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Interply hybrid composites with carbon fiber reinforced polypropylene and self-reinforced polypropylene

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ABSTRACT

The focus of the present study is on hybrid composites with interplied carbon fiber reinforced polypropylene (CFRPP) between self-reinforced polypropylene (SRPP) layers. SRPP is produced by hot compaction of a woven fabric of highly oriented polypropylene and has an intrinsic behavior of shrinkage under high temperatures. The aim of this research is to enhance the tensile properties of the CFRPP/SRPP hybrid composites by using the SRPP shrinkage to introduce a compressive pre-strain in CFRPP. The results from tensile testing show that the failure strain of the hybrid composites is improved in comparison with CFRPP. The modulus and strength are noted to be lower than the ones expected from the rule of mixture. This may be attributed to the introduction of local misalignment (waviness) of carbon fibers caused by the SRPP shrinkage during consolidation.

1. Introduction

Carbon fiber reinforced polymer composites have become widely used in many engineering fields where high mechanical properties and light weight are required. In recent years, thermoplastic polymers have attracted a lot attention as matrix material due to the benefit of omitting the curing process, to a less hazardous chemical composition and to its better recyclability. Among various polymer options, polypropylene (PP) is extraordinarily low density and cheap, thus preferably used in the automobile industry. Since carbon fibers are one of the strongest materials, carbon fiber reinforced PP (CFRPP) has a potential to achieve high specific modulus and strength.

In addition, self-reinforced PP (SRPP) is known to achieve much higher mechanical properties than conventional PP. Many researchers have worked on characterizing the processing and mechanical behavior of SRPP [1–8]. Propex Fabric commercialized SRPP sheet as Curv® [1], which is produced by hot compaction of a woven fabric made of highly oriented PP tapes. During hot compaction, the surface of the tapes is selectively melted and integrated together. The SRPP achieves excellent modulus, strength and impact resistance. Among other characteristics, SRPP has a tendency to shrink under high temperature [2,8], which is triggered by the entropy increase in a polymer packing state. If SRPP is heated under constrained conditions to prevent shrinkage, a recovery stress is generated. In this research, we aim to utilize the recovery stress by laminating SRPP with CFRPP in a hybrid composite.

The first hybrid composite reported in the literature was a composite combining together carbon and glass fiber. It exhibited increased failure strain in comparison with all carbon fiber composite [9]. The source of the hybrid effect was presumed to be a compressive residual stress in carbon fiber developed by the difference of thermal expansion coefficients of carbon and glass fiber [10]. The hybrid composite proposed in the present research is made of CFRPP and SRPP. The active shrinkage of SRPP should also apply a compressive pre-strain into the CFRPP, enhancing its tensile properties compared to CFRPP without SRPP.

This paper is organized as follows. Section 2 describes the preparation of CFRPP, which is made by PP film stacking impregnation of a woven carbon fabric. The influence of processing conditions on impregnation and tensile properties is investigated, and the conditions are optimized with respect to maximizing the tensile sustainable stress, while keeping the fiber volume portion constant. Section 3 is devoted to characterization of SRPP. The influence of processing conditions on tensile properties and recovery stress of SRPP is investigated. Section 4 presents the hybrid effect in the interply hybrid composite with CFRPP and SRPP. The hybrid composites are tested under tensile loading and their mechanical properties are compared with the ones expected from the rule of mixture.

2. Preparation of carbon fiber reinforced polypropylene

A prepreg made of continuous carbon fibers and PP was commercially unavailable as this research started. Thus, CFRPP was prepared by stacking a woven carbon fabric and PP film, and hot pressing them for impregnation.

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The fabric was twill 2/2 of HexForce® G0986 D1200 (Hexcel), woven with carbon fibers Tenax® HTA 5131 6 K (Toho Tenax). The tensile properties of this fiber were a Young's modulus of 238 GPa, a strength of 3950 MPa and a failure strain of 1.7% [11]. The PP film (Amcor), made of maleic anhydride modified PP, had a thickness of 100 μm, a melting temperature of 160 °C and a melt flow index (MFI) of 5.2 g/10 min.

The basic fabrication procedure for CFRPP was as follows. The carbon fabric cut in 300 × 300 mm^2 square sheets was sandwiched between two PP films and the stack was then inserted between aluminum plates, with Teflon sheets between the stack and the plates; the aluminum plates were placed in a compression machine and hot pressed to impregnate PP into the fabric; after the aluminum plates were cooled down at the same pressure to consolidate the material; the CFRPP ply was demolded from the aluminum plates. For preparation of a CFRPP laminate, three CFRPP plies (aligned in warp direction) were stacked and consolidated together using the above procedure.

The impregnation was difficult to achieve because PP had to completely wet a large surface area of carbon fibers with a diameter of only 7 μm. Furthermore, the MFI of the PP film was too low to lead to perfect impregnation. Fig. 1a compares the cross-sections of well and poorly impregnated laminates. PP permeates the fibers in the well impregnated laminate (top), while at the center of the fiber bundles in the poorly impregnated laminate, a non-impregnated area colored in black can be seen (bottom). Fig. 1b compares the tensile fracture coupons of the well and poorly impregnated laminates. The well impregnated laminate was broken in a direction perpendicular to the tensile load – the same way as conventional woven carbon fiber/epoxy composites, except for the occurrence of fiber pull-out. The poorly impregnated laminate, on the other hand, was broken at an angle with a step-wise, irregular fracture surface including much more fiber pull-out.

The influence of processing conditions on the impregnation quality and on the tensile properties was investigated. The hot pressing temperature, pressure and duration were selected as processing parameters (Table 1). In the fabrication procedure, the materials, inserted between aluminum plates, were placed in the compression machine at maximum 50 °C and then heated at 5 °C/min with minimum pressure of approximately 0.2 bar. When the materials reached the prescribed temperature, the prescribed pressure was applied for prescribed time. After completing the hot pressing, the plates were cooled down at 5 °C/min with the prescribed pressure maintained and finally demolded at below 50 °C. The prescribed temperature was 180, 200 or 220 °C; the prescribed pressure was 20, 30 or 40 bar; the prescribed duration time was 10, 30 or 50 min. The above conditions were applied not only for fabrication of CFRPP plies but also for consolidation of CFRPP plies into laminates.

To assess the impregnation quality of the obtained laminates, the fiber volume fraction (V_f) and the void volume fraction (V_v) were calculated from Eqs. (1) and (2), respectively,

$$V_f = \frac{\lambda_f N}{t_c \rho_f} \tag{1}$$

$$V_v = 1 - \frac{M_c}{A_c t_c \rho_m} + \frac{\lambda_f N(\rho_f - \rho_m)}{t_c \rho_f \rho_m} \tag{2}$$

where λ_f, N, M_c, A_c, t_c, ρ_f and ρ_m denote the areal weight of the carbon fabric, the number of stacked carbon fabrics, the laminate weight, the laminate area, the laminate thickness, the carbon fiber density, and the PP density, respectively. This study used the following values: λ_f = 285 g/m^2, N = 3, ρ_f = 1.76 g/cm^3, ρ_m = 0.9 g/cm^3. Tensile testing was performed according to ASTM D3039. The load was applied in the warp direction. The modulus was calculated on the average slope of the stress–strain curves in the range of 0.1–0.3% strain. The number of specimens was five each. As summarized in Table 1, the influence of processing conditions on the void

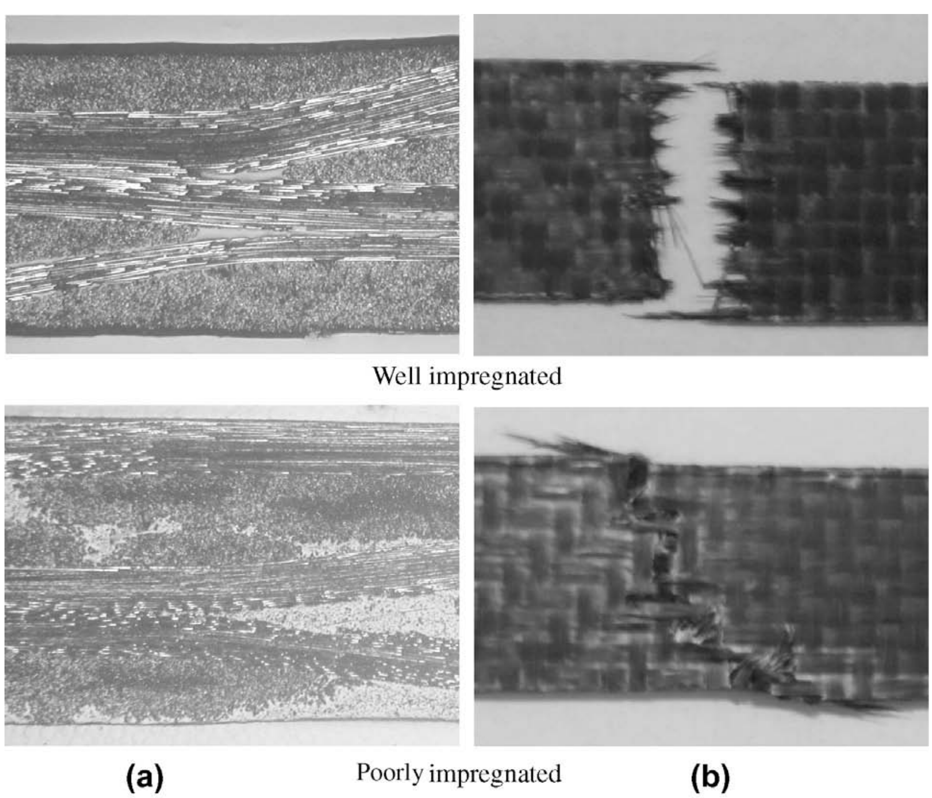

Fig. 1. Comparison of cross-sections (a) and tensile fracture coupons and (b) of CFRPP between well and poorly impregnated laminates.