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Co-woven carbon and nylon fibres for manufacturing thermoplastic composite plaques

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Abstract

Thermoplastic composites are in high demand and continually growing in use due to their inherent properties. Commingled fibre is one of the recent solutions developed for thermoplastic composites, but has not yet ready for weaving. An alternative to commingling approach, co-weaving of reinforcing and thermoplastic fibres is investigated in this study. In this work, the carbon and nylon fibres were woven separately through the warp and weft directions, respectively. A 5-multilayer 3D weave architecture was designed to produce the co-woven fabrics. By varying the weft filling or pick density, a set of woven fabrics of different thermoplastic content was obtained. The hot press was used to consolidate the composite plaques. Samples of the thermoplastic composites were physically characterised through density, fibre volume fraction and void content and then optically investigated. The composite samples were also mechanically tested to determine the interlaminar shear strength via the short beam bending test. The result proves that co-weaving method for thermoplastic composites is a feasible approach as the composite shows a low void content of approximately 1.14 percent. Comparing the four co-woven composites tested in this study it is found that the maximum achievable strength (ILSS) is ~ 41.36MPa in the case of lowest matrix (PA66) and the highest fibre (CF) contents, i.e. 13PA/7CF.

Keywords: Thermoplastic; Nylon; Fibre; Woven; Composites

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1. Introduction

Recently, industrial demand for thermoplastic (TP) composites is continuously growing as a result of their outstanding properties over thermosets such as high impact tolerance, chemical resistance, long shelf life, reusability and recyclability. However, TP composites are still a niche market because of their inherent properties such as high melting temperature and viscosity which results in significant difficulty in processing.

TP composites have some limitations that could constraint their widespread applications. Among them is the wettability which is the biggest challenge. The typical TP melting viscosity is 500-1000 times higher than that of a thermoset [1]. This inherent property results in serious issues such as enormous impregnation pressure, high-energy input, expensive tooling cost and entrapped air.

TP matrices are used in fibre reinforced polymer (FRP) composite in various textile forms; granules, powders, films, veils, nonwovens and fibres. Most TP matrix forms need prepregging process to produce prepreg tapes for composite consolidation [2]. Now the interest is to eliminate the prepregging process and to manufacture TP composites from dry fibres in one go. One of the recently developed technologies is to commingle the reinforcing and TP fibres in a

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single yarn for post processing such as weaving and tailored fibre placement (TFP).

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Alternatively, thermoplastic fibres and fibre reinforcement can be woven simultaneously to produce the co-woven fabric. To date and due to the lack of literature, the properties of the composite made by the co-woven fabric have still not been comprehensively investigated. Therefore the study presented here could be one of the early investigations of the co-weaving method for the thermoplastic composite which will contribute to the development of the thermoplastic composites.

In this work, the investigations, especially regarding the optimal thermoplastic fibres content required in co-woven fabric to wet the fibre reinforcement throughout the composite, were carried out on a five multi-layer 3D co-woven fabric made of the PA66 fibres (weft filling) and carbon fibre tows (warp ends). By varying the weft (filling) density, a set of co-woven CF/PA fabrics was manufactured using a dobby loom. The co-woven fabrics were converted to composite plaques using hot press. To assess the quality of TP composites obtained, the physical, optical and mechanical tests were performed.

2. Materials and Experiments

2.1. Materials

Materials used are carbon fibre (CF) tows of 400 tex, T300-6k and nylon or polyamide PA66 of 333tex. CF tows used in the warp direction of same density (12.66 ends/cm). A mix of CF and PA66 fibres of different pick densities; 20PA/0CF, 17PA/3CF, 15PA/5CF and 13PA/7CF used in the weft direction.

2.2. Design and weaving

A weave-design software called ‘EAT-3D composite-Module’ is used to design a 3D multi-layer plain weave with 5 layers, 5L-PW. Fig. 1 shows the schematic cross section, 3D simulated view and co-woven fabric of the 5L-PW. In Fig. 1, the top left image shows the cross-section schematic of the weave unit cell which consists of 20 wefts (black), 20 warp (colored) and the interlayer stitching warp yarns (e.g. the blue yarn between the 2nd and 3rd layers).

Table 1 shows the information of the co-woven fabric which were produced with different pick or weft densities of CF and PA66. Thus, a total of four groups of 5L-PW co-woven 3D fabric with various pick densities were obtained. It can be seen that the PA66 content in the mix pick density is gradually reduced from 20 to 13 picks/cm while the CF weight fraction increases from 43.42% to 64.7%, as the result of raising CF filling in the weft. The co-woven fabric is shown in Fig. 1 (right), in which the white PA66 fibres in the weft direction interlace with the black carbon fibres in the warp direction.

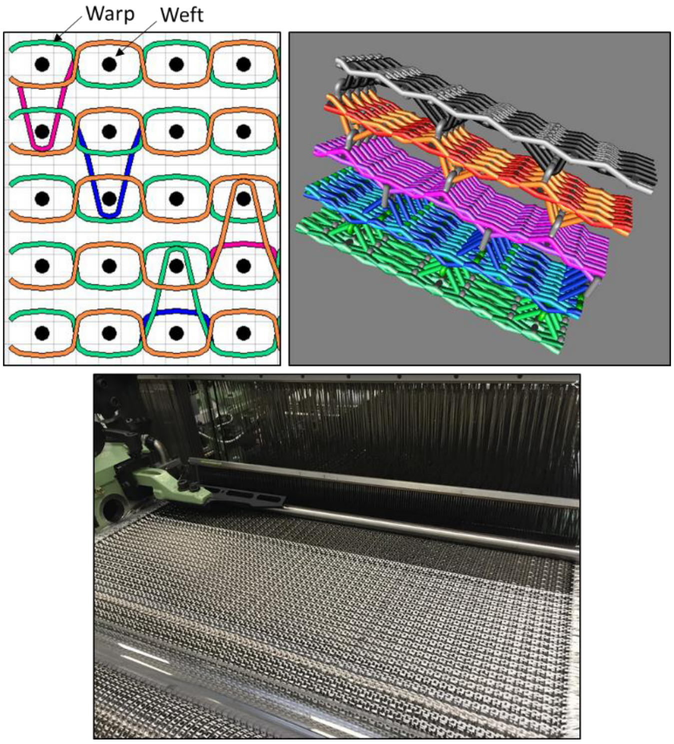

Fig. 1. Cross section (top left), 3D simulation (top right) and CF/PA66 fabric of 5L-PW (bottom) co-woven by AMRC’s weaving machine.

Table 1. Co-woven samples produced.

Name of design	Areal weight (g/m2)	Weft (picks/cm)		CF % by wt.
		PA66	CF	
20PA/0CF	1166.40	20	0	43.42
17PA/3CF	1187.40	17	3	52.75
15PA/5CF	1201.40	15	5	58.80
13PA/7CF	1215.40	13	7	64.70

2.3. Composites manufacturing

In order to determine the specific processing temperature at which the PA66 can melt completely, the differential scanning calorimetry (DSC) was carried out. It is found that the average glass transition T_g, melting and crystallinity temperatures are 76.56, 264.33 and 269.32 respectively.

For composites manufacturing, four layers of 250mm x 250mm were cut from each fabric and stacked symmetrically

(0/90/90/0). Then the stacks were transferred to the hot press whereby the composite plaques were consolidated according to the consolidation profile shown in Fig. 2. Temperature was ramped up to 290˚C.

Once the temperature was achieved, the fabric stacks were placed in between the press platens. The temperature drops below 290ºC then back to 290˚C, the 20-bar pressure was applied for 5 minutes. After that, the cooling system ran at 15˚C/min while maintaining the pressure until the temperature went down to 40˚C. Finally, the consolidated laminates are de-moulded out, and the same cycle was repeated for the other samples.

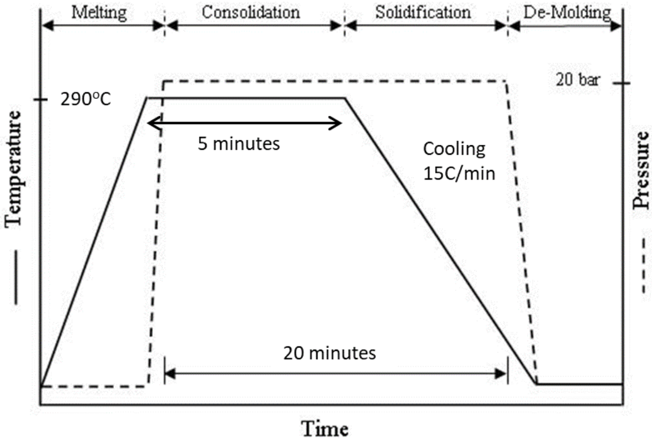

Fig. 2. Hot press consolidation profile

3. Results and Discussion

Due to the melting of PA66 during the consolidation process, the laminate thickness was expected to change from panel to the next depending on the PA66 content. Table 2 gives the measured thicknesses of laminates produced.

Table 2. Measured thickness of composites samples.

Sample	20PA/0CF	17PA/3CF	15PA/5CF	13PA/7CF
Thick. mm	1.25±0.05	2.07±0.00	2.89±0.19	3.25±0.04

The physical characteristics of manufactured plaques were determined through density (ρ), fibre volume fraction (V_f), matrix volume fraction (V_m) and void content (V_v). A gas pycnometer was used to measure the density of the specimens. A muffle furnace was used to burn off the samples at 600 ºC following the guidelines of Procedure G in the standard ASTM D3171 [9]. Five test repeats were carried out. The summary of volume fractions is listed in Table 3.

It is expected “or logical” that the carbon fibre content gradually increases with the reduction of nylon (Table 3). Highest and lowest fibre volume fraction respectively were achieved at 13PA/7CF and 20PA/0CF samples of 59.45% and 42.79%. The opposite trend was found for the matrix (PA66) content. Alongside Table 3, graphically Fig. 3 shows the increase of V_f when the CF content increases in the pick density.

Table 3. Summary of volume fractions for fibres, matrix and voids.

Sample	ρ (g/cm^3)±SD	V_f (%)±SD	V_m(%)±SD	V_v (%)±SD
20PA/0CF	1.449 ± 0.009	42.79 ± 0.20	56.15 ± 0.56	1.06 ± 0.76
17PA/3CF	1.492 ± 0.045	48.73 ± 2.30	50.01 ± 2.73	1.27 ± 0.07
15PA/5CF	1.528 ± 0.010	54.53 ± 1.09	44.25 ± 1.26	1.23 ± 0.19
13PA/7CF	1.546 ± 0.005	59.45 ± 0.96	39.54 ± 0.97	1.01 ± 0.23

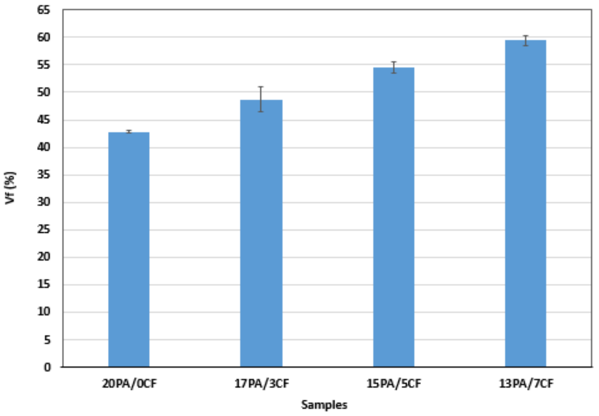

Fig. 3. Fibre volume fraction V_f versus pick density

In terms of porosity, it is known that the thermoplastic is a highly viscous polymer and air can easily get trapped in it during the consolidation process. Successfully the V_v obtained was found to be in the range of 1% to 1.27%, which is quite good within the acceptable tolerance in the field of composites manufacturing [10]. Polished cross sections of each type were prepared and scanned using optical microscopy to validate the composites’ quality and integrity. Clearly, the obtained optical micrographs (Fig. 4) confirmed the burn out test results and showed that the four composite plaques have low porosity. Samples with low carbon content; 20PA/0CF and 17PA/3CF exhibited some resin rich areas (RRA) compared to those of higher V_f percent.

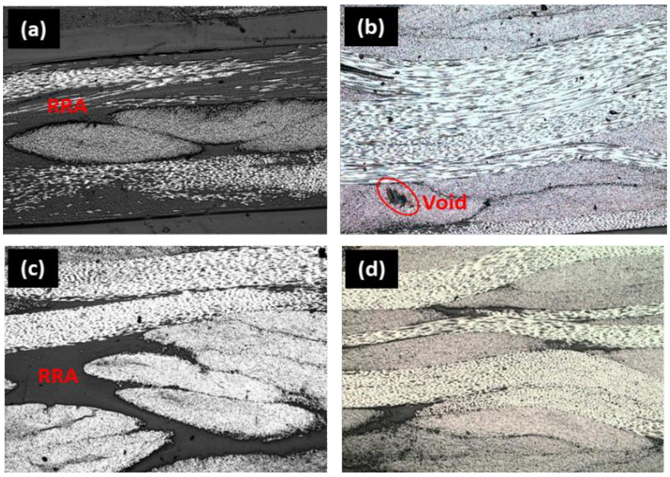

Fig. 4. A selection of optical micrographs of 20PA/0CF (a), 17PA/3CF (b), 15PA/5CF (c) and 13PA/7CF (d) composites.

According to the standard ASTM D2344 [11], the short-beam strength test was done to determine the interlaminar shear strength (ILSS) response for the four composite panels. Five test repeats were carried out for each composite. The dimension of each test specimen was prepared according the following equations.

Specimen length, $L = \text{thickness} \times 6$ (1)
Specimen width, $b = \text{thickness} \times 2$ (2)

The ILSS was calculated using the following formula.

$$\text{ILSS} = 0.75 \times F_{max} / (b \times h) \quad (3)$$

Where: F_{max} is the maximum load observed during the test and measured in N. b & h are the specimen width and thickness and measured in mm.

The average ILSS are determined (Fig. 7) where the highest ILSS value obtained is approximately 41.36MPa in the case of 13PA/7CF laminate. It is noted that, the 20PA/0CF exhibited a higher ILSS compared to the following laminate (17PA/3CF) with pick density contacting 3CF. Then the ILSS started to increase from 17PA to 13PA, this trend can be explained in the light of the thickness increase. According to the classical laminate theory [12], the bending stiffness of the composite laminate is a function of the stacking sequence and the location of the zero degree plies from the mid-plane. The further apart they are from the mid-plane, the higher the resistance which is dictated by the D matrix in the A B D matrix. However, Due to the interlacing nature of these three types (17PA/3CF, 15PA/5CF and 13PA/7CF), their response is a bit difference from the 20PA/0CF one which behaves as UD plies with less waviness, meaning that the stiffness of the zero degree plies are higher as they have the least undulation. Thus in spite of the lesser thickness in this case, 20PA/0CF still can afford higher loads in bending compared to the 17PA for instance. The same argument can be driven for the resistance to interlaminar shear. The less waviness in the 20PA/0CF makes it more resistance to interlaminar shear compared to the 17PA/3CF for instance. After adding more CF in the weft direction the interlacing improved and the fabric become tighter and stronger leading to significant and gradual increase in the ILSS upon the increase of CF content in pick density as shown in Fig. 5.

Comparing the four co-woven composites tested, it is found that the maximum strength achieved in the case of lowest matrix (PA66) and the highest fibre (CF) contents. Hence, it could conceivably conclude that the 13PA/7CF pick density woven into the weft direction is the best choice in terms of the ILSS obtained and compared to the rest of densities investigated in this study.

In order to enhance the co-weaving approach presented in this work, weaving of TP fibres through the warp and weft directions has been recommended for a further investigation.

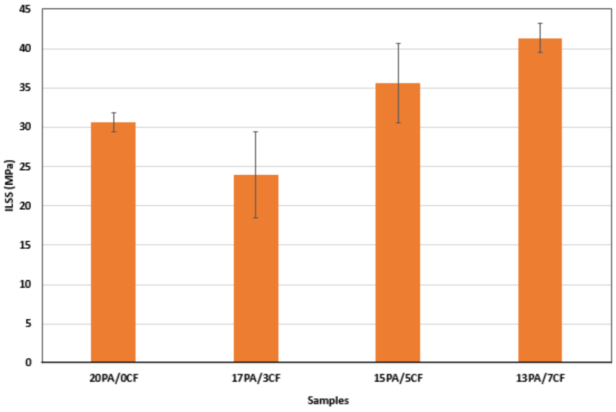

Fig. 5. ILSS of composite samples tested.

4. Conclusion

This study conducted out to comprehensively investigate the co-weaving approach to manufacture thermoplastic composites. A PA66/CF multi-layer 3D co-woven fabric with different PA content was designed to find the optimal PA density required to fully wet the CF in the co-woven fabric. Through the quantitative (physical and mechanical) and qualitative (optical microscope) test, the optimal PA pick density was identified at 13PA/7CF picks/cm which contains the highest carbon fibre content. The 13PA/7CF composite laminate, where 39.54% (13PA) of PA66 co-woven with 59.45% (7CF) of carbon fibre, exhibited the improved integrity compared to the other laminates combined with the lowest void content and highest ILSS. Also, the low porosity of all composites (~1.14%), confirmed the feasibility of using the co-woven fabric as an alternative to commingling in thermoplastic composites manufacturing and applications.

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