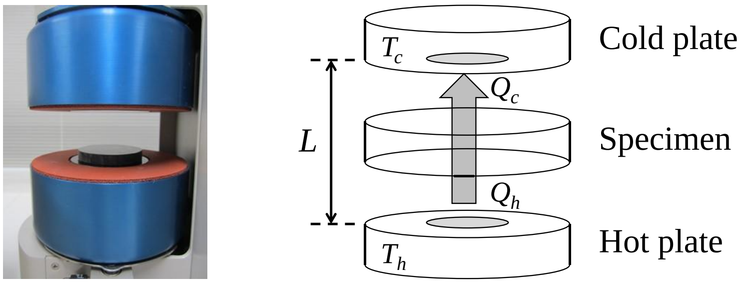

Figure 7. Measurement method of thermal conductivity of thickness direction.

3. Results and discussions

3.1. Electrical conductivity

Figure 8 shows the results of electrical conductivity measurement of in-plane direction. Of course, UD material had quite high electrical conductivity and the value was almost the same as the product of V_f and electrical conductivity of carbon fiber. So, it can be said that the two terminals method used in this study worked accurately. Also, it was found that CMT had relatively high electrical conductivity although it consisted of discontinuous carbon fiber. In contrast, electrical conductivity of CTT material was much smaller in spite of its higher V_f. It is caused by the difference of fiber morphology. That is, CMT is made from of carbon fiber mat, so there are a lot of conductive paths in the fiber mat. On the other hand, CTT consists of chopped tapes, so there are a certain resin layers between carbon fibers.

Figure 9 shows the results of the measurement of electrical conductivity of thickness direction. Electrical conductivity of thickness direction of CMT was much higher than that of CTT or UD material, so in the case of CMT material, there are some conductive paths in thickness direction. However, in the case of CTT or UD material which was composed of UD tapes, there were few conductive paths. Probably, it is also due to the resin layers between UD tapes.

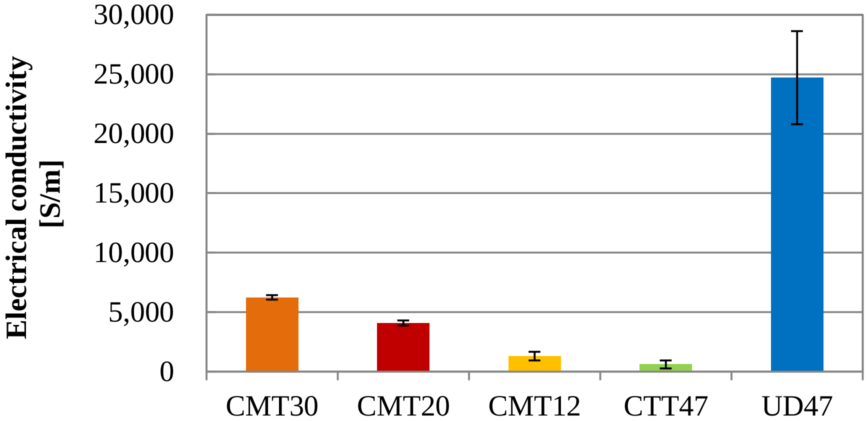

Figure 8. Electrical conductivity of in-plane direction.

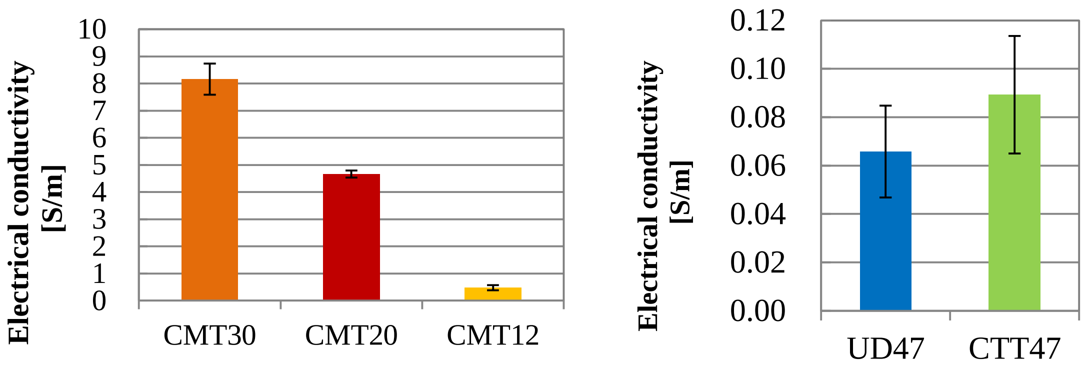

Figure 9. Electrical conductivity of thickness direction.

3.2 Theoretical study about electrical conductivity of CMT

The relationship between electrical conductivity of CMT and its V_f was shown in Figure 10. The results are estimated to be amenable to percolation theory which is well-known as a theory about the mechanism of electrical conductivity of composite materials [7]. In this theory, electrical conductivity can be expressed by the following equation (7).

$$\sigma_c = \sigma_0 \left(V_f - V_{crit}\right)^t \tag{7}$$

Where, σ_c: conductivity of composite [S/m], σ_0: conductivity of conductive reinforcement [S/m], and V_{crit}: percolation threshold. This equation is valid well to carbon black or CFRP with shorter fiber (< 1 mm). However, it may not be applicable to like CFRP with longer fiber, such as CMT material. Hence in this study, equation (7) was improved like equation (8).

$$\sigma_c = \alpha \sigma_f \left(V_f - V_{crit}\right)^t \tag{8}$$

Where, α: constant of fiber orientation and σ_f: conductivity of carbon fiber (axial direction) [S/m]. CMT can be regarded as an isotropic material, so α is 1/3, like rule of mixture about Young's modulus. Carbon fiber used in CMT was T700S, so σ_f was calculated from volume resistivity of T700S, 1.7×10^{-5} [$\Omega\cdot$m]. The measurement results were approximated by the least square method and V_{crit} and t were calculated. As a result, V_{crit} was 0.102 and t was 0.696. These results were substituted to equation (8) and plotted as approximate curve.

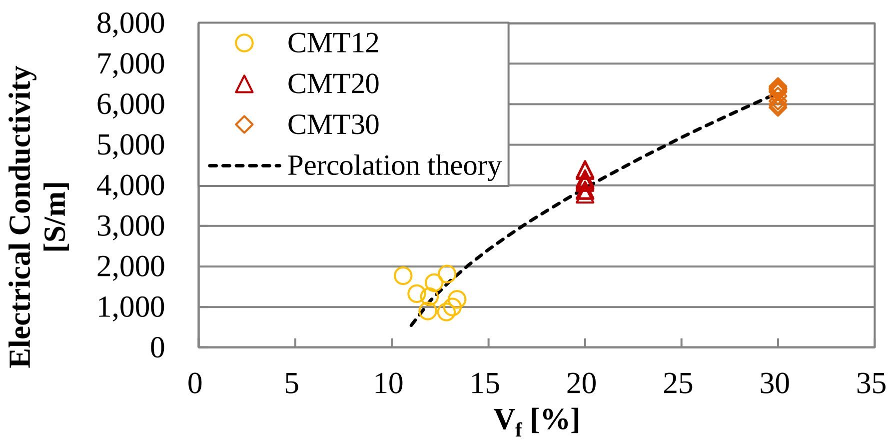

Figure 10. Relationship between electrical conductivity of CMT and its fiber volume fraction.

3.3 Measurement of EMI SE

The measurement results of EMI SE were shown in the left side of Figure 11. It was found that SE of CMT materials were quite high value of 70 to 80 dB in almost all frequency from 10 MHz to 1 GHz. CMT and CTT are both discontinuous carbon fiber reinforced sheet, and V_f of CMT materials are much lower than that of CTT material, but SE of CMT is higher than that of CTT. This is considered to be caused by the difference of conductive path and it is the same as in the case of electrical conductivity. The tendency was also pointed out in the conventional study, and it can be said that the connectivity in conduction path is more important than the value of V_f.

The right part of Figure 11 shows the relationship between EMI SE at 800 MHz and thickness of specimen. From the results of CMT30 as shown in this figure, EMI SE increases due to the increase of specimen thickness from 0.8 mm to 1.6 mm. However, EMI SE of 1.6 mm thickness and 2.5 mm thickness were almost the same, so it can be estimated that EMI SE saturated in these thickness. Therefore, it can be said that EMI SE gradually becomes large due to the increase of thickness, but it saturates if the thickness is increased after a certain thickness.

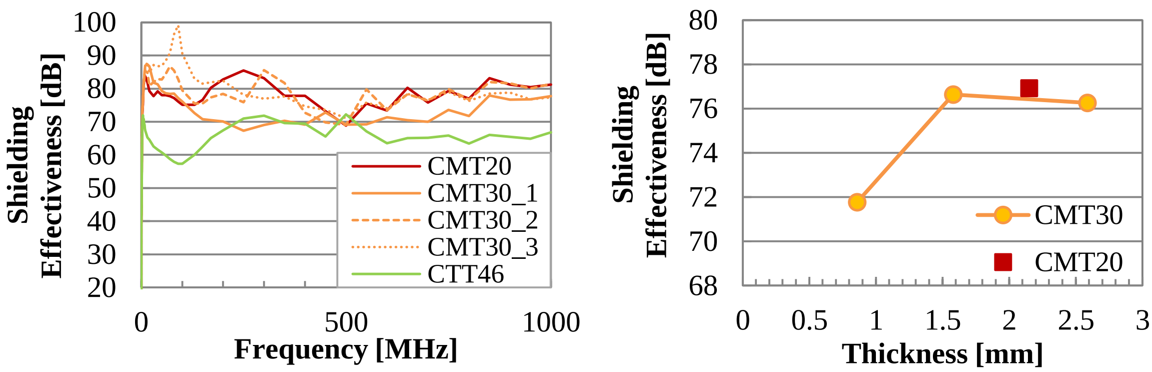

Figure 11. Electromagnetic interference shielding effectiveness of CF/PP materials (left: the relationship between EMI SE and frequency, right: relationship between EMI SE and thickness of specimen at 800 MHz).

3.4 Thermal conductivity

The measurement results of thermal conductivity of thickness direction were shown in Table 3. The conductivity of CMT and CTT was slightly higher than that of PP, but there were no significant change as a whole. This is probably because there are few contact points between carbon fibers and few conductive paths. However, in the case of thermal dissipation property, thermal diffusivity of in-plane direction is one of the important parameters as well as thermal conductivity of thickness direction, so it is necessary to study about it in the future. Also, the improvement of thermal property can be expected about in-plane direction rather than thickness direction based on the results of electrical conductivity.

Table 3. Thermal conductivity of thickness direction about two kinds of CMT and CTT.

Material	V_f [%]	Thermal conductivity [W/(m・K)]
CMT	20	0.32
CMT	30	0.38
CTT	47	0.49

4. Conclusions

In this study, fundamental electrical and thermal properties of CMT were evaluated by some measurements and the theoretical study. First, measurement of electrical conductivity was performed and it was found that electrical conductivity of CMT was much higher than that of CTT in spite of its shorter fiber length and lower V_f. It is because there are a lot of contacts between carbon fibers and hence electrical conductive paths in carbon fiber mat. Also, from the result of theoretical study, it was found that the electrical conductivity of CMT was amenable to percolation theory by introducing constant of fiber orientation. In the future, it is necessary to expand the theory to CMT with another fiber length. In addition, EMI SE of CMT was also higher than that of CTT caused by its uniformity of carbon fiber mat, so CMT can be expected as EMI shielding material as well as structural material. Concerning thermal conductivity, there was no significant change about thickness direction. This was the same tendency as the case of electrical conductivity, that is, electrical conductivity of thickness direction was much lower than that of in-plane direction.

Acknowledgment

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