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The brittle-to-ductile transition in tensile and impact behavior of hybrid carbon fibre/self-reinforced polypropylene composites

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A B S T R A C T

Hybrid composites combining two fibre types with distinctly different mechanical properties have the potential to surpass the stiffness-toughness dilemma, which is characteristic to standard (single fibre type) composite materials. The current work demonstrates this potential on the example of carbon fibre/self-reinforced polypropylene (SRPP) hybrids. The aim is to understand the transition from brittle to ductile behaviour under tensile and impact loadings and to identify the parameters affecting this transition. It was found that the volume fraction (V_f) of carbon fibres at which the transition occurs can be increased by using a dispersed layup with thinner layers. The use of a high adhesion matrix results in higher modulus and yield strength but lowers the transition V_f. The experimental program is supported by analytical models used to predict modulus, strength and energy absorption. Results indicate that pseudo-ductile carbon fibre/SRPP hybrids are competitive with composites produced from bulk and sheet moulding compounds.

1. Introduction

Most materials conform to the stiffness-toughness dilemma, meaning that they are either stiff but brittle or tough but compliant. Conventional composite materials are no exception in this regard. On one side of the spectrum are carbon fibre composites. They offer high stiffness and strength that make them attractive for a wide range of applications from sporting goods to aircraft components. However, they fracture in a brittle manner with little or no warning before final failure, hence leading to conservative designs and over-designed components. On the other side of the spectrum are self-reinforced polymer composites, in which the matrix and the reinforcement are made from the same polymeric material. These composites exhibit high levels of ductility and toughness [1–4]. However, they have low stiffness and yield stress, which has been hindering their implementation in structural and semi-structural applications.

This stiffness-toughness dilemma has stimulated research in the field of pseudo-ductile hybrid composites. The latter combine both stiff but brittle (low elongation) and tough (high elongation) fibres or reinforcements [5–14]. For instance, Czél et al. [5,7] developed pseudo-ductile hybrids by combining carbon fibres with a failure strain of 2% with glass fibres with a failure strain of 5%. They achieved gradual damage development resulting in a pseudo-ductile response with failure strains up to 4%.

Much higher failure strains (> 15%) were achieved by Swolfs et al. [8–10] by hybridising continuous carbon fibres with self-reinforced polypropylene (SRPP), which has a failure strain of up to 20%. In that set of studies, various architectures (unidirectional vs. woven) and dispersion levels (layer-by-layer vs. co-woven) were tested. While high ductility was achieved with these hybrids, the stress–strain curves were not smooth. They showed repeated load-drops caused by fragmentation of the carbon fibre component accompanied by delamination between carbon fibre layers and SRPP, or debonding between carbon fibre and SRPP tapes in the co-woven configuration. It has been difficult to suppress delamination and eliminate the load drops in these hybrids because of the high levels of energy released when carbon fibres fracture. For a more comprehensive review of hybrid composites, the reader is referred to [15].

Design of ductile hybrids is challenging and requires a thorough understanding of the failure mechanisms that occur during loading [15–17]. The damage scenarios that can occur in interlayer hybrids were outlined by Czél et al. [7,16] and Swolfs et al. [9]. After the initial failure of the low elongation layer hybrid composites may undergo one of the following events [7,9,16–18]:

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(a) instant failure of the high elongation layer as it cannot sustain the load that is transferred to it,
(b) catastrophic delamination, which is then followed by the failure of the high elongation layers,
(c) stable fragmentation of the low elongation material, which is accompanied by no or minimal delamination, and finally failure of the high elongation material upon further load increase.

Initiation and propagation of damage depend primarily on the strength, stiffness, volume fractions of the high and low elongation components, the stacking sequence, ply thickness and mode II fracture toughness of the interface between the high and low elongation layers [7,9,16–18]. Depending on the combination of these properties, failure can be either gradual or abrupt (showing no loss of stiffness up to the final failure). Hence, the right combination of parameters is required to achieve a pseudo-ductile response.

Impact properties of hybrids have been the focus of numerous studies [15]. It was shown that the stacking sequence has a strong influence on the impact performance of composites, as it affects the flexural stiffness and strength as well as the damage mechanisms. Studies on hybrids have shown that penetration impact resistance is improved when the low elongation layers are placed inside the hybrid and are shielded by the high elongation layers at the outside [19–21].

The present work investigates the tensile and impact properties of a novel type of hybrid composites that contain randomly oriented discontinuous carbon fibres and woven SRPP. The brittle-to-ductile transition is of key interest here. It is desirable to increase the volume fraction (V_f) at which this transition occurs to increase the stiffness and yield stress while maintaining the pseudo-ductile behaviour and impact performance. The effect of the stacking sequence and the fibre–matrix interface on the V_f at the transition will be investigated. To achieve a stronger interface between the fibres and the matrix, maleic anhydride grafted polypropylene (MAPP) is used to impregnate the carbon fibres instead of the regular polypropylene (PP). Simple analytical models are proposed for prediction of stiffness, strength and the transition from brittle to ductile tensile behaviour.

2. Experimental

2.1. Materials and composite processing

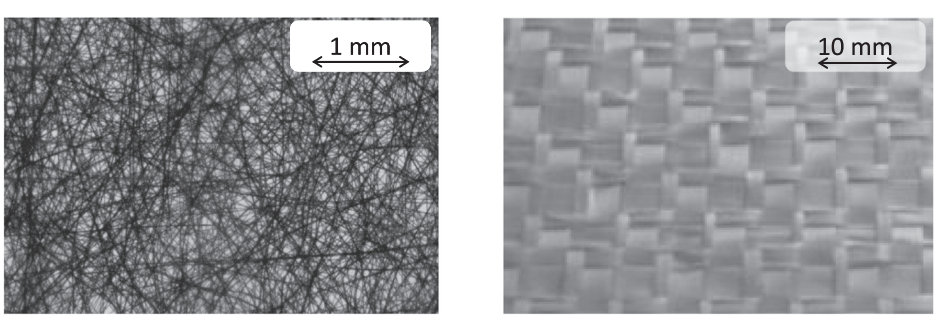
Hybrid layups consisted of carbon fibre mats, PP tape fabrics and PP films, and each of these materials will be discussed hereafter. The dry carbon fibre mats were provided by Toray Industries Inc. (Japan) and consisted of in-plane randomly oriented 6 mm long T700S fibres held together by a binder, see Fig. 1a. The areal density of the mats was either 10 or 30 g/m^2. A balanced 2/2 twill PP tape fabric was provided by Propex Fabrics GmbH (Germany), see Fig. 1b. The tapes used to create the fabric are drawn 10–15 times, have a rectangular cross-section and are about 2.4 mm wide. During the weaving process, some of the tapes in both the warp and the weft directions are folded along their length, which makes them look narrower in Fig. 1b. This manufacturing feature is known as overfeeding and is described in more detail in [1]. The average area density of the produced fabric is 130 g/m^2 [1,2]. Upon heating, the outer sheath of the PP tapes melts, while the inner core maintains its molecular orientation. During the cool-down, the molten PP consolidates and forms the “matrix” component of the SRPP layer [22]. The purpose of the PP films is therefore not to impregnate the PP tape fabric, but to impregnate the carbon fibre mat.

Table 1
Summary of tested composites. *S* stands for SRPP, / for PP or MAPP films, and 10 or 30 represent the areal weight in g/m^2 of the carbon fibre mat. Hybrid configurations that were considered for each film type are identified by *X*.

Layup	Internal fibre volume fraction (%)	Global fibre volume fraction V_f (%)	Film type PP	MAPP
S/S/S/S/S/S/S/S/S/S/S/S	0	0	X	
S/S//30////30//S/S	16.7	4.1	X	
S//30//S	16.7	4.4	X	X
[S//30//S//30//S//15]s	16.7	6.2		X
//30//SS//30//	16.7	6.9		X
S//30////30//S	16.7	6.9	X	X
S//30////30////30//S	16.7	8.6	X	X
//30//S//30//S//30//	16.7	8.6	X	X
[S//30////30//S//30////30//S//30//]s	16.7	9.0	X	
S//30////30////30////30//S	16.7	9.8	X	X
[S//30////30////30////30//]s	16.7	12.3		X
//30////30////30////30//	16.7	16.7	X	X
/S//10/S/S/S/10//S/	8.5	1.2	X	
S/10/S	11.8	1.7	X	X
/S///30//S/S/S//30///S/	14.3	3.2	X	
/S//30/S/S/S/30//S/	21.7	3.5	X	
/S//30/S/S/30//S/	21.7	4.2	X	
/S//30/S/30//S/	21.7	5.3	X	
S//////30 30 30 10//////S	18.8	9.5	X	

Propex Fabrics GmbH also provided two types of 20 µm thick films: homopolymer PP and maleic-anhydride modified PP, in short MAPP. The homopolymer PP is the same grade as that used to produce the PP tape fabric. This PP has low affinity to carbon fibres, resulting in poor adhesion between the fibres and PP [23]. MAPP on the other hand has better adhesion to carbon fibres. It was previously shown that interfacial shear strength between carbon fibres and polypropylene matrix can be increased from 6 to 16 MPa by switching from PP to MAPP [23]. The actual content of the modifier was not disclosed.

Different interlayer hybrids were produced, as summarised in Table 1. “*S*” stands for SRPP, “/” for a single PP or MAPP film, and the



(a) (b)

Fig. 1. Structure of the materials studied: (a) carbon fibre mat and (b) twill PP tape fabric.