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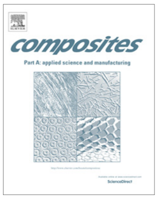

Hybridisation of two ductile materials – Steel fibre and self-reinforced polypropylene composites

Y. Swolfs *, P. De Cuyper, M.G. Callens, I. Verpoest, L. Gorbatikh

Department of Materials Engineering, KU Leuven, Kasteelpark Arenberg 44, B-3001 Leuven, Belgium

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ABSTRACT

Hybridisation of self-reinforced polypropylene (SRPP) with ductile steel fibres is proposed as a way to create composites with a high stiffness, failure strain and toughness. The stiffness and yield stress of SRPP were significantly increased without sacrifice of toughness, even after normalisation to the composite density. The measurements revealed a higher stress level and slope after yielding than the predictions by the linear rule-of-mixtures. This effect was attributed to differences in the Poisson contraction of the two constituents and was supported by modelling predictions. The absolute penetration impact resistance of SRPP was increased, whereas the specific impact resistance remained the same, despite the high density of steel fibres. Placing steel fibre layers on the outside of the laminate maximised the penetration impact resistance, as it allowed the steel fibres to exploit their full plastic potential. These results can guide the optimisation of other hybrid composites with two ductile fibres.

1. Introduction

Traditional fibre-reinforced composites possess excellent mechanical properties, but often suffer from a lack of toughness. Carbon and glass fibres are both brittle fibres, which limits the failure strain of their composites to 1.5–3.5%. They often display early damage initiation under off-axis loading (below 0.5% strain) [1,2] and a relatively low impact resistance.

One solution to improve the performance is to toughen the matrix or to tune the fibre/matrix interface. This strategy, however, has little effect on the fibre-dominated properties [3,4]. A more promising strategy for improving toughness of composites is to use ductile instead of brittle fibres. Among the ductile fibre families, the two most important ones are polymer and metal fibres.

Even though large property variations arise depending on draw ratio and molecular structure, many polymer fibres have a high failure strain and are inherently ductile. Self-reinforced composites, and self-reinforced polypropylene (SRPP) in particular, are a commercially successful example. SRPP has a low density (900–920 kg/m^3), a high failure strain (15–20%) and an excellent impact resistance (20–35 J/mm) for a woven version [5–7]. Unfortunately, woven SRPP also has a low stiffness (3–5 GPa) and strength (130–180 MPa) compared to carbon or glass fibre-reinforced composites.

Metal fibres may be a better solution for structural applications where stiffness is an important requirement. Depending on the thermal treatment, the failure strain of these fibres can be tailored with nearly no effect on their high stiffness. Annealed stainless steel fibres, for example, combine a stiffness of 193 GPa with a failure strain of 20% [8–10]. Steel fibres also have an enormous potential for energy absorption. The penetration impact resistance was found to be up to 70 J/mm for a cross-ply laminate [11]. This is more than twice as high as for SRPP, which is already considered to have excellent impact resistance [6,7]. The drawback of metal fibres, however, is that their density is significantly higher than carbon, glass and polymer fibres.

A potential solution would be to combine a metal fibre with a polymer fibre. This could potentially lead to interesting combinations of stiffness and ultimate failure strain with a reduced effect of the high metal fibre density. Most hybrid composites so far have focused on combining two brittle fibre types, such as carbon/glass [12–16], carbon/aramid [17,18] and carbon/flax [19,20]. Much of the focus of the early research was on synergetic effects between both fibres. The so-called hybrid effect can be defined as a deviation from a simple rule-of-mixtures. This can be a constant, linear, bilinear or more complex rule depending on the property under investigation. No hybrid effects are reported for the elastic modulus, but positive effects are common for strength and failure strain [21,22]. Many researchers have reported an increase in the failure strain of carbon fibre layers when they were hybridised with glass

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* Corresponding author.
E-mail address: yentl.swolfs@kuleuven.be (Y. Swolfs).

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fibre layers [23–25]. This hybrid effect has been discussed in detail in a recent review paper on hybrid composites [22].

There is, however, a recent trend to hybridise brittle fibres with ductile fibres [22]. Pegoretti et al. [26] for example hybridised glass fibres with polyvinyl alcohol (PVA) fibres. With a failure strain of about 7%, these PVA fibres are more ductile than carbon or glass fibres. Even more ductile hybridisation fibres are found in the work of Swolfs et al. [27–30], where carbon fibres were hybridised with SRPP. Despite the large energy release upon carbon fibre fracture, the SRPP failure strain of 20% was maintained.

Hybrid composites containing two ductile fibres (metal and polymer) have not been reported yet in literature. The family of composites that comes closest is fibre-metal laminates (FMLs) with SRPP [31–34]. The low SRPP density of 900–920 kg/m^3 can be exploited to create an FML with a lower density (1200–1800 kg/m^3) than the 2100–2500 kg/m^3 density of most aluminium-based glass fibre FMLs. An additional benefit of SRPP FMLs compared to FMLs with brittle fibre composites is that a much higher impact resistance can be achieved. In the present work, we investigate hybridisation of steel fibre composites with SRPP as a route to make tough structural composites. The focus lies on understanding and optimising their tensile behaviour and penetration impact resistance. To the best of our knowledge, there are no publications on hybrid composites consisting of two ductile fibres.

2. Materials & methods

2.1. Materials

Annealed stainless steel yarns, made of a 316 stainless steel alloy, were supplied by NV Bekaert SA. These yarns were produced in a bundle drawing process [35], in which fine steel wires were embedded in a copper matrix to form a composite rod. This rod was then drawn into a small wire. Finally, the copper matrix was removed, resulting in irregular polygonal fibre cross-sections with an equivalent average diameter of 30 μm and yarns containing 275 fibres and having a linear density of 1525 tex. The yarns were woven in a quasi-unidirectional fabric, consisting of steel weft yarns and thin polyethylene terephthalate (PET) warp yarns (see Fig. 1). The PET yarns had a linear density of 20 tex and the areal density of the weave was 1425 g/m^2.

Propex Fabrics GmbH (Germany) provided a balanced twill 2/2 weave of drawn PP tapes. These tapes had a draw ratio of 10–15 and a linear density of 110 tex. The weave was overfed by 50% in both warp and weft direction, meaning that the distance from one tape to the next was less than the tape width [36]. The areal density of the weave was 130 g/m^2.

Propex Fabrics GmbH also provided two types of PP film made from the same PP grade as the drawn PP tapes. The only difference between the films was their thickness: 20 μm and 50 μm. They were used to broaden the processing window and to impregnate the steel fibres, respectively.

2.2. Production

All composites were produced using hot pressing. The lay-up, consisting of some or all of the above three components, namely the steel fibre fabric, the woven PP tape fabric and the PP films, was inserted into a heated press and compacted with a pressure of 50 bar for 5 min at a set temperature of 186.5 °C. During this process, the outer sheaths of the PP tapes were melted and this formed the matrix upon cooling. Simultaneously, the steel fibres were impregnated with the molten PP films. After a dwell time of 5 min, the laminates were cooled to 40 °C in about 5 min and under a constant pressure of 50 bar.

The reference SRPP laminates were produced using 20 layers of woven PP tapes, leading to an average thickness of 3.57 ± 0.06 mm (see Table 1). A 20 μm film was added in between each of the woven PP tape layersto ensure a homogeneous laminate quality. No films were added to the top or bottom of the laminate.

The above process was used to produce both hybrid and reference composites. The reference composites were prepared for comparative purposes and to allow determination of the fundamental properties of the discrete plies assumed to constitute the

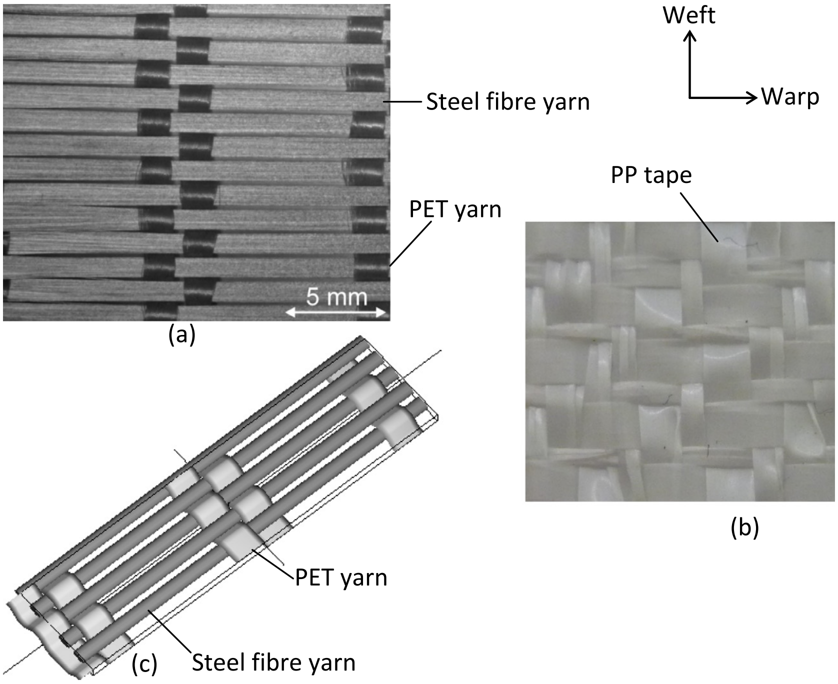

Fig. 1. Overview of used materials (a) photograph of the quasi-unidirectional steel fibre fabric with steel fibre yarns in the warp direction and PET yarns in the weft direction, (b) the PP tape fabric, and (c) geometric model of the steel fibre fabric. The unit cell in (c) is drawn larger than strictly necessary for visual reasons.