ANALYSIS OF VISCOELASTIC BEHAVIOUR OF ULTRA-THIN CHOPPED CARBON FIBER TAPE REINFORCED THERMOPLASTICS WITH DIFFERENT TAPE LENGTHS

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Abstract

Carbon fiber reinforced thermosetting resins (CFRTS) are gaining widespread use in automotive industry owing to their outstanding specific modulus and strength. Carbon fiber reinforced thermoplastics (CFRTP) have excellent advantages of short molding cycle and excellent in-plant recyclability in comparison to CFRTS. Ultra-thin chopped carbon fiber tape reinforced thermoplastics (UT-CTT), as one typical type of discontinuous CFRTP with excellent formability, are now being developed specifically to achieve high volume production of light-weight automobiles in the future. Unlike thermosetting resins, thermoplastics have significant viscoelastic behaviour (e.g., temperature and strain rate dependence) due to the molecules' non-chemical reactions (cross-linking) during repeated heating and cooling process. Viscoelastic behaviour of UT-CTT with different tape lengths (i.e., 6 mm, 18 mm and 30 mm) is investigated in this study. The results indicate viscoelasticity of UT-CTT have remarkable dependence on tape length. When testing temperature varies from -30 ℃ to 120 ℃, the modulus reduction ratio of UT-CTT (6 mm), UT-CTT (18 mm) and UT-CTT (30 mm) are around 32%, 23% and 20%, respectively.

1. Introduction

Carbon fiber reinforced plastics (CFRP) composites divided into carbon fiber reinforced thermosetting resin (CFRTS) and carbon fiber reinforced thermoplastics (CFRTP) depending on polymer types of matrix, have high specific strength (strength-to-mass ratio) and specific modulus (modulus-to-mass ratio) [1,2]. CFRTS are earning high popularity in the field of aerospace due to their marvelous role in reducing fuel consumption. Compared to CFRTS, CFRTP hold several key advantages of manufacturing cycles and in-plant recyclability, which makes it more prevalent on mass-produced lightweight vehicles [3,4].

Different with continuous CFRTP, discontinuous CFRTP will be more suitable to manufacture complicated structure on account of their excellent molding performance [5,6]. Most discontinuous CFRTP, or rather short carbon fiber reinforced plastics, were characterized by the fiber length distribution (FLD) and fiber orientation distribution (FOD) [7,8]. Bacause carbon fiber mat reinforced thermoplastics (CMT) material has the upper limit of fiber content and low mechanical properties. Therefore, ultra-thin chopped carbon fiber tape reinforced thermoplastics (UT-CTT) with high mechanical properties, are being developed specifically to achieve high-volume lightweight auto production in the current Japanese project [9].

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UT-CTT laminate is transverse isotropic material, or rather in-plane quasi-isotropic material, and manufactured by compressing innumerable randomly oriented carbon fiber tapes. Unlike thermosetting resins, which remain in a permanent solid state once cured, thermoplastics could be melted into liquid state and cooled back into solid state cyclically. Consequently, UT-CTT laminate exhibit significantly strain rate and temperature dependent mechanical properties. Extensive work has been performed to analyze the strain rate dependent behavior of short fiber reinforced composites [10]. B. Alcock investigated the effect of temperature and strain rate on the mechanical properties of highly oriented polypropylene tapes [11]. C. Elanchezhian [12] explored the mechanical behaviour of carbon fibre reinforced composites at varying strain rates and temperatures. However, relatively less attention has been paid close to temperature dependence of elastic modulus of UT-CTT laminate.

In this study, the temperature dependent modulus of UT-CTT laminate was investigated. Three kinds of chopped tapes were used to analyze further the reinforcement effect of different tape lengths. Meanwhile, micromechanics are introduced to explore the underlying mechanism of the tape length dependent mechanical properties.

2. Materials and Experiment

2.1. UT-CTT Material

Detailed information of UT-CTT material investigated in this study is listed in Table 1. UT-CTT material is provided by Industrial Technology Center of Fukui Prefecture. The UT-CTT laminate is manufactured by compressing innumerable randomly oriented carbon fiber tapes (see Figure 1 (a)). The specific molding process for UT-CTT laminate (see Figure 1 (b)) is illustrated in detail. If observing UT-CTT laminate at macro-level (see Figure 2 (a)), the unidirectional prepreg tapes are distributed randomly in a plane. If observing CTT laminate at meso-level (see Figure 2 (b)), the local representative volume element (RVE) with the stacking unidirectional prepreg tapes is more like a quasi-isotropic continuous fiber reinforced laminate. In addition, the macro-deformation of stacking tapes could be observed distinctly from the exploded cross-sectional view of CTT laminate (see Figure 2 (c)). After molding, the tape occur flexural deformation in the through-thickness direction of laminate, no longer keep a flat plane.

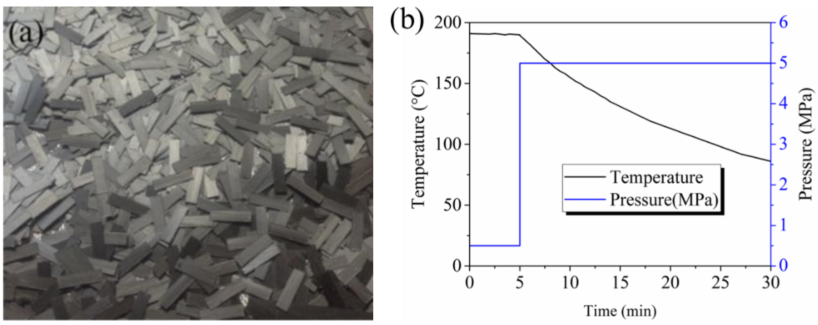

Figure 1. Manufacturing of UT-CTT laminate: (a) dispersion of tapes; (b) molding process.

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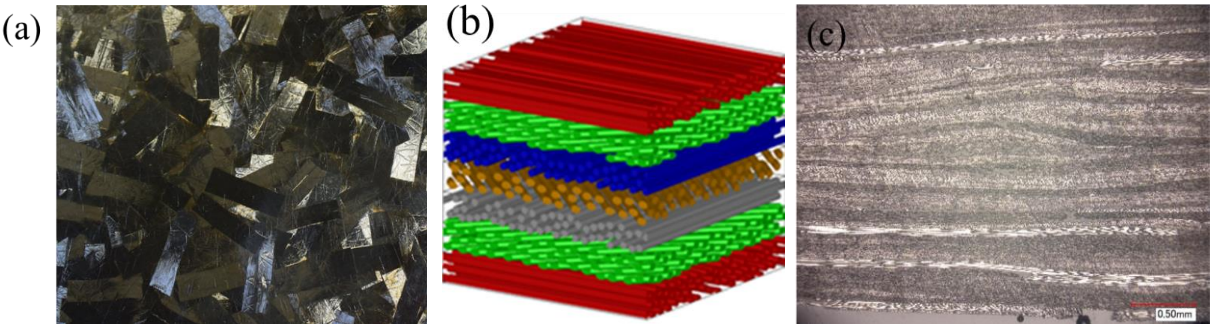

Figure 2. Observation of UT-CTT laminate from different scales: (a) surface at macro-scale; (b) schematic of representative volume element (RVE) at meso-scale; (c) cross-section at macro-scale.

Table 1. Detailed information of UT-CTT material used in this study.

Specimen Type	Matrix	Fiber content (%)	Tape			Laminate		
			Length (mm)	Width (mm)	Thickness (mm)	Length (mm)	Width (mm)	Thickness (mm)
UT-CTT -A	PA6	55	6	5	0.044	250	38	2.0
UT-CTT -B	PA6	55	18	5	0.044	250	38	2.1
UT-CTT -C	PA6	55	30	5	0.044	250	38	2.2

2.2. Experiment

Quasi-static tensile test is conducted with a loading speed of 1 mm/min. Thermostatic chamber was utilized to adjust testing temperature (-40 to 120℃) for tensile test (see Figure 3). Extensometer with measuring range of 100 mm and computer-aided thermometer are adopted to measure specimen's strain and testing temperature in real time. Elastic modulus was determined by extracting data of stress-strain curve with straight line portion (strain varying from 0.1 % to 0.2 %).

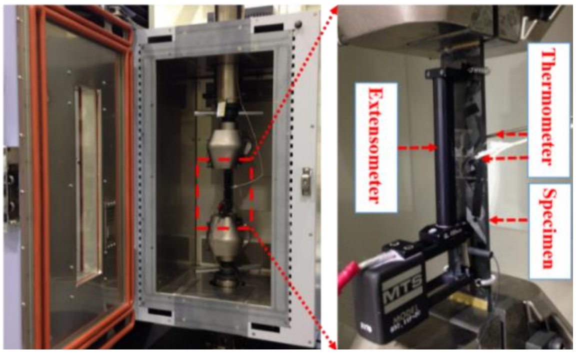

Figure 3. Apparatus of tensile test in a thermostatic chamber.

The temperature dependence of PA6 was measured by DMA instrument (Dynamic mechanical analyzer TA-RSA-G2) shown in Figure 4. The sinusoidal stress was applied under a frequency of 1 Hz, and the strain was set under 0.1 %. Testing temperature was elevated from -40 to 120℃ at a heating rate of 3 ℃/min for temperature dependence measurement.

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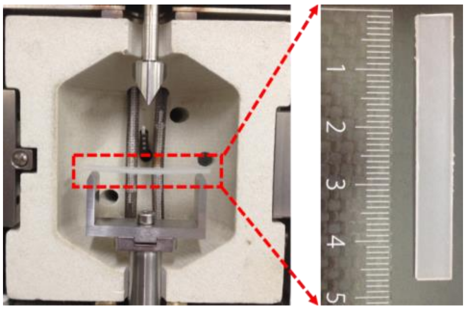

Figure 4. Apparatus and specimen for dynamic mechanical analysis (DMA) test.

3. Results and Discussion

As shown in Figure 5, dynamical properties of specific polyamide 6 (PA6) used in this study were tested by DMA. The glass transition temperature (Tg) of PA6 is around 45℃. During the transition process from glass state to rubbery state, the movability of polymer molecules increase gradually with elevating temperature. The molecules would move and slide past each other, then their mechanical properties such as elastic modulus would change markedly. Storage moduli related to the elastic modulus reduce from 3.4 GPa to 0.23 GPa. That's the main reason why the modulus of UT-CTT (see Figure 6) reduces remarkably when the testing temperature is around Tg.

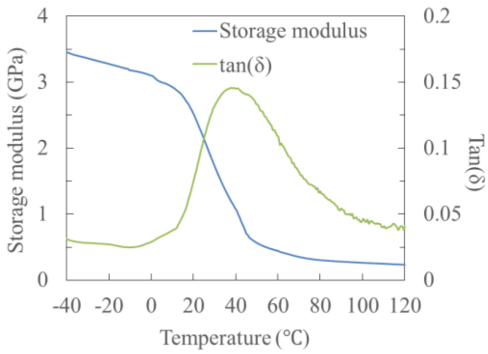

Figure 5. DMA test of specific PA6.

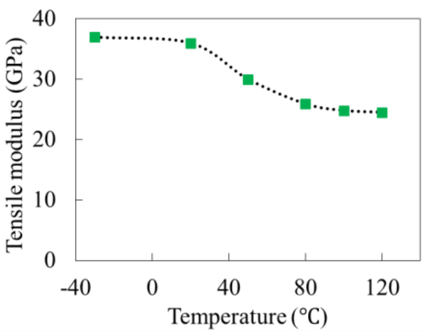

Figure 6. Temperature dependent tensile modulus of UT-CTT (6 mm).

In order to compare the temperature dependence of the three different kinds of UT-CTT materials, corresponding modulus of PA6 and UT-CTT are normalized as exhibited in Figure 7. The critical length of tape will increase with elevating temperature due to the reduction of shear strength between

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fiber and matrix. Therefore, the UT-CTT material with shorter tapes has higher decrease ratio than that of UT-CTT martial with longer tapes. The normalized tensile modulus of UT-CTT and PA6 resin can be fitted well with different reduction ratio. The specific temperature dependence of different UT-CTT materials are quantified in the Table 2.

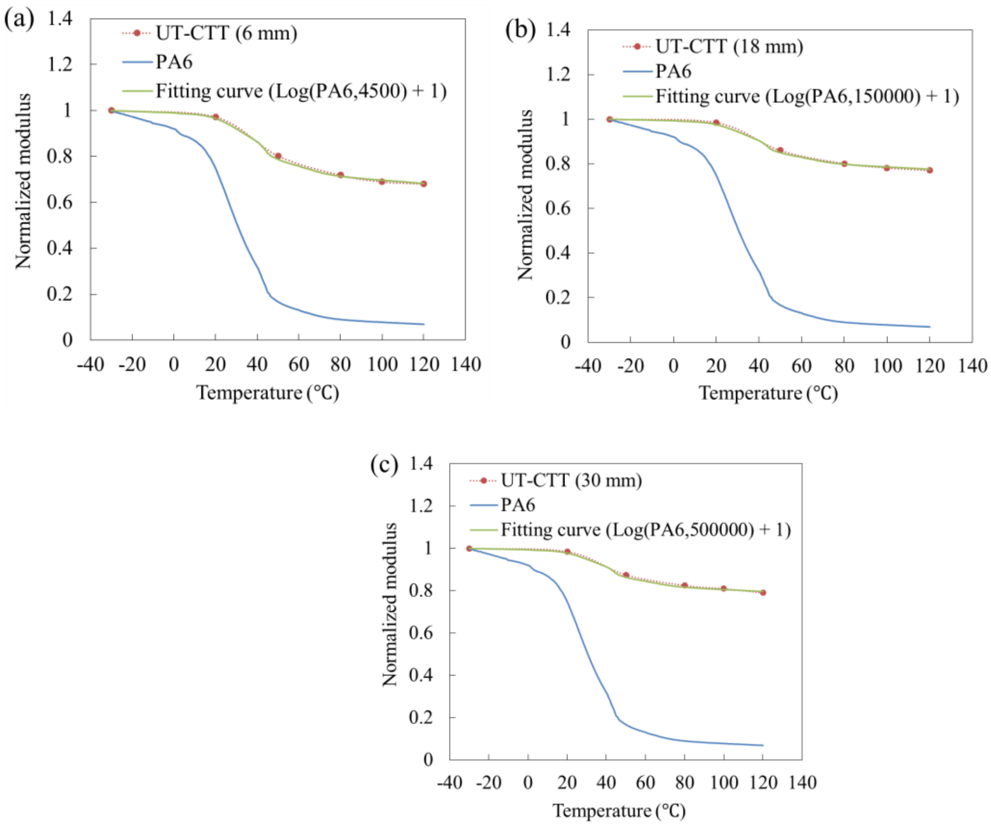

Figure 7. Comparison of temperature dependence of UT-CTT materials.

Table 2. The summary of temperature dependence of UT-CTT materials.

Tape length (mm)	6.0	18.0	30.0
Base	4500	150000	500000
1/Log(Base,10)	0.274	0.193	0.175
Normalized value	1.56	1.10	1.00

As shown in Figure 8, one innovative method is proposed to describe the aspect ratio of tape, and the corresponding aspect ratio of fiber is derived by the volume equivalence principle. The process of derivation is listed in the Equations 1-5 below. The curve-fitting parameter (k= 0.38) is obtained from the Figure 9 (a). Therefore, the aspect ratio correspondence between fiber and tape is calculated (see Table 3). The validation is verified by the Figures 9 (b) and (c). By means of micromechanics (Mori-Tanaka method), the effective modulus of CTT laminate is obtained by calculating modulus of randomly 2D discontinuous carbon fiber reinforced thermoplastics (DCFRTP) (see Figure 9).

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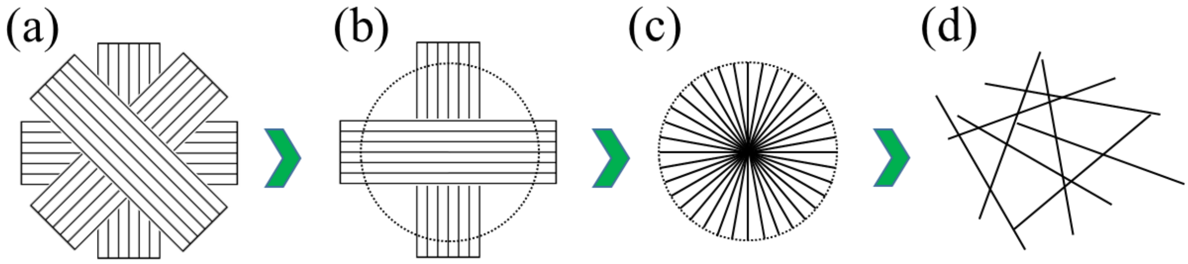

Figure 8. Schematic of equivalent aspect ratio for tape: (a) quasi-isotropic element; (b) two binding tapes; (c) equivalent intermedia; (d) randomly orientation fiber.

$$V_t = L_t * W_t * t \tag{1}$$

$$V_I = \pi L^2 * 2 * t \tag{2}$$

According to the volume equivalence principle

$$V_t = V_I \tag{3}$$

$$\left(\frac{L}{d}\right)_{int.} = \frac{1}{\sqrt{2\pi}}\left(\frac{\sqrt{L_t * W_t}}{d}\right) \tag{4}$$

$$\left(\frac{L}{d}\right)_{int.} = \frac{1}{k}\left(\frac{L}{d}\right) \tag{5}$$

$$\left(\frac{L}{d}\right) = \frac{k}{\sqrt{2\pi}}\left(\frac{\sqrt{L_t * W_t}}{d}\right) \tag{6}$$

where,

L_t = length of the tape
W_t = width of the tape
t = thickness of the tape or intermedia
L = length of the fiber
V_I = volume of the intermedia
V_t= volume of the tape
k= curve-fitting parameter
d= diameter of the fiber

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Table 3. The aspect ratio correspondence between fiber and tape.

Tape length (mm)	6.0	18.0	30.0
Tape thickness (mm)	0.044	0.044	0.044
Tape width (mm)	5.0	5.0	5.0
Diameter of fiber (mm)	0.007	0.007	0.007
Equivalent aspect ratio of fiber	120	200	260

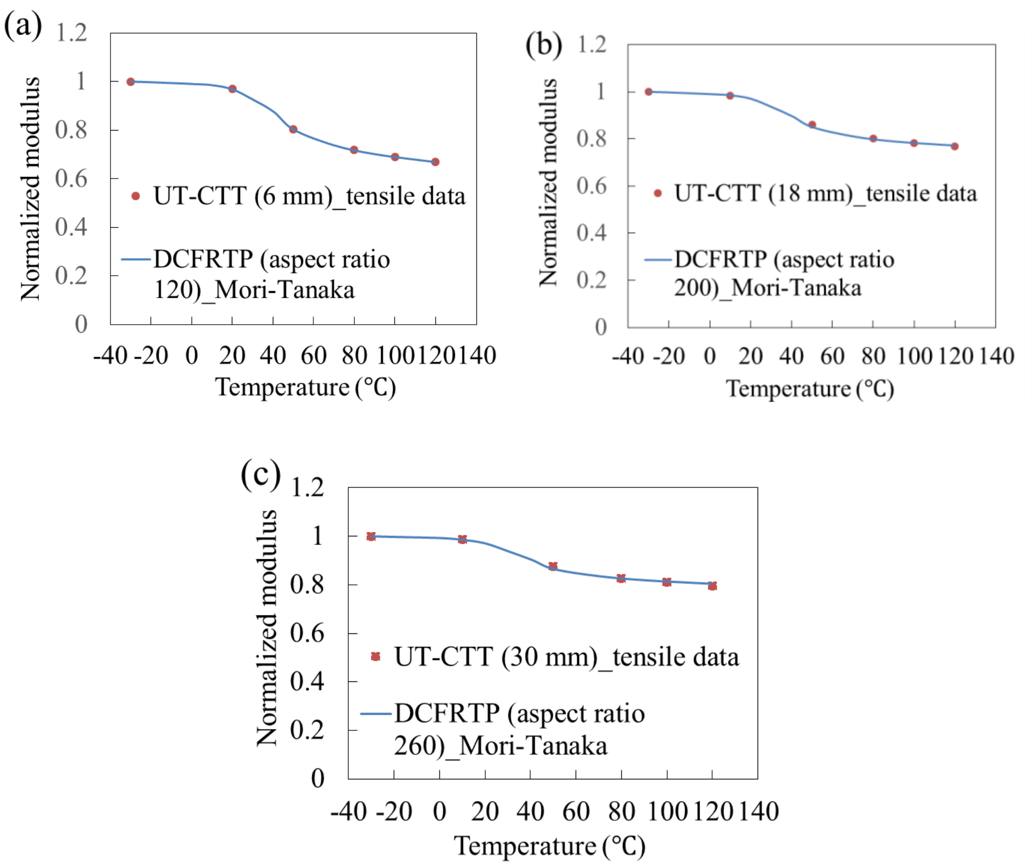

Figure 9. Verification of equivalent aspect ratio: (a) UT-CTT (6 mm); (b) UT-CTT (18 mm); (c) UT-CTT (30 mm).

4. Conclusions

The modulus of UT-CTT reduces remarkably when the testing temperature is around Tg. The UT-CTT laminate with shorter tapes has higher decrease ratio than that of UT-CTT laminate with longer tapes. The normalized tensile modulus of UT-CTT and PA6 resin can be fitted well with different reduction ratio. Therefore, one innovative method is proposed to describe the equivalent aspect ratio of tape by using the corresponding aspect ratio of discontinuous fiber. By means of micromechanics (Mori-Tanaka method), the effective modulus of CTT laminate is obtained by calculating modulus of randomly 2D discontinuous carbon fiber reinforced thermoplastics.

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References

[1] P. Morgan. *Carbon fibers and their composites.* CRC Press Taylor & Francis Group, 2005.

[2] M. Biron. *Thermoplastics and Thermoplastic Composites.* William Andrew, 2007.

[3] R.F. Gibson. *Principles of Composite Material Mechanics.* CRC Press, 2015.

[4] J. Takahashi and T. Ishikawa. Next challenge in CFRTP for mass production automotive application. *Proceedings of the SAMPE Europe's 35th International Conference SEICO-14, Paris, France,* March 9-11 2014.

[5] I. Taketa, T. Okabe, H. Matsutani and A. Kitano. Flowability of unidirectionally arrayed chopped strands in compression molding. *Composites Part B: Engineering,* 42: 1764–1769, 2011.

[6] D. LeBlanc, B. Landry, A. Levy, P. Hubert, S. Roy and A. Yousefpour. Study of Processing Conditions on the Forming of Ribbed Features Using Randomly Oriented Strands Thermoplastic Composites. *Journal of the American Helicopter Society.* 60: 1–9, 2015.

[7] S. Fu. Effects of fiber length and fiber orientation distributions on the tensile strength of short-fiber-reinforced polymers. *Composites Science and Technology,* 56:1179–1190, 1996.

[8] J. Xue, W. Wang, J. Hu, J. Zhang, S. Wu. Influence of fiber length on the tensile behavior of fiber metal laminates with discontinuous reinforcement. *Journal of Reinforced Plastics and Composites,* 34:1651–1661, 2015.

[9] J. Takahashi and T. Ishikawa. Recent Japanese Activity in CFRTP For Mass Production Automobile. *Proceedings of the 2nd International Conference & Exhibition on Thermoplastic Composites, Bremen, Germany,* October 27-28 2015.

[10] J.D. Ferry. *Viscoelastic Properties of Polymers.* John Wiley & Sons, 1980.

[11] B. Alcock, N.O. Cabrera, N.M. Barkoula and C.T. Reynolds. The effect of temperature and strain rate on the mechanical properties of highly oriented polypropylene tapes and all-polypropylene composites. *Composites Science and Technology,* 67: 2061–2070, 2007.

[12] C. Elanchezhian, B.V. Ramnath and J. Hemalatha. Mechanical Behaviour of Glass and Carbon Fibre Reinforced Composites at Varying Strain Rates and Temperatures, *Procedia Materials Science,* 6: 1405–1418, 2014.

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