A PARAMETRIC STUDY OF ULTRA-THIN CHOPPED CARBON FIBER TAPE REINFORCED THERMOPLASTIC IN DOUBLE-SHEAR TESTS

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Abstract

Chopped carbon fiber tape reinforced thermoplastic (CTT) comprises good mechanical performance and outstanding formability, its advantages show promising potential for lightweight production of automobile to mitigate the fossil consumption and global warming. In the present work, experimental studies were conducted to investigate the bearing strength and coefficient of variation (*CoV*) under the effects of tape dispersion method (sheet molding-CTT and bulk molding-CTT) and tape thickness (44 μm, 88 μm, 132 μm) in pin-loaded double-shear tests. In addition, the failure process was characterized by fractography of bearing cross section with digital microscope. The experimental results indicate the bearing strength improved when the tape thickness decrease and the molding method changes from bulking molding to sheet molding.

1. Introduction

Carbon fiber reinforced polymer (CFRP) material has grown steadily in the application of engineering components for the past several years. On account of the outstanding specific strength and stiffness properties, CFRP has been generally applied in numerous fields such as aerospace, automotive and civil engineering to promote substantial weight reductions. Comparing with high price thermoset resins, thermoplastic is considered more suitable for mass production automotive thanks to its better recyclability, easier manufacture process and relative low cost. As innovative CFRP, chopped carbon fiber tape reinforced thermoplastic (CTT), a sort of randomly oriented strands (ROS) made of discontinues CF/PA6 prepreg tapes, is considered as desirable material for automotive application because CTT combines the merits of continuous fiber composite with good mechanical performance and discontinuous fiber composite with outstanding formability.

ROS material has been utilized in several engineering fields, such as the rear door frame of Toyota Prius Plug-in hybrid [1] and Lamborghini's Aventator [2]. In the case of ROS material, tensile and compressive experiments of CTT has been investigated with different tape size [3-4]. However, bearing experiment is different from ordinary tensile or compression tests, which is strongly affected by stress concentration, clearance, torque and etc. [5-7]. Most of research and application [8-9] use bulk molding method when dispersing carbon fiber tapes, because it's fast and easy molding advantages. However, bulk molding always make the tapes became wrinkle, winding and out of plane after molding, which makes the decreasing of mechanical property and the increasing of scatter. Thin-ply laminated composites can suppress the microcracking, delamination and splitting damage for static, fatigue and impact loading, which draws more and more attention these days [10].

The application for mechanical fastening remains inescapable due to its overcoming advantages of high strength, easy to disassembly to repair or replacement and low cost. Nevertheless, improper design of the joints may cause structural problems or conservative design, which will lead to overweight structures and higher cost. In addition, due to the stress concentration around the hole, the joining becomes the weakest link, and the *CoV* is difficult to predict since the exist of cut off tapes around the hole. Consequently, in this paper, a parametric study was conducted to investigate the influence of molding method and tape thickness on the failure strength and failure process of CTT material. Moreover, *CoV* of the failure strength was also concerned by us because stable failure plays an important role in engineering application. Finally, fractography was conducted to analyze the failure process of CTT with different molding method and tape thickness.

2. Material fabrication

As innovative CFRP, chopped carbon fiber tape reinforced thermoplastic (CTT) is considered as desirable material for mass production automobile. The carbon fiber and polyamide 6 were TR50S and Diamiron C® provided by Mitsubishi Chemical Co., Ltd. To investigate the influences of molding method and tape thickness on bearing failure, tapes of 3 different thickness (44 µm, 88 µm, 132 µm) are prepared by automated cutter and Tomson cutter. After that, thin tapes of 44 µm thickness were molded by sheet and bulk molding method to investigate the influence of molding method. The tapes with different tape thickness are all molded by sheet molding method to understand the effects of tape thickness in bearing failure. All the tapes with a fiber volume fraction (V_f) of 55%, and the size of 18mm length and 5mm width.

2.1 BM-CTT fabrication

As shown in Fig. 1, the tapes were bulkily mixed and put into the molding die directly. Compression molding was conducted by 30ton hydraulic presses machine (Pinette Emidecau Industries) under the condition of 260 °C with a molding pressure of 5 MPa. This method has time-saving and low-cost production cycle due to less preparation process and seldom waste. Nevertheless, the Bulking molding- CTT (BM-CTT) plate molded by this method always highly individual dependent, and also, tapes are easy to become wrinkle, winding and out of plane after molding, which makes the mechanical property decreased. [11-12]

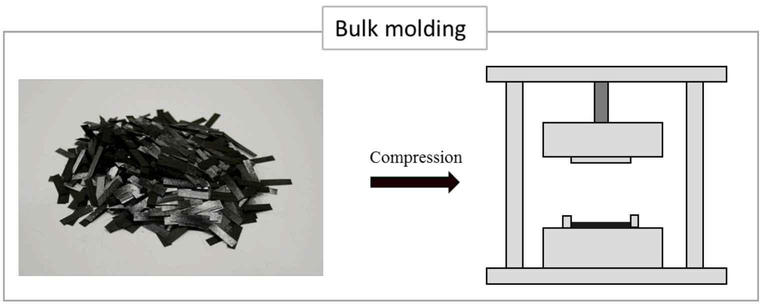


Figure 1. Fabrication of bulk molding-CTT using direct pouring.

2.2 SM-CTT fabrication

Instead of putting the tapes directly into the molding die, tapes were put into water tank to make in-plane isotropic sheets first as show in Fig. 2. By stirring the water, the tapes were randomly distributed in the water, then the water was pumped out suddenly, the wire net on the bottom of the tank will hold all the tapes to form wet CTT sheet. After that, dispersed tapes were dried and heated to attach the neighbor tapes to each other in order to make a portable sheet, then the sheets were stacked in several layers to fabricate sheet molding-CTT(SM-CTT) plate by compression molding under same molding condition as mentioned in bulk molding section.

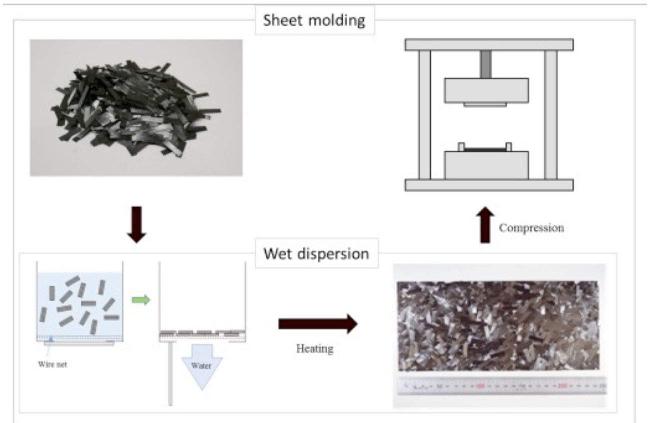


Figure 2. Fabrication of sheet molding-CTT using wet dispersion.

3. Test configuration

The configuration of CTT specimen is shown in Fig. 3(a), following the ASTM D5961/D5961M-13 standard [13], the information of the specimen are shown in Tab. 1. The specimens were tested in Shimadzu testing machine of 250 kN load capacity. A double-lap fixture shown in Fig. 3(b) was used to perform the tests.

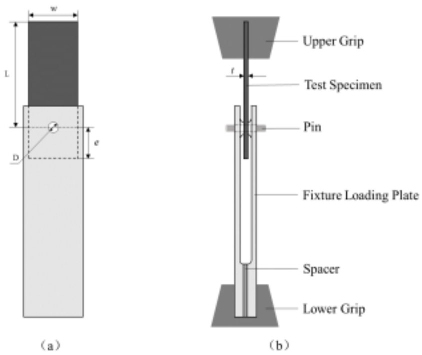


Figure 3. Specimen configuration (a) and experimental setup for double-lap, single pin joint (b).

Table 1. Specimen information

Specimen Type	L [mm]	D [mm]	*e* [mm]	*w* [mm]	*t* [mm]	Tape thickness [μm]	Number of specimen
BM-THIN	100	6.07	30	30	3.25	44	6
SM-THIN	100	6.06	30	30	3.16	44	6
SM-MED	100	6.09	30	30	3.34	88	6
SM-THICK	100	6.06	30	30	3.43	132	6

Load is applied slowly with a speed of 2 mm/min for each type of specimen, during the loading, the specimen is allowed to deform until it reaches ultimate failure load, afterwards, bearing strength is calculated with Eq. 1 [13] as following,

$$F^{bru} = P^{\max} / (k \times D \times t) \tag{1}$$

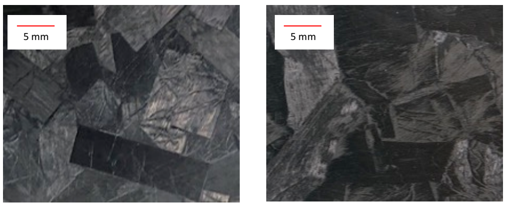
where F^{bru} is ultimate bearing strength, P^{max} is maximum force prior to failure, k equals to 1 for single-fastener test, D is the diameter of the hole and t is the thickness of specimen.

To understand the bearing failure process until to the peak load, 3 additional specimens of each type were unloaded after loading to setting levels for fractography, specimens were cut along the centerline, afterwards observed by KEYENCE VHX-1000 digital microscope in detail. Three different loading levels were defined as 50%, 75% and 100% of the maximum force prior to failure.

4. Results and discussion

4.1 Effect of molding method

In this section, bulking molding and sheet molding method are compared with each other to investigate the difference of bearing strength and failure process with different molding method. The appearance image of SM-CTT and BM-CTT are shown in Fig. 4, tapes in SM-CTT are could hold their original shape, while the tapes in BM-CTT are distorted. As shown in Fig. 5, bearing strength are 496 MPa and 432 MPa respectively for SM- and BM-CTT. The bearing strength decrease when the molding method changed to bulk molding from sheet molding. Besides, the *CoV* of bearing strength is 4.72% and 3.75% for SM- and BM-CTT, the *CoV* of bearing strength by direct molding is smaller than the results of water dispersion molding, which is counter-intuitive.



(a) SM-THIN (b) BM-THIN

Figure 4. The appearance of bulk molding- and sheet molding-CTT.

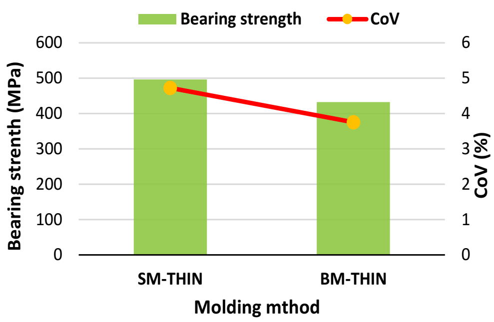


Figure 5. Bearing strength and *CoV* of bulking molding- and sheet molding-CTT.

The typical results obtained for SM-THIN CTT are shown in Fig. 6. The results of three levels of failure photographs clearly show that the main damage patterns are fiber compressive failures involving fiber buckling and lamina delamination. As we could see from Fig. 6, failure could not be observed at the load level of 50% of maximum load. When the load was increased to 75% of maximum load, fiber bulking could be observed. Delamination occurred at the peak point of the load curve and accumulated bulking could be observed along loading direction. The accumulated bucking and delamination makes the surface lamina deform toward exterior. On the other hand, as shown in Fig. 7, kinking and bulking failure could be observed at when the load reach to 100% of maximum load, seldom delamination occurred, which is due to BM-CTT is not molded by stacked sheets, some of the tapes are in out of plane direction and entangled together. Comparing to layer by layer laminate structure, delamination are difficult to occur during the failure process due to unclear layer. In addition, less 0° fibers in BM-CTT results in the decrease of bearing strength.

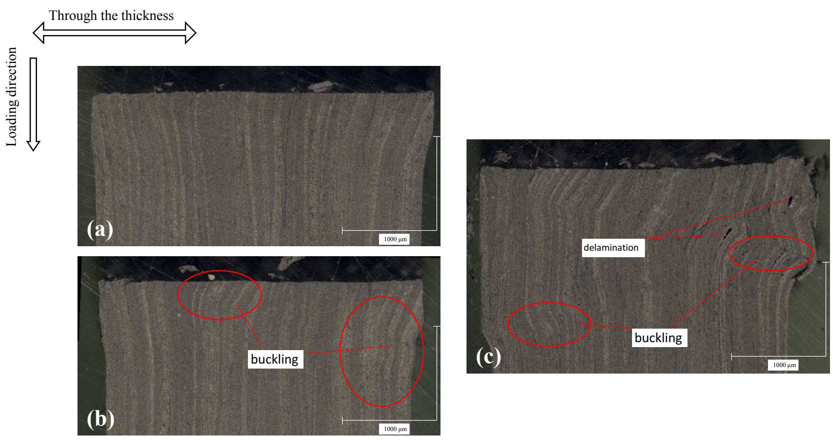


Figure 6. Damage evolution of bearing failure at (a) 50%, (b) 75% and (c) 100% of maximum load in SM-THIN CTT.

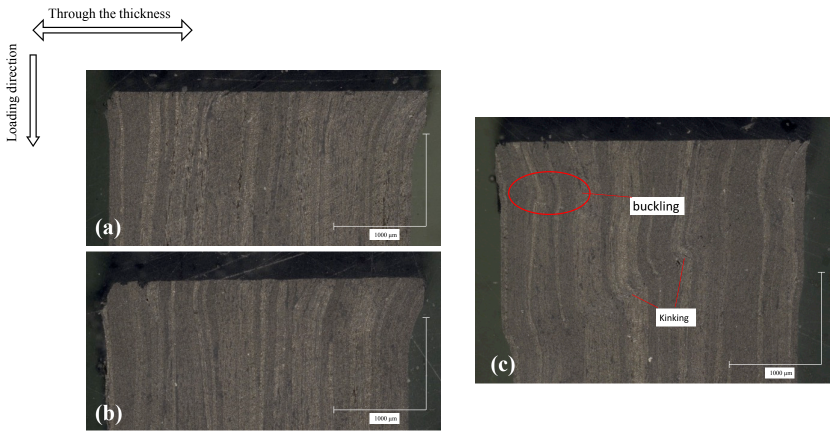
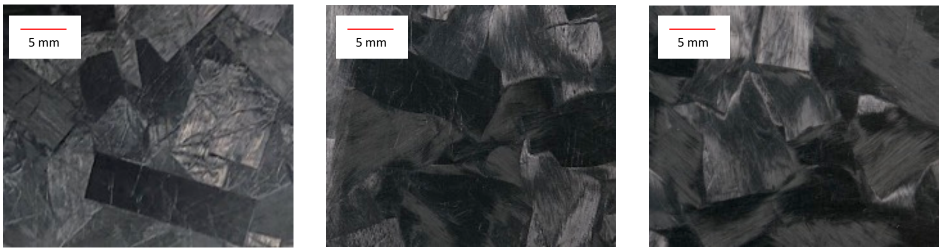


Figure 7. Damage evolution of bearing failure at (a) 50%, (b) 75% and (c) 100% of maximum load in BM-THIN CTT.

4.2 Effect of tape thickness

As shown in Fig 8, THIN tapes could keep their shapes while MED and THINK tape are deformed after compression molding. The bearing strength and coefficient of variation (*CoV*) with different tape thickness were calculated and the results are shown in Fig. 9. The bearing strength are 495 MPa, 446 MPa and 414 MPa when the tape thickness are THIN, MED and THICK respectively. The bearing strength decrease with the increasing of tape thickness. However, the *CoV* are not influenced by the tape thickness and didn't show obvious trend with the variation of tape thickness. The *CoV* ranges from 3.81% to 5.65% with different tape thickness (THIN, MED, THICK) in pin-loaded double-shear tests.



(a) SM-THIN (b) SM-MED (c) SM-THICK

Figure 8. The appearance of fabricated SM-THIN, SM-MED and SM-THICK CTT.

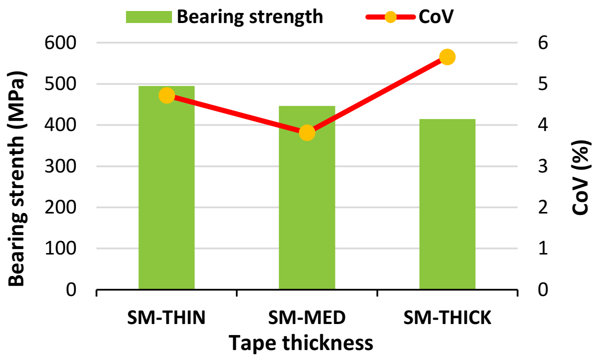


Figure 9. Bearing strength and *CoV* of SM-THIN, SM-MED and SM-THICK CTT.

Similar to the previous section, three levels of failure photographs were observed. Comparing Fig. 6, Fig 10 and Fig.11, the main damage patterns are fiber compressive failures involving fiber buckling, fiber kinking and lamina delamination in different tape thickness specimens. Failure almost could not be observed at the load level of 50% of maximum load, fiber bulking starts to occur at the load level of 75% of maximum load. As we could see from the sectional images, the failure of thinner tapes are more brittle with clear bulking. On the other hand, thicker tapes are more ductile. The failures at peak point are accumulated buckling and kinking, which lead to the fibers in loading direction are in a wavy curve shape. As we know that 0° fibers play the most important role to support the pin load during tests, but thicker tapes result in the curved fibers in molding. Thus, the curved tapes will decrease the ability to sustain the load, which results in the decrease of bearing strength when the tape thickness increase.

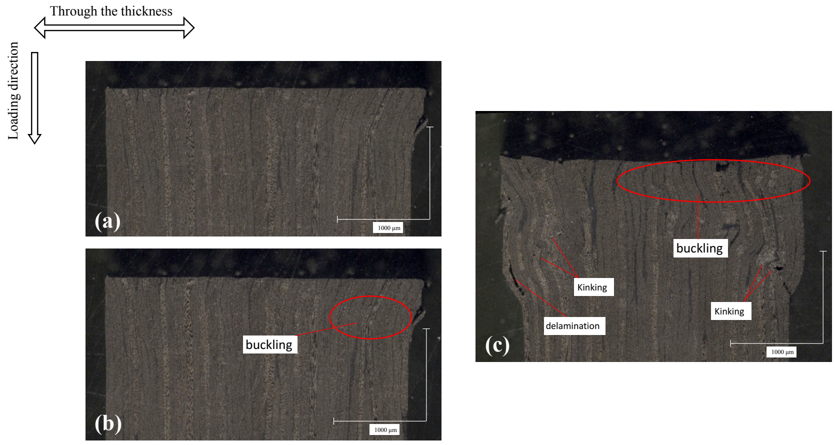


Figure 10. Damage evolution of bearing failure at (a) 50%, (b) 75% and (c) 100% of maximum load in SM-MED CTT.

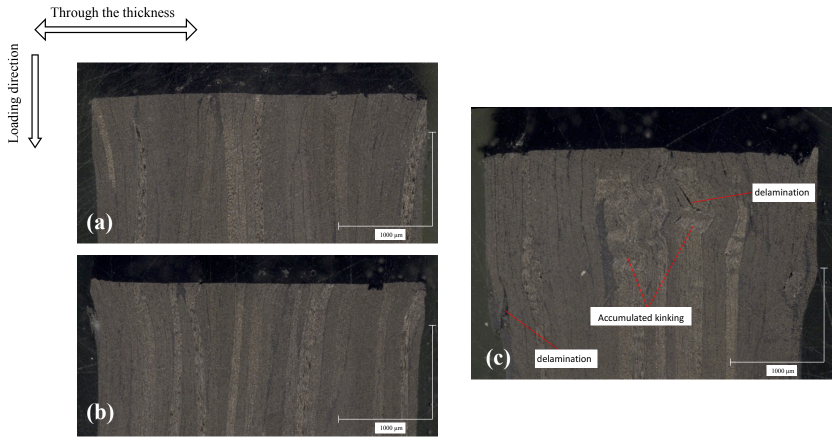


Figure 11. Damage evolution of bearing failure at (a) 50%, (b) 75% and (c) 100% of maximum load in SM-THICK CTT.

5. Concluding remarks

In the present research, research about effects of molding method and tape thickness on bearing strength and *CoV* in pin-loaded double-shear tests was conducted. In general, several conclusions are given as below:

The bearing strength are 496 MPa and 432 MPa for SM-CTT and BM-CTT, and the bearing strength decrease when the molding method changed to bulk molding from sheet molding. However, the *CoV* of bearing strength is 4.72% and 3.75% for SM-CTT and BM-CTT respectively, the *CoV* of bearing strength of BM-CTT is smaller than the results SM-CTT. The fractography indicates the main damage patterns are fiber compressive failures involving fiber buckling and lamina delamination for SM-CTT, and BM-CTT could suppress the delamination phenomenon in the failure process.

The bearing strength decrease with the increasing of tape thickness and the *CoV* didn't show obvious trend with the change of tape thickness. The *CoV* ranges from 3.81% to 5.65% with different tape thickness (THIN, MED, THICK). Specimens with thicker tapes show more ductile failure process. Delamination, accumulated bulking and kinking could be observed at 100% of maximum load.

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