NOVEL CARDING PROCESS TO IMPROVE MECHANICAL PROPERTIES OF RECYCLED CARBON FIBER CARD WEB REINFORCED THERMOPLASTICS

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Keywords: CFRTP, Carding process, Recycled carbon fiber, Alignment

ABSTRACT

Possibility of non-woven carding process as a potential approach for reusing recycled carbon fiber (r-CF) was discussed in this study. Preforms with variable volume fraction (V_f) of carbon fiber were manufactured by carding process. Unidirectional and cross stacking of preforms were carried out in compression molding for fabricating specimens for mechanical test. To illustrate the contribution of carding process on the degree of fiber alignment, mechanical property was evaluated in two directions that are perpendicular to one another. Tensile test and three point bending test were performed, also practical V_f of the specimens for mechanical tests were measured by ash test. As predicted, mechanical properties increased with the growth of V_f. However, increased V_f of carbon fiber inducing complex packing geometry results in relatively high void content on the specimens fabricated by the preforms with high V_f. In addition, stretched preforms were manufactured by applying tension on as-fabricated preforms along carding direction. Consequently, carbon fiber card web reinforced thermoplastics (CWT) made by stretched preforms show desirable mechanical property, since improved carbon fiber alignment and decreased void content attribute to stretching process. To demonstrate the consequence made by mechanical test, fiber orientation distribution (FOD) of CWT fabricated by two types of preforms were evaluated.

1 INTRODUCTION

Carbon fiber reinforced plastics (CFRP) have been widely used in structures for commercial aircrafts, luxury automobiles and leisure fields because of their high specific properties [1]. Additionally, the applications in mass-produced automobiles and wind turbines have created an urgent need for greater demand and lower cost in CFRP manufacturing [2]. At the same time, the amount of CFRP waste generated from the in-plant cut-offs and the end-of-life products have grown to cause the concerns of environmental issues. However, the carbon fibers (CF) included in the CFRP waste are proven to be valuable for second use by several researchers [3]. Therefore, tremendous attention and effort have been devoted to how to recycle and reuse CF. Even though, recycled carbon fibers (r-CF) have been generally acknowledged that the mechanical properties will not deteriorate after recycling processes, the application of r-CF still has the issues of unstable fiber length distribution and misaligned orientations because of CFRP manufacturing processes and recycling procedures. Therefore, how to reuse the discontinuous and misaligned r-CF is the key to close the CF recycling loop [4-7].

As an approach for reusing r-CF, carbon fiber paper reinforced thermoplastics (CPT) has been proposed in previous research [8]. By using a water-agent dispersion process, r-CF can be uniformly orientated. However, a large amount need of water is common concern for environment. Additionally, uniformly in-plain distribution cannot make higher volume fraction (V_f) of r-CF possible for further applications, especially for those in automotive industries. Therefore, we need to provide a second approach to increase the potential V_f.

In this study, carbon fiber card web reinforced thermoplastics (CWT) were proposed as the second approach for reusing r-CF. A non-woven carding process was applied in CWT fabrication in order to improve the alignment of discontinuous CF and increasing V_f. In order to illustrate the influence of carding process on the alignment effect and investigate the upper limit of V_f, mechanical properties of CWT with various V_f were measured in two perpendicular directions, L-direction (the carding direction) and T-direction. Unidirectional and cross stacking of preforms were carried out in compression molding for fabricating specimens for evaluating mechanical properties. Aiming for further improvement of alignment degree, stretched preforms were fabricated by applying tension on as-fabricated preforms along L-direction. Additionally, fiber orientation distribution (FOD) of two types of preforms were evaluated by X-ray CT.

2 EXPERIMENTAL

2.1 Materials

In order to avoid negative influence of CF degradation on the mechanical properties of CWT, TORAYCA®T700S fresh carbon fiber and polyamide 66 (PA66) was used in fabricating preforms. CWT preforms with 20, 30 and 40% of V_f were manufactured initially by carding process and stretched preforms were fabricated by applying tension on as-fabricated preforms with 30% of V_f for further improvement of FOD.

2.2 Carding process

As a vital process involved in non-woven sheet producing procedure, carding process is contributed by the ahead programmed moment of hundreds of needles, CF are mixed with matrix fibers [9]. The continuous movement of carding machine induced a concern about the fiber orientation distribution of CWT preforms. The CF will be aligned preferably with L-direction, the carding direction. Therefore, the outcome CWT has anisotropic properties. To illustrate the contribution of carding process on the degree of fiber alignment, mechanical properties were evaluated according to L-direction and T-direction that is perpendicular to L-direction. After that, the mixed CF and matrix fibers were heated by hot press for fabricating CWT sheet.

2.3 Specimen preparation

Unidirectional and cross stacking architectures were applied for different V_f of CWT non-stretched preforms. Stretched CWT preforms were fabricated into panels only by unidirectional stacking method. According to the V_f and the stacking architectures, the different types of CWT are defined as CWT20, CWT30, CWT40, C-CWT30 (cross-plied CWT) and S-CWT30 (stretched CWT). The details are shown in Table 1. Each CWT panels were molded by compression molding by the molding temperature of 280 °C. The molding pressure of 7 MPa was carried out for all CWT panels except CWT40, which was molded under 9 MPa in order to decrease the possible void content.

Table 1. Types of CWT with different V_f and stacking method.

	V_f 20%	V_f 30%	V_f 40%	Stretched V_f 30%
Unidirectional stacking	CWT20	CWT30	CWT40	S-CWT30
Cross stacking	-	C-CWT30	-	-

2.4 Ash test

In order to quantitatively assess the correlation between V_f and mechanical properties, precise V_f and void content (V_v) of each CWT panels were observed by measuring ignition loss of polymer matrix at inert gas atmosphere. Five specimens with 15mm in length and width were cut out from each CWT panels. The operating condition is constant as 500 °C for 2 hours.

2.5 Tensile test

Tensile property of CWT was measured by axial tensile test according to JIS K 7073 with universal testing machine (AUTOGRAPH AGS-X plus 100KN, Shimadzu Co.). Five specimens were prepared in L-direction and T-direction respectively. The size of specimen is 110mm in the length, 15mm in the width and the thickness of 2.5mm. The test speed is 1mm/min and 50mm long extensometer is employed for measuring the strain in the load direction.

2.6 Three point bending test

Flexural property of CWT was measured by three point bending test according to JIS K 7074 with universal testing machine (AUTOGRAPH AGS-X 5KN, Shimadzu Co.). As in the tensile test, five specimens were prepared in each direction. The size of specimen is 50mm in the length, 10mm in the width and the thickness is 1.5mm. The span of the supporters on the testing machine is determined by the thickness of the specimens with the span-to-thickness ratio of 16:1 and the crosshead speed is 1mm/min.

3 RESULT AND DISCUSSION

3.1 Ash test

In order to obtain more accurate evaluation on mechanical properties, ash test was processed for each CWT panel and the actual V_f and V_v were calculated by following equation:

$$V_f = \frac{m_f / \rho_f}{m_c / \rho_c} \tag{1}$$

where m_f is the weight of carbon fiber after ash test. m_c is the weight of specimen before test. ρ_f is density of carbon fiber, the value is 1.80g/cm^3 (T-700). ρ_c is the density of specimen, which is measured by electric densimeter (MDS-300, ALFA MIRAGE). The actual V_f and V_v of specimens which were used in tensile test and three point bending test are shown in Table 2 and Table 3 respectively. The results indicate that increased V_f of CF induced complex packing geometry, resulting in high V_v on the specimens fabricated by the preforms with high V_f. In addition, due to the complicated internal structure of C-CWT30, relatively higher V_v was observed compared with CWT30. On the contrary, contribution to the improvement of FOD, lower V_v was observed in S-CWT30. As shown in Table 2, the actual V_f of CWT20 is almost close to 30% caused by massive resin overflow during the molding.

Table 2. V_f and V_v of the specimens for tensile test.

	CWT20	CWT30	C-CWT30
V_f [%]	23.83	31.94	31.65
V_v [%]	1.03	1.41	2.93

Table 3. V_f and V_v of the specimens for three point bending test.

	CWT20	CWT30	CWT40	C-CWT30	S-CWT30
V_f [%]	29.83	30.74	42.35	31.30	29.26
V_v [%]	1.55	1.66	5.55	1.92	1.28

3.2 Tensile property

To investigate the influence of carding process on FOD of CWT and the effect of cross stacking, axial tensile test was processed on CWT20, CWT30 and C-CWT30 in L-direction and T-direction.

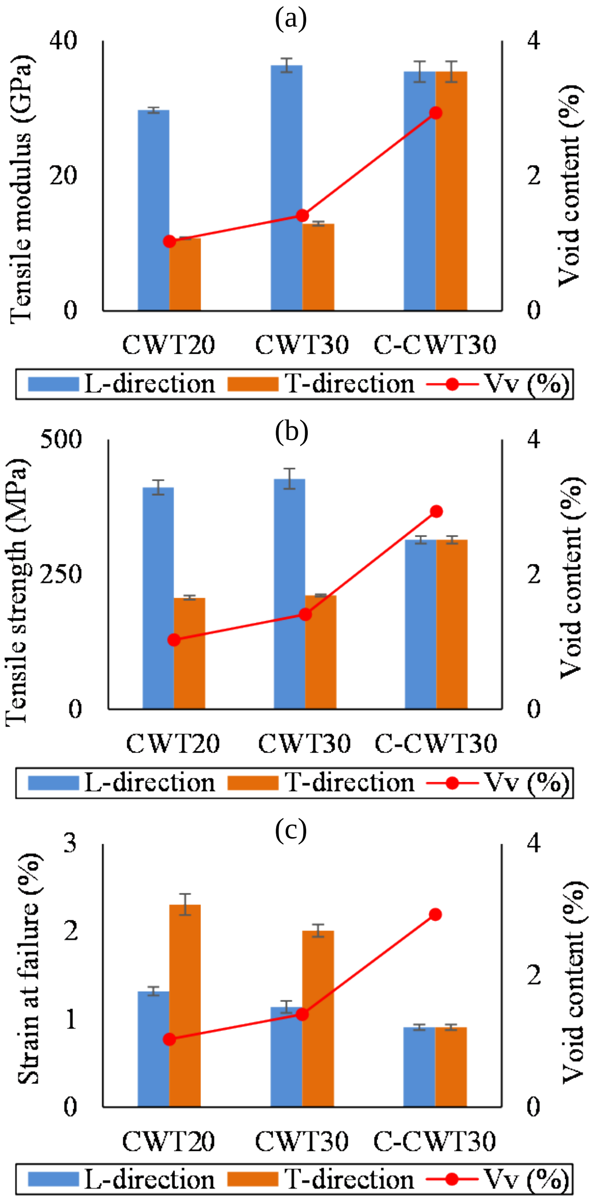

Fig. 1 Tensile property of CWT: (a) tensile modulus, (b) tensile strength, (c) strain at failure.

As shown in Fig. 1 (a), contributed by the increased reinforcement content in the CWT with higher V_f, higher tensile modulus was observed in the CWT30 in each direction. The variation of tensile modulus in T-direction reveals the fibers potentially aligned along L-direction by carding process. The tensile modulus of C-CWT30 is compatible to CWT30 in L-direction and it is almost 3 times higher in T-direction.

The results of tensile strength are shown in Fig. 1 (b). Tensile strength has similar V_f tendency with tensile modulus. However, in the case of C-CWT30, the tensile strength is even lower than CWT20 in L-direction. Degradation of tensile strength on L-direction is reasonable due to the tensile strength is mainly influenced by the content of reinforcement and the V_v, and the CF is relatively uniformly dispersed in in-plane by cross stacking and the complicated geometry generating high V_v. Improvement of tensile strength on T-direction also contributed by the enhancement of CF content in T-direction by cross stacking.

The results of strain at failure are shown in Fig. 1 (c). The strain at failure was deceased with the increase of V_f, since the CWT become more brittle with the increment of CF content. As a result, the strain at failure decreased in both directions.

3.3 Flexural property

In order to investigate the upper limit of V_f and the effect of the cross stacking more precisely, the flexural property of CWT20, CWT30, CWT40 and C-CWT30 were measured by three point bending test. Additionally, the flexural property of S-CWT30 was also evaluated for investigating the influence of stretching process on FOD of CWT.

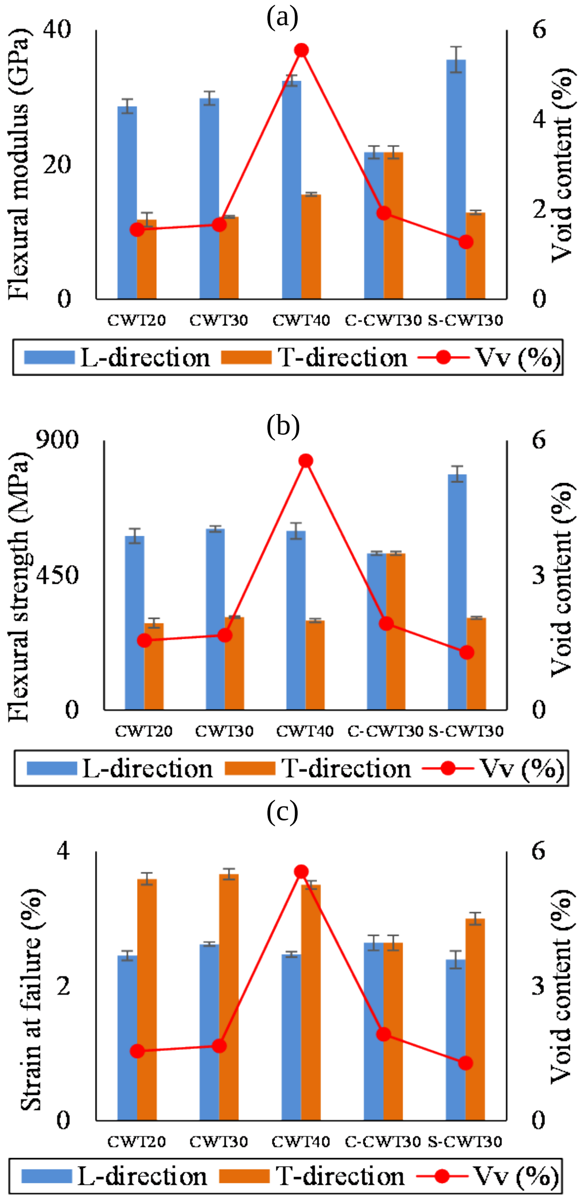

Fig. 2 Flexural property of CWT: (a) flexural modulus, (b) flexural strength, (c) strain at failure.

As shown in Fig. 2, the flexural properties show the analogous V_f tendency with the tensile properties, because the fracture was occurred at the tensile side in three point bending test. However, in the case of CWT40, although the flexural modulus was slightly improved with the enhancement of CF content, the flexural strength and the strain at failure decreased in both directions. Since the high V_v in CWT40 induces the fracture occurred at the earlier stage and results in the decline of flexural strength along with the strain at failure.

Comparing to the CWT30, both of the tensile modulus and strength of C-CWT30 were decreased in each direction. Therefore, although the C-CWT30 shows the quasi-isotropic property by the cross stacking, it is hard to achieve the desirable performance on mechanical property by stacking non-stretched CWT preforms.

In the case of S-CWT30, the flexural modulus and strength were greatly improved comparing with the CWT30. Because the FOD of CWT was improved by the stretching process and the content of CF was increased on L-direction. More details will be discussed in 3.4 part.

3.4 Evaluation of FOD

In order to investigate the correlation between the FOD and mechanical properties, the FOD of CWT30 and S-CWT30 were measured with X-ray CT system. In this measurement, probability distribution function was used to evaluate the FOD, additionally, the angle θ between fiber and 1 axis and the angle φ between fiber and 3 axis indicate the in-plane and out-of-plane fiber orientation respectively [10-12]. The schematic illustration is shown in the Fig. 3. The direction of 1 axis represents the L-direction and 2 axis represents T-direction.

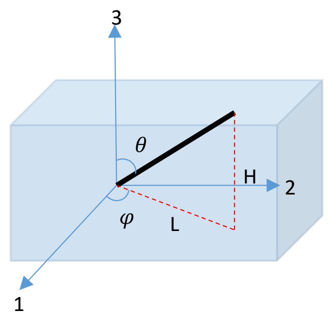

Fig. 3 Description of fiber orientation in 3-dimension.

The results of in-plane FOD are shown in Fig. 4 (a). It is clear that the relative frequency around 0 and 180 degree were obviously improved in S-CWT30 compared with CWT30. Furthermore, the value of relative frequency around 90 degree was decreased. That means the content of CF was increased in L-direction and decreased in T-direction. As a result, the in-plane FOD is significantly improved by the stretching process.

The results of out-of-plane are shown in Fig. 4 (b). In this histogram, 90 degree indicates the perpendicular direction to out-of-plane direction. That means the higher relative frequency around 90 degree, the less CF is facing to out-of-plane. Additionally, the sum of relative frequency around 90 degree is almost same in each CWT. Hence, it can be considered that there is no influence on the out-of-plane FOD by stretching process.

In summary, stretching as-fabricated CWT preforms along L-direction could significantly improve the FOD and that could achieve desirable performance on mechanical properties.

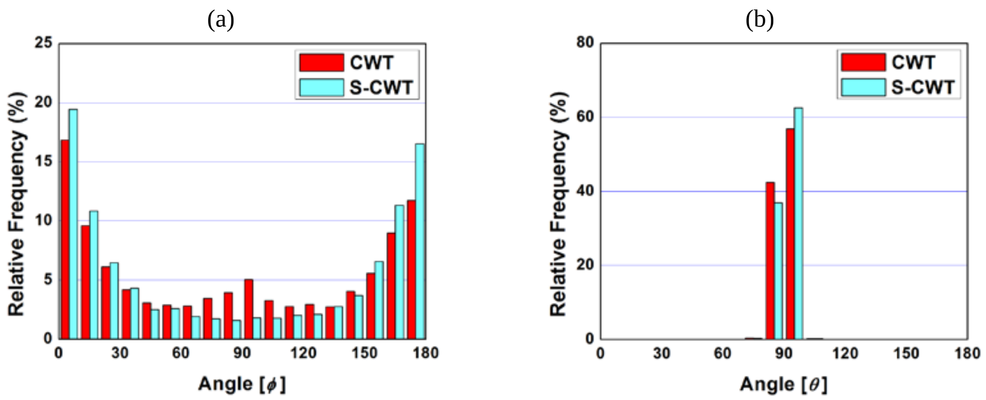

Fig. 4 Fiber orientation distribution of CWT and S-CWT: (a) In-plane, (b) Out-of-plane.

4 CONCLUSIONS

The viability of non-woven carding process as a potential approach for reusing r-CF was evaluated by investigating mechanical properties of CWT with various V_f. Unidirectional and cross stacking methods were applied in fabricating CWT panels for mechanical tests. Considering the contribution of the carding process on the FOD of CWT, mechanical properties were evaluated in L-direction and T-direction. The gaps on performance of mechanical property between two directions demonstrate the improvement of FOD by carding process. Comparing the tensile and flexural properties of CWT20, CWT30 and CWT40, it reveals that 30% of V_f is most suitable for fabricating CWT with non-stretched preforms. However, in the case of C-CWT30, although the C-CWT30 shows the quasi-isotropic properties by cross stacking, it is hard to achieve the desirable performance on mechanical properties by stacking non-stretched CWT preforms. Aiming to improve FOD of CWT, stretched preforms were manufactured by applying tension on as-fabricated preforms with 30% of V_f along L-direction. In consequence, due to the improvement of FOD, desirable mechanical property and relatively lower V_v were observed in S-CWT30. The result of FOD measured by X-ray CT also reveals the significant improvement of FOD by stretching process.

ACKNOWLEDGEMENTS

Part of this study belongs to Japanese METI project "the Future Pioneering Projects/ Innovative Structural Materials Project" since 2013fy. Authors express sincere appreciation to the project members who have provided valuable information and support.

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