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Tensile and compressive properties of chopped carbon fiber tapes reinforced thermoplastics with different fiber lengths and molding pressures

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Tensile and compressive behaviors of chopped carbon fiber tapes reinforced thermoplastics have been investigated by varying compression molding conditions (to study the effect of the molding pressure) and the tape length (to analyze the fiber length effect on the mechanical properties of produced composites). Fractographic analysis of prepared specimens conducted after the experiments indicated that the obtained modulus values were almost independent of both the tape length and molding pressure, while the measured strengths exhibited high molding pressure sensitivity. Interlaminar shear strength was considered to be the dominate factor in damage determination during tensile testing, while interlaminar tensile strength played the main role in compression fracture. Increase in the tape length led to a slight increase in the strength magnitude, but also a significant increase in the standard deviation of strength due to the decrease in structural regularity.

1. Introduction

Carbon fiber reinforced polymers (CFRP) have been widely used in the engineering field where lightweight materials with good mechanical properties are required. Thermoplastics have attracted researchers' and engineers' attention as matrix materials due to the absence of the curing stage, less hazardous chemical compositions, and better recyclability as compared to conventional thermosetting resins [1]. In addition, randomly oriented discontinuous fiber systems have been widely utilized for CFRP compression molding. In contrast to continuous fiber systems, short-fiber systems show the superiority in complex shape design and flowability. The application of randomly oriented carbon fiber reinforced thermoplastics (RCFRTP) in the automotive industry can possibly reduce fossil fuel consumption and mitigate environmental impacts. However, using RCFRTP in motor vehicles requires basic knowledge of the utilized materials and manufacturing processes. A variety of RCFRTP, chopped carbon fiber tape-reinforced thermoplastics (CTT), have been previously developed in our research group [2] and can be potentially used as materials for manufacturing critical components of automotive parts.

Various researches of the compression molding process and its influence on the material structure and mechanical properties have been extensively conducted in the past decades. Kim and co-workers investigated compressibility during molding and deconsolidation behavior of mat-reinforced RCFRTP [3]. A proposed analytical model and experimental studies of the impregnation during compression molding of woven CFRTP were reported by Phillips et al. [4], while the effects of the stamping conditions on the mechanical properties of the woven CFRTP have been examined by Vieille et al. [5], and the related optimal molding parameters were determined for CFRTP laminates using a Taguchi method [6]. The effects of the compression molding conditions on the RCFRTP shear properties were studied by Li and co-workers [7], while the void [8] and defect [9] generation processes in RCFRTP during compression molding and their influence on the material mechanical performance were investigated by professor Pascal from McGill University and his research group.

Tensile and compressive properties are the most basic mechanical parameters of materials utilized in automotive structural components (the related studies have been extensively conducted during the past few decades [10–23]). Fu et al. calculated the tensile modulus and strength of RCFRTP using the modified rule of mixtures that took into account fiber length and orientation distributions [10–12]; they also utilized a laminate analogy approach to evaluate the tensile modulus of RCFRTP [13]. Hashimoto et al.

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predicted the tensile strength parameters more accurately by using a multi-scale finite element method [14], while Argon et al. reported that the initial fiber misalignment along the compressive loading direction would lead to the decrease in compressive strength, which depended on the fiber yield stress [15]. The previously reported studies on the CFRP compressive properties were mainly focused on the kinking phenomenon, while the CFPR laminates are still considered the most examined and well-prepared materials [16,17]. Budiansky and Fleck investigated the shear deformation caused by local fiber buckling (corresponding to the general plastic behavior) when kink bands are generated during compressive fracture; they significantly contributed to the strength theory describing the behavior of CFRP subjected to compressive kinking and established versatile constitutive equations that could be used for quantitative analysis [18–21]. The orientation dependences of the tensile and compressive properties of short glass fiber-reinforced polypropylene were investigated by Hartl et al. [23]. However, still only a few research studies focused on both the tensile and compressive behaviors of RSFRTP. Also the RCFRTP impregnation qualities generally considered as a key factor in the compression molding processes. Nevertheless, the relationship between the impregnation quality of RSFRTP and its tensile/compressive properties still need further investigations.

The objective of this work was to study tensile and compressive properties of CTT composites manufactured from ultra-thin semi-prepreg tapes. Material molding conditions were changed by varying the compression pressure, while fiber lengths were modified by using the ultrathin semi-prepreg tapes with different lengths, and the effects of these parameters on the tensile and compressive properties of the obtained composites were examined. In addition, the effects of the molding conditions on the polymer structural properties were investigated through the microstructure observation and the material fracture analysis.

2. Materials and methods

Ultra-thin chopped carbon fiber tape reinforced thermoplastics (UT-CTT), which contained in-plane randomly oriented ultra-thin unidirectional semi-prepreg tapes manufactured from carbon fiber tow (TR 50S, Mitsubishi Rayon Co., Ltd.) and Polyamid-6 film (PA6, DIAMIRON™ C, Mitsubishi Plastics, Inc.), were utilized in this study. The average tape thickness (between 40 μm and 50 μm) was much smaller than that of a conventional tape (approximately 150 μm); therefore, it was referred to as a "UT (ultra-thin) tape" (Fig. 1). UT tape-containing unnotched specimens exhibited superior fracture resistance under static, fatigue, and impact loading (as compared to that for the conventional materials) [24]. In addition, the UT tapes were characterized by better structural integrity after compression molding due to the more uniform molding pressure distribution [25–27] (in this work, unidirectional semi-prepreg UT tapes were provided by the Industrial Technology Center of the Fukui Prefecture). In order to study the effect of the fiber length, the semi-prepreg UT tapes were cut into pieces with different lengths (6 mm, 12 mm, 18 mm, and 24 mm).

UT-CTT sheets with random orientations were prepared by using a wet-type paper manufacturing process described in Fig. 2. First, the obtained discontinuous tapes were collected and placed inside a water-filled container with a filter and an aperture on the bottom side. After the tapes were randomly dispersed, the aperture was opened to remove the water from the container. Then, the UT-CTT sheets were temporarily fixed by heating and cooling hand presses under two procedures: firstly, under 90 °C and 0.1 MPa pressure for 1 min to remove the water; secondly, under 230 °C and 0.5 MPa pressure for 1 min to temporarily fix the sheet. Because of the high water absorption of PA6, the UT-CTT sheets were put into a vacuum dryer before molding. The temperature of the dryer was set to 90 °C and the sheets were vacuuming for 12 h before the sheets were stacked and molded. Finally, heat-and-cool compression molding was applied to mold UT-CTT specimens from the stacked UT-CTT sheets.

Because impregnation qualities significantly affect material mechanical properties, while impregnating thermoplastics is more difficult than impregnating thermosetting polymers due to their high viscosity after melting, two different molding processes were utilized for UT-CTT manufacturing: high-pressure molding (M_h) and low-pressure molding (M_l). The detailed molding conditions are described in Fig. 3; as a result, four UT-CTT composites with different tape lengths were molded at both the M_h and M_l conditions. The molded plates were in 3 mm thickness, and the plate size was 250 mm in length and 125 mm in width. Before the specimens were cutout, the molding edge effects were eliminated by cutting off 10 mm from each edge.

Tensile and compressive tests were conducted by using a universal testing machine (AUTOGRAPH AG-X plus, Shimadzu Co., Ltd.). To prevent early-stage damage at the end portions of tested specimens, a compression jig described in Fig. 4 was utilized. Five specimens were prepared for each UT-CTT type using different tape lengths and molding conditions. The tensile specimens were cut to 35 mm $*$ 150 mm size while the compressive specimens were cut to 16 mm $*$ 70 mm due to the limitation of the compressive jig. Tensile and compressive modulus values were measured by extensometer and strain gauges, respectively. The experiment conditions were partially follow the JIS K 7073 (1.0 mm/min tensile test speed) and JIS K 7076 (0.5 mm/min compressive test speed). The 50 mm extensometer was utilized for tensile specimens and both sides of the compressive specimen surfaces were installed with 5 mm strain gauge to measure the average strain value. After the specimens were broken, the fractographic analysis was conducted using a microscope (VHX-1000, Keyence Co., Ltd.), a 3D X-ray scanner (TDM1000-II, Yamato Scientific Co., Ltd.), and an image processing software (TRI/3D-BON, RATOC System Engineering Co., Ltd.).

Fiber volume fractions (V_f) and Void volume fractions (V_v) of the UT-CTT with different tape lengths manufactured under different molding conditions were evaluated through ash testing, during which the sample volume V and sample weight M was measured by a densitometer, while the CF weight, M_{CF}, was determined by burning off the polymer resin under 500 °C for three hours in a

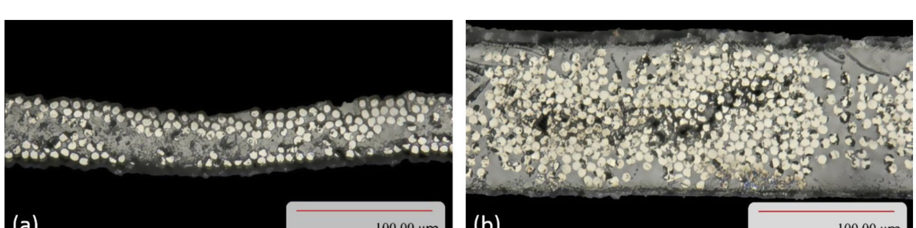

Fig. 1. Cross-sections of the UT (a) and conventional (b) tapes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)