FIBER LENGTH EFFECT ON TENSILE AND COMPRESSIVE STRENGTH OF SHORT FIBER REINFORCED THERMOPLASTICS

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Abstract
The mechanism of the fiber reinforcement and the mechanical properties of fiber reinforced composites are considered important for the manufacture and application. In the present study, randomly oriented short carbon fiber reinforced thermoplastics were prepared with compression molding techniques. The tensile properties and compressive properties of this composite were investigated. The fiber length shows different effect on each mechanical property. The fiber efficiency factors of different properties were predicted using the modified rule of mixtures equation and the fiber efficiency factor of strength and modulus show different sensitivity to the fiber length. The fractures of the specimens were analyzed after the tests, the tensile fracture mechanism and the compressive fracture modes were discussed.

1. Introduction

Carbon fiber reinforced thermoplastics (CFRTP) is considered to be promising ultra-lightweight material for automotive manufacturers not only because it can be applied in the special automobiles to realize extremely driving performance but also because it can improve the energy efficiency of mass-production vehicles to mitigate the global petroleum consumption and CO_2 emission [1]. To ensure the application of CFRTP on mass production, we need to develop comprehensive knowledge about the mechanical properties of the CFRTP materials, parts and the structures.

In the industrial application of CFRTP, the randomly orientated short fiber reinforced thermoplastics (RSFRTP) show advantages of good high cycle and complex shaped molding properties compare to the traditional unidirectional laminate and woven materials. However, due to the complex internal structure and the interaction between the fibers and the matrix during the molding process, the mechanism of the fiber reinforcement and the mechanical properties of RSFRTP are still under study.

The theoretical research of mechanical properties of RSFRTP was begun from 1990s. Fu et. al. managed to derived the tensile strength and tensile modulus of RSFRTP as functions of fiber length and fiber orientation distribution [2, 3]. The compressive strength of laminates and the tensile properties of RSFRTP with different fibers were studied then [4, 5]. Since the residual flexure stress is easily generated due to the impregnation process of fibers during the molding process of RSFRTP, the mechanical properties of the material is greatly affected by the molding condition[6, 7].

The objective of the present work is to investigate the effect of fiber length on the tensile and compressive properties of the RSFRTP. A kind of RSFRTP was manufactured under the considering the reducing of the residual flexural stress. Tensile and compressive tests of RSFRTP with different fiber length have been conducted. The effect of the fiber length to the mechanical and the fracture properties have been studied.

2. Materials and methods

2.1 Materials

A kind of RSFRTP named as UT-CTT (ultra-thin chopped carbon fiber tape reinforced thermoplastics) were used in this study. The UT-CTT is composed with randomly oriented ultra-thin unidirectional prepreg tapes. The tape is manufactured with carbon fiber (TR 50S, Mitsubishi Rayon Co., LTD.) and Polycaprolactam (Nylon 6). The tape size is 5 mm in width and about 45 µm in thickness and cut in four different tape lengths: 6 mm, 12 mm, 18 mm and 24 mm. The cut tapes were randomly oriented and the UT-CTT plates were manufactured through compression molding. The molding pieces of UT-CTT are shown in Figure 1. And the materials mechanical properties of the components are listed in the Table 1. The fiber volume fractions were calculated by ash test after the molding and the details are listed in the Table 2.

The intermediate substrate used in this study were provided by the Industrial Technology Center of Fukui Prefecture and AWA PAPER MFG. CO., LTD.

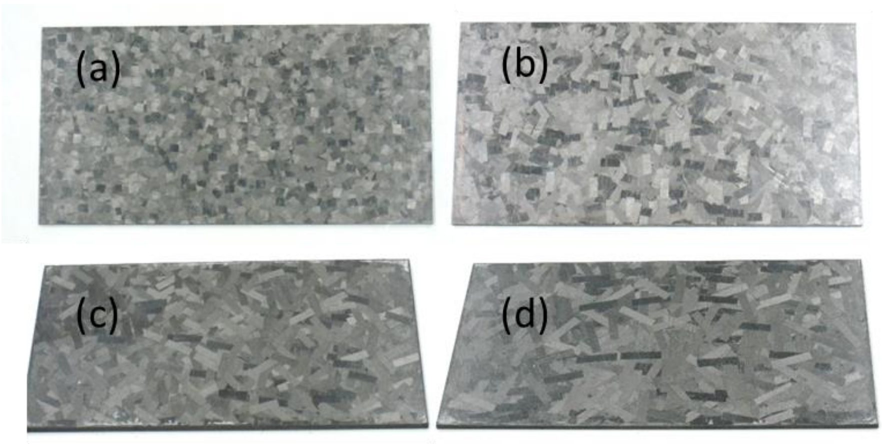

Figure 1. The UT-CTT material in the tape length of 6 mm (a), 12 mm (b), 18 mm (c) and 24 mm (d).

Materials	Tensile strength [MPa]	Tensile modulus [GPa]	Compressive strength [MPa]	Compressive modulus [GPa]
Carbon fiber (TR 50S)	4900	240	4900	240
Polycaprolactam (Nylon 6)	77	1.9	91	1.75

Table 1. Mechanical properties of materials at ambient temperature.

Tape length	6 mm	12 mm	18 mm	24 mm
V_f	54.4%	56.1%	55.2%	54.5%
Void ratio	1.6%	1.7%	1.2%	1.3%

Table 2. Fiber volume fraction and void ratio of specimens.

Tests	Thickness [mm]	Width [mm]	Height [mm]	Number of tests
Tensile	3	30	100	6
Compressive	3	12.5	55	5

Table 3. Specimen size for tensile and compressive tests.

2.2 Methods

Tensile and compressive tests have been conducted in present study. The specimen sizes were shown in Table 3. Both tensile test and compressive test was conducted with a 10 tons universal testing machine (AUTOGRAPH AG-100kNXplus, Shimadzu CO.). The stroke speed of tensile test was set to 1 mm/min and the stroke speed of compressive test was set to 0.5 mm/min respectively. After the tensile and compressive tests, the fractures of the specimens were observed visually under optical microscope and 3D X-ray scanner.

3. Results and Discussions

The effect of the tape length on the tensile strength, tensile modulus, compressive strength and compressive modulus were calculated from the results of the tests separately (Figure 2-5). The effect of the tape length has different influence on the different mechanical properties. The tensile strength increase with the increase of the tape length and reached a plateau when the tape length becomes 18 mm (Figure 2), while the tape lengths have no clear effect on the tensile modulus (Figure 3). Both the compressive strength and compressive modulus show increase tendency with the increase of the tape length, but the compressive strength increasing become saturated at the tape length of 12 mm (Figure 4) while the compressive modulus demonstrate a slight decrease when the tape length is longer than 18 mm (Figure 5).

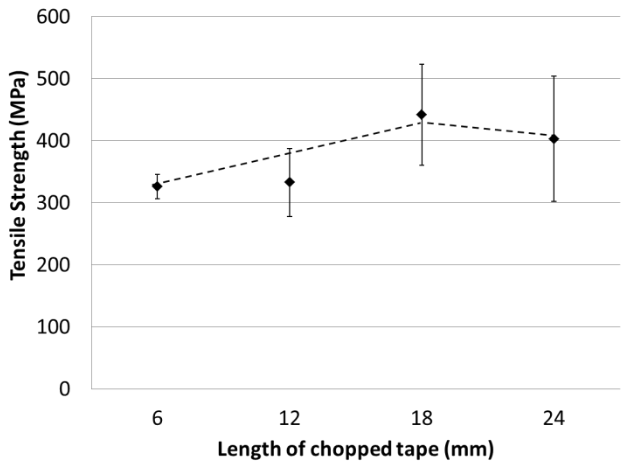

Figure 2. Tensile strength of UT-CTT by different tape length.

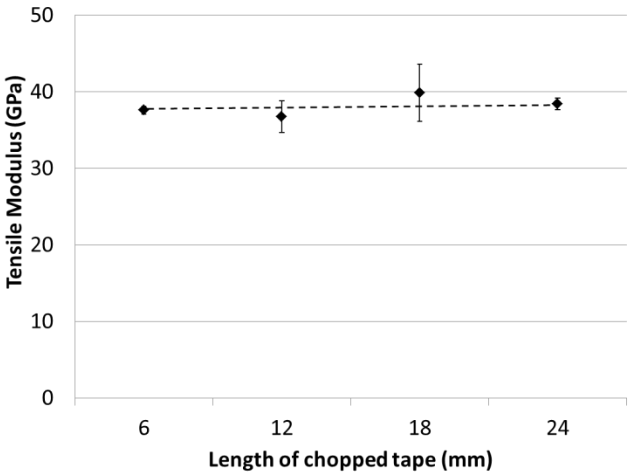

Figure 3. Tensile modulus of UT-CTT by different tape length.

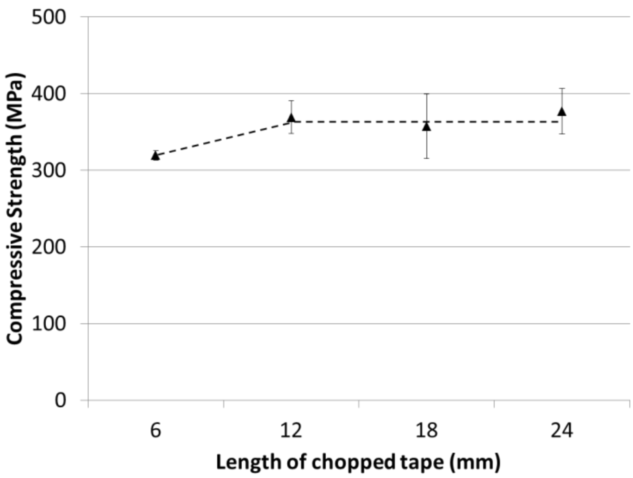

Figure 4. Compressive strength of UT-CTT by different tape length.

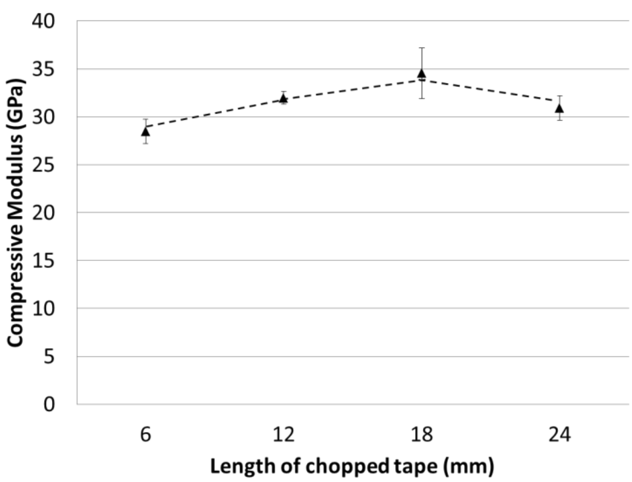

Figure 5. Compressive modulus of UT-CTT by different tape length.

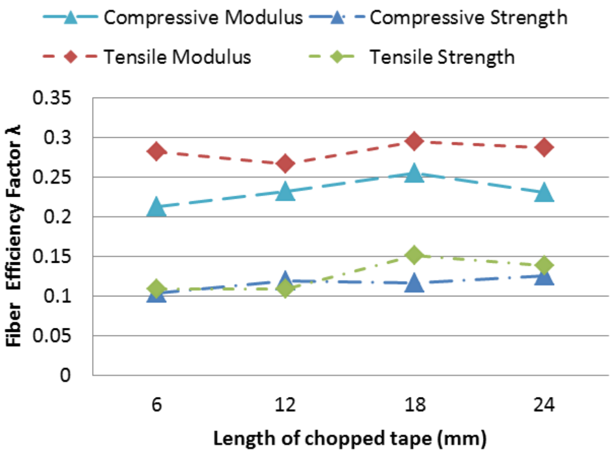

Figure 6. Fiber efficiency factors for the strength and modulus of UT-CTT by different tape length.

According to the previous studies, the tensile strength ($\boldsymbol{\sigma_t}$) and the compressive strength ($\boldsymbol{\sigma_c}$) of RSFRTP composites can be predicted using the modified rule of mixtures equation [2]:

$$\begin{cases} \sigma_t = \lambda_{\sigma t} \sigma_{ft} V_f + \sigma_{mt}(1-V_f) \\ \sigma_c = \lambda_{\sigma c} \sigma_{fc} V_f + \sigma_{mc}(1-V_f) \end{cases} \quad (1)$$

where $\lambda_{\sigma t}$ and $\lambda_{\sigma c}$ are the fiber efficiency factor for the composite tensile strength and compressive strength taking into account the effects of fiber length and orientation. V_f is the fiber volume fraction. σ_{ft} and σ_{mt} are the tensile strength of fiber and matrix, while σ_{fc} and σ_{mc} are the compressive strength of fiber and matrix, respectively.

Similarly, the tensile modulus (E_t) and the compressive modulus (E_c) of RSFRTP composites can be predicted by the modified rule of mixtures equation [3]:

$$\begin{cases} E_t = \lambda_{Et} E_{ft} V_f + E_{mt}(1-V_f) \\ E_c = \lambda_{Ec} E_{fc} V_f + E_{mc}(1-V_f) \end{cases} \quad (2)$$

where λ_{Et} and λ_{Ec} are the fiber efficiency factor for the composite tensile modulus and compressive modulus considering the effects of fiber length and orientation. E_{ft} and E_{mt} are the tensile modulus of fiber and matrix, while E_{fc} and E_{mc} represented the compressive modulus of fiber and matrix, respectively.

Figure 7. Cross section of specimen by the tape length of 24 mm.

For our study, the change in fiber orientation can then be neglected since the fiber tapes are randomly oriented for all specimens and thus the change in the tape length, otherwise the change in fiber length would mainly affect the change of fiber efficiency factors.

Figure 6 shows the relationship between the tape length and the fiber efficiency factor λ of tensile strength, tensile modulus, compressive strength and compressive modulus. It can be seen from Figure 6 that the λ of tensile and compressive strength/modulus have no significant difference while the fiber efficiency factor λ_σ for the strength is much lower than the fiber efficiency factor λ_E for the modulus. This can be considered as an evidence of that the modulus of RSFRTP composites is a property of material at low strain and is not very sensitive to the fiber–matrix interface or fiber length while the strength of RSFRTP composites is a property considering the fracture and debonding of the interface and more sensitive to the fiber length [5].

From the Figure 2-5, it is clear that despite the residual flexure stress of the fibers have been restricted through the molding process, the individual difference of the specimens is still big in some mechanical properties. This phenomenon is considered lead by the molding quality. For example, the specimens of the tape length 24 mm are generally show poor mechanical properties than the specimens of the tape length 18 mm. Under the observation of the cross section of the 24 mm tape specimens we found that the tapes were folded thought the thickness direction (Figure 7). This wrinkle of tape is regarded emerged through the molding process and have great influence to the mechanical properties.

After the tests, the fractures of the specimens were analyzed. The fracture of tensile tests specimens were illustrated in Figure 8. As the tensile strength show increase tendency with the increase of the tape length, the longer tape was considered can prevent the growth of the cracks (Figure 9).

In the compressive tests, two main fracture modes were observed: the bucking (Figure 10) and the delamination (Figure 11). And in the compressive test, the fracture of most specimens included both fracture modes (Figure 12).

Figure 8. Fracture of UT-CTT in tensile tests.

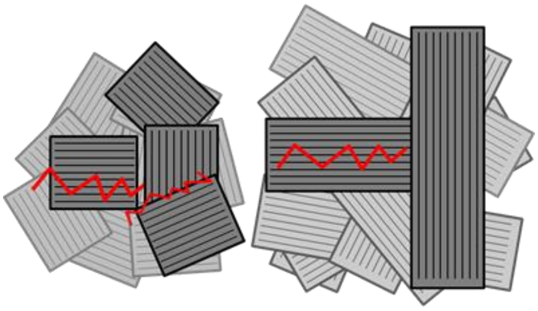

Figure 9. Effect of the tape length on the tensile fracture.

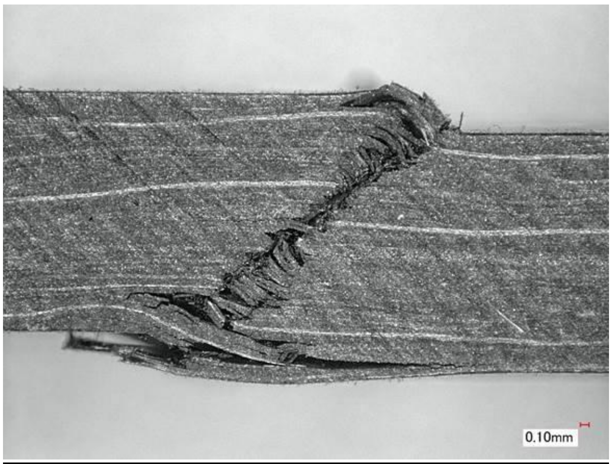

Figure 10. Bucking in the compressive tests.

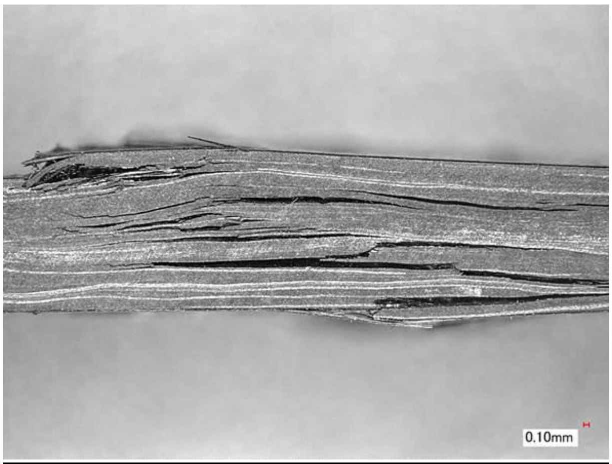

Figure 11. Delamination in the compressive tests.

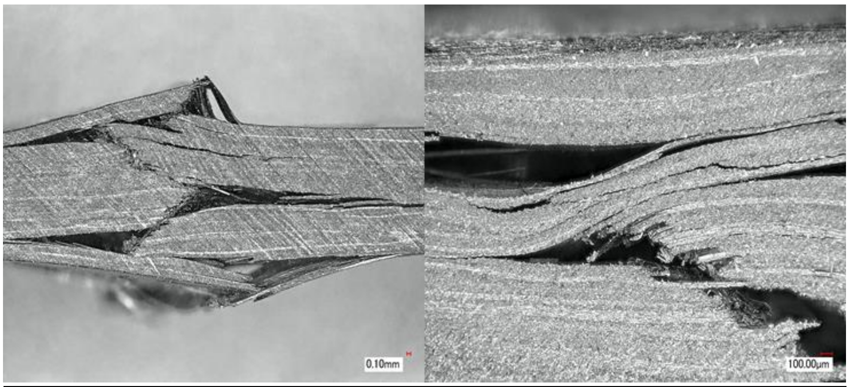

Figure 12. General fracture of UT-CTT in compressive tests.

4. Conclusion

We conducted tensile and compressive tests of RSFRTP in different fiber length and the fiber length show different effect on the different mechanical properties. The fiber efficiency factor of strength is more sensitive to the fiber length than the fiber efficiency factor of modulus. The fiber efficiency factors between tensile properties and compressive properties have no conspicuous difference. The molding conditions have great effect on the mechanical properties. The tape length shows the property to prevent the growth of the cracks on the tensile strength and two different fracture modes have been observed in compressive tests.

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