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Tensile properties and aspect ratio simulation of transversely isotropic discontinuous carbon fiber reinforced thermoplastics

Yi Wan*, Jun Takahashi

Department of Systems Innovation, The University of Tokyo, Room 414, Eng. Bldg. 3, Hongo 7-3-1, Bunkyo-ku, Tokyo, Japan

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ABSTRACT

Discontinuous carbon fiber reinforced thermoplastics (DCFRTPs) are regarded as potential substitutes for metallic materials used in the mass production of automotive parts. For predicting the mechanical properties of these composite materials, the analytical homogenization method as Mori-Tanaka model is one of the most efficient and accurate approaches, but the application of this model is limited because both the aspect ratio of the fibers and their volume fraction in the composite have to be low. In the present study, the tensile properties of two transversely isotropic DCFRTPs, carbon fiber mat reinforced thermoplastics (CMT), and ultra-thin chopped carbon fiber tape reinforced thermoplastics (UT-CTT), were investigated experimentally and analytically. The components and structural properties were evaluated in detail. A comparison between the Mori-Tanaka simulations and the experimental results showed a difference in the trends of the present results from those reported previously. In UT-CTT with a high volume fraction and high aspect ratio, the experimental results and the Mori-Tanaka model simulations were in good agreement. Conversely, a mismatch between the experimental and simulation results was observed in CMT with a wide aspect ratio distribution and low volume fraction. This difference in the predictive power of the Mori-Tanaka model for the two materials could be attributed to the difference in the microstructural regularity between CMT and UT-CTT. The effects of tape length on the tensile properties of UT-CTT were also studied.

1. Introduction

Carbon fiber reinforced thermoplastics (CFRTP) exhibit outstanding suitability for lightweight applications and have been recently put to practical use in the automotive manufacturing industry [1]. Among the different types of CFRTPs, so-called discontinuous carbon fiber reinforced thermoplastics (DCFRTPs) are the preferred composites for applications involving mass-production vehicles because of the achievability of high cycles and complex-shaped molding. However, issues related to the safety and predictability of performance are serious obstacles to the reliable application of DCFRTPs in manufacturing. Because DCFRTPs exhibit meso-scale structural irregularities and molding process sensitivity, it is difficult to precisely characterize their mechanical properties.

There have been efforts to characterize the mechanical properties of DCFRTP accurately and effectively using a number of different approaches. Using the modified rule of mixtures, Fu et al. calculated the tensile modulus and strength of DCFRTP for different fiber aspect ratios and orientations [2,3]. Piggott et al. verified the accuracy of the shear-lag model for the simulation of the mechanical performance of short fiber reinforced plastics [4]. An accurate multi-scale finite element (FE) model had been developed by Hashimoto et al. for simulating the tensile strength of discontinuous carbon fiber/polypropylene composites with fiber orientation distributions [5]. Further, a comparison between the analytical and numerical homogenization methods was conducted by using a complex multi-scale FE model, as well as a one-step Mori-Tanaka model, two-step Self-Consistent/Voigt model, and Lielens (Li)/Voigt model [6]. Recently, Pimenta and co-workers simulated the tensile properties of discontinuous composites pre-impregnated with resin—so-called prepreg composites—using a shear-lag-based equivalent laminate method [7]. Thus far, the combination of the Mori-Tanaka type model [8] with Eshelby's equivalent inclusion method [9] has been one of the most efficient and accurate approaches for the prediction of composite stiffness [9–14]. However, previous researches indicated that the reliability of this approach is limited to conditions with a low volume fraction and restricted

* Corresponding author.
E-mail address: wan-yi@cfrtp.t.u-tokyo.ac.jp (Y. Wan).

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orientation distributions of the inclusions [6,15–17]. The reason for these limitations remains unclear.

In the present research, two different transversely isotropic DCFRTPs were prepared in order to analyze the limitation of the Mori-Tanaka model and the effect of the inclusion aspect ratio on tensile properties. The components and structural properties were studied in detail. The results were input into the Mori-Tanaka model for comparison with the experimental results. Finally, the effect of the inclusion aspect ratio on the tensile properties was studied.

2. Materials and methods

2.1. Materials

Two transversely isotropic DCFRTPs with different molding processes and structural features are introduced in this study. Both of these materials are considered potential substrates for mass-production vehicles.

One material is carbon fiber mat reinforced thermoplastic (CMT) (see Fig. 1 (a)), which is composed of polypropylene (PP) and randomly oriented carbon fiber monofilaments (CF papers, T700SC, TORAY Industries, Inc.). CMT are manufactured by heating-and-cooling compression molding, and are regarded as typical mat-structured composites that show very good in-plane isotropy. However, the carbon fiber volume fraction (V_f) of CMT are restricted to be below 35% because the paper-like structure needs an enormous molding pressure in order to reach the required impregnation condition at high V_f [18]. This material is therefore not appropriate for applications in parts of vehicles that are under high stress. In this paper, we study two CMT, designated as CMT 1 and CMT 2. These two CMT differ in their values of V_f. Both use 6 mm-long carbon fibers before molding; however, because the compression process causes fiber breakage, the fiber length distribution is measured together with the V_f after molding.

The other material is an ultra-thin chopped carbon fiber tape reinforced thermoplastic (UT-CTT), which is composed of randomly oriented ultra-thin unidirectional prepreg tapes (UT tapes) (see Fig. 1(b)). The tape is manufactured with carbon fiber (TR 50S, Mitsubishi Rayon Co., LTD.) and Polyamide-6 (PA6, DIAMIRON™ C, Mitsubishi Plastics, Inc.), and it is relatively thin (40 μm–50 μm, see Fig. 1 (c)) compared with conventional tape (about 150 μm or more, see Fig. 1 (d)), which is why this material is referred to as ‘ultra-thin’. Composites molded by the ultra-thin tape show superior suppression of microcracking, reduced delamination, and reduced splitting damage for static, fatigue, and impact loadings, compared with those molded by the conventional tape [19]. UT tapes are usually cut into the required shape. In this study, the tape width is fixed to 5 mm, and 12 mm, 18 mm, 24 mm, 30 mm tape lengths are adopted for the experiments and simulations. The UT-CTT were named by the tape length, as the 12 mm length one is called UT-CTT 12. To manufacture the UT-CTT, the discontinuous tapes are dispersed by a wet-type paper making process. The tapes are randomly distributed in water, and the tape sheets are stacked to make the UT-CTT plate by heating-and-cooling compression molding. The molding condition of UT-CTT is shown in Fig. 2. This material shows good transverse isotropy, and because the fibers were impregnated before molding, the UT-CTT can be molded under relatively low pressure, which is an important advantage for mass-production applications. Additionally, since V_f can reach over 50%, this material is presumed to be suitable for critical

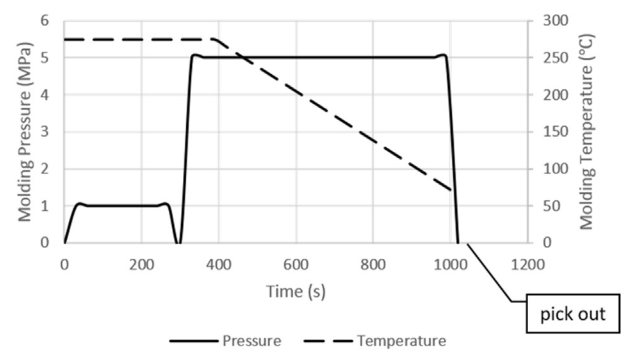

Fig. 2. Molding condition of UT-CTT materials.

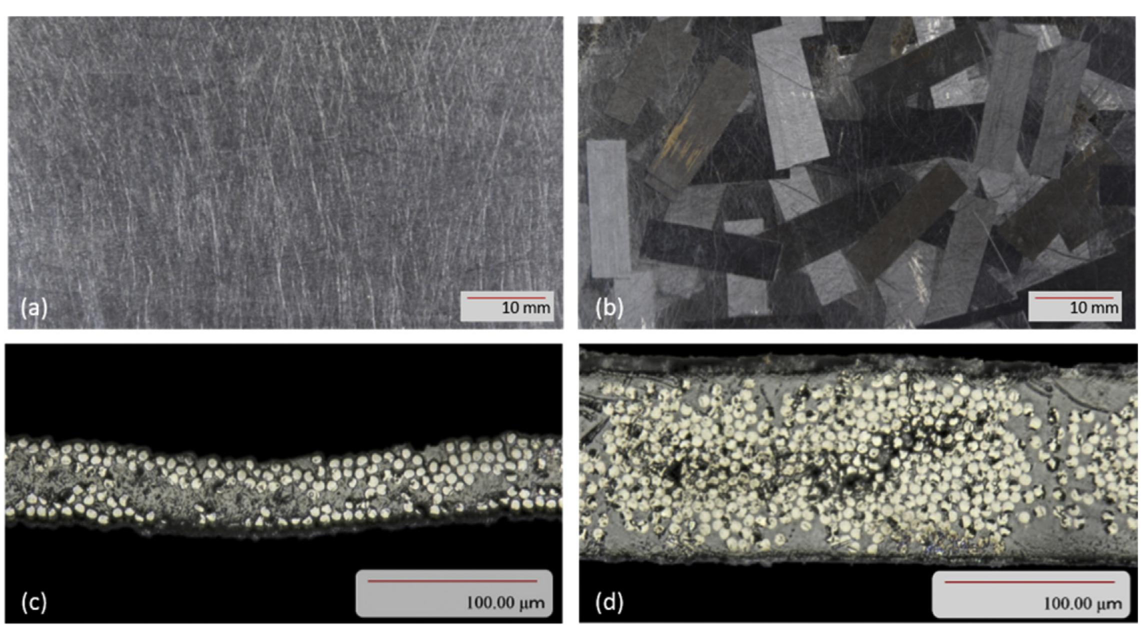

Fig. 1. CMT (carbon fiber mats reinforced thermoplastics) (a), UT-CTT (ultra-thin chopped carbon fiber tape reinforced thermoplastics) (b), cross section of UT tape (c) and conventional tape (d).