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

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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.

Keywords: A. Hybrid; A. Polymer-matrix composites (PMCs); C. Laminate mechanics; Self-reinforced composites

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 fiber/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/m³), 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 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/m³ can be exploited to create an FML with a lower density (1200-1800 kg/m³) than the 2100-2500 kg/m³ 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/m².

Figure 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.

Propex Fabrics GmbH (Germany) provided a balanced twill 2/2 weave of drawn PP tapes. These tapes had a draw ratio of 10 to 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/m².

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 μ m film was added in between each of the woven PP tape layers to 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 hybrids in subsequent modelling. The reference steel fibre/PP laminates were produced using 8 layers of the steel fibre fabric in a (0,90)_{2s}-layup. Two 50 μ m PP films were added above and below every steel fibre layer. The thickness of this reference laminate was 3.13 ± 0.03 mm (see Table 1) and the fibre volume fraction based on areal density calculations was 46%.

Table 1: Tensile properties of the reference materials and the three hybrids. The indicated errors are the 95% confidence intervals.

	Sample thickness	Modulus (GPa)	Yield stress (MPa)	Tensile strength (MPa)	Failure strain (%)	Energy (J/mm ³)
Reference steel/PP	3.13 ± 0.03	38.7 ± 1.5	85.8 ± 1.8	127.8 ± 4.0	12.9 ± 1.6	14.2 ± 2.1
Hybrid: steel distributed	3.10 ± 0.04	22.4 ± 0.7	55.9 ± 2.7	136.3 ± 5.3	9.8 ± 1.8	9.2 ± 1.5
Hybrid: steel outside	3.16 ± 0.03	22.5 ± 1.7	55.7 ± 4.2	144.5 ± 15.1	11.4 ± 0.5	11.3 ± 0.8
Hybrid: steel inside	3.13 ± 0.04	20.7 ± 1.7	52.9 ± 2.8	140.9 ± 11.7	11.7 ± 0.9	11.3 ± 1.7
Reference SRPP	3.57 ± 0.06	4.2 ± 0.4	17.4 ± 2.8	148.9 ± 8.7	13.4 ± 1.3	9.6 ± 0.6

Three types of hybrids were produced to analyse the influence of the layup: steel fibre layers in the middle, on the outside and distributed throughout the laminate (see Fig. 2). The relative number of layers of woven PP tape and steel fibre fabric was chosen so that the hybrid composites contain 50% by volume SRPP plies and 50% steel/PP plies. A 20 μ m film was added in between each of the PP tape fabric layers and on the surface if the outer ply were PP tape fabrics. Two 50 μ m films were added above and below each steel fibre layer. The quality of the laminates was investigated using optical microscopy. Impregnation of the PP tapes as well as the steel and PET fibres was found to be excellent. This is attributed to the relatively large diameter of the steel fibres compared to traditional reinforcing fibres, which greatly facilitates impregnation [37].

Figure 2: Schematic representation of the three hybrid configurations: (a) Hybrid: steel inside, (b) Hybrid: steel outside, and (c) Hybrid: steel distributed.

2.3 Tensile tests

Quasi-static tensile tests were performed according to ASTM D3039 on an Instron 4505. The specimens were 250 mm x 25 mm in size and were tested in the 0° laminate direction at a gauge length of 150 mm. The displacement rate was set to 2 mm/min, corresponding to a strain rate of 1.33 %/min. A 100 kN load cell was used to measure the load. A speckle pattern was applied to the specimen surface. The surface strain was measured using digital image correlation of this pattern, thereby allowing the calculation of the longitudinal and transverse modulus as well as the Poisson's ratio. The Poisson's ratio was only measured for the SRPP composite, as the Poisson's ratio of the other composites were too low to achieve reliable measurements. Five samples were tested for each configuration.

The tensile modulus was calculated in the strain interval 0.02%-0.1%. This interval is lower than the usual 0.1%-0.3% to avoid any plasticity in the steel fibres. The yield stress was calculated as the point where the plastic strain is 0.2%. The absorbed energy/volume was calculated from the area underneath the stress-strain curve, and will be expressed in J/mm³.

2.4 Impact tests

Penetration impact tests were performed according to the ISO 6603-2 standard. A hemispherical striker was dropped onto the sample from a height of 1 m. The striker had a diameter of 20 mm and weighed 26.17 kg. The inner clamp diameter was 40 mm, and the total clamping force on the samples was 5600 N. Each impact sample was at least 90x90 mm large. The force was measured by a 20 kN load cell in the striker tip, whereas the displacement was measured by a laser distance sensor. At least 3 samples were tested for each layup. The penetration impact resistance was calculated by measuring the area underneath the force-displacement diagram until the load dropped below half the peak force. This value was divided by the specimen thickness for the absolute penetration impact resistance, or by the thickness and the density for the specific penetration impact resistance.

3 Model description

The modelling of the hybrids using classical laminate theory requires a knowledge of the mechanical properties of the different plies considered to constitute the hybrid as well as the composition and architecture of the layup. Here, it is assumed that the different hybrids can

be considered to be stacks of SRPP and unidirectional steel/PP plies. This section will first develop a model for small strains and then for large strains.

3.1 Linear model

A geometric model of the weave was created to predict the elastic constants of the steel fibre/PP composite. This model was generated using an in-house developed software tool, WiseTex [38]. The dimensions of the elliptical yarns were measured from optical microscopy images. The major and minor axes of the ellipses were 0.4 x 1.05 mm for the steel yarns and 0.1 x 2 mm for the PET yarn. The yarn counts were measured to be 10/cm for steel yarns and 1.89/cm for PET yarns. Combined with the information in “2.1 Materials”, this led to the geometric model depicted in Fig. 1c.

The geometric model was then transferred into the TexComp tool to predict elastic moduli based on the inclusion-based homogenisation technique. For the calculations, the Young's modulus E and Poisson's ratio ν were taken as $E = 193 \text{ GPa}$ and $\nu = 0.3$ for stainless steel fibres, $E = 3 \text{ GPa}$, $\nu = 0.3$ for PET fibres, and $E = 1.45 \text{ GPa}$, $\nu = 0.3$ for the PP matrix. The steel fibre volume fraction inside the steel fibre layers was $46.4\% \pm 0.4\%$ based on areal density calculations and $45.6\% \pm 2.1\%$ based on matrix burn-off measurements according to ASTM D2584. Therefore, a value of 46% was used.

3.2 Non-linear model

The moduli of the reference and hybrid materials were modelled using the classical laminate theory (CLT), which was modified to account for the non-linear behaviour of the constituent materials. This was achieved by using the secant modulus at the applied strain as an input. The secant modulus is essentially a linear stress-strain relationship for the plastically deforming material, which is a prerequisite for CLT. This relation is only valid at this specific applied strain and thus new input values are needed for the calculation at each strain.

Since there was no experimental data available for 0° steel/PP composites, the model is based on the properties of the cross-ply laminate. Therefore, the experimental tensile diagram of the reference cross-ply steel/PP composite was used. The longitudinal modulus was derived from the experimentally measured secant modulus on the cross-ply laminate. The transverse and shear modulus as well as the Poisson's ratio were calculated using the linear model, as the transverse and shear strains on the cross-ply steel/PP layers were small. They were calculated from the geometric unit cell model for the quasi-unidirectional ply, and then entered into CLT to predict their values for a cross-ply laminate.

The longitudinal SRPP modulus was based on the secant modulus taken from the tensile test data. The transverse modulus was assumed to be independent of the applied strain and equal to the elastic modulus. This may not be entirely correct, but its effect on the predictions is anyway very small. The Poisson's ratio was taken from the experimental measurements, and these results will be revealed later. The shear modulus has no influence on the model predictions. Its value was calculated using the Poisson's ratio and the longitudinal secant modulus and assuming isotropic properties.

4 Results and discussion

4.1 Tensile behaviour

Fig. 3 depicts representative stress-strain diagrams for the reference and hybrid laminates. The reference materials have an almost identical failure strain, but the modulus of the cross-ply steel fibre/PP laminate is nearly 10 times higher than that of the SRPP laminate (see Table 1). The measured modulus of the hybrids agrees well with the 21.5 GPa predicted by the linear rule-of-mixtures. This rule-of-mixtures uses iso-strain assumptions and is essentially a volume averaging of the properties. By hybridising 50% woven SRPP with 50% cross-ply steel fibre/PP, the modulus of the hybrid composites can be increased by a factor of 5 compared to SRPP. Similarly, the yield stress of the hybrid was increased by a factor of 3 compared to the SRPP yield stress, which can be vital for practical applications.

Figure 3: Representative stress-strain diagrams of the reference materials and the three hybrids.

The tensile strength of the reference SRPP was higher than that of the reference cross-ply steel fibre/PP laminate. Only the distributed hybrid revealed a significantly lower tensile strength than for the reference SRPP. The tensile strength of the other hybrids was slightly lower than that of the reference SRPP, but these differences were not statistically significant.

While the failure strain of the reference materials was almost identical, the failure strain of the hybrids was slightly lower. The lower failure strain of “hybrid: steel distributed” compared to the other hybrids will be explained later, based on the outcome of modelling predictions. The energy dissipated by the hybrids during the tensile test was approximately equal to 11.9 J/mm³, which was the average value for the reference materials.

Visual and auditory observations during the tensile tests revealed that the steel fibre plies started failing first. This occurred gradually and released a sound similar to slow tearing of a paper sheet. This is followed by sudden and drastic failure of the SRPP layers, which coincided with final failure of the entire specimen.

For lightweight applications, the mechanical properties per density are more important than the absolute values. Since the SRPP density is very low, its specific properties are high. Table 2 summarises the specific tensile properties of the reference and hybrid composites. Despite the much higher density of steel fibre/PP, the specific modulus of the hybrids is still two times higher than of the reference SRPP. This is because the modulus is increased by a factor of five

and the density only by a factor of 2.5. This essentially means that SRPP applications that are dominated by tensile stiffness can be made lighter by the addition of steel fibres. The higher density would be compensated by thinner wall thicknesses due to the higher material stiffness.

Table 2: Tensile properties per density of the reference materials and the three hybrids. The indicated errors are the 95% confidence intervals.

	Density (kg/m ³)	Specific modulus (GPa.cm ³ /g)	Specific yield stress (MPa.cm ³ /g)	Specific tensile strength (MPa.cm ³ /g)	Specific energy (J/kg)
Reference steel/PP	4100	9.4 ± 0.4	20.9 ± 0.4	31.2 ± 1.0	3.5 ± 0.5
Hybrid: steel distributed	2500	8.9 ± 0.3	22.4 ± 1.1	54.3 ± 2.1	3.7 ± 0.6
Hybrid: steel outside	2500	9.0 ± 0.7	22.3 ± 1.7	57.6 ± 6.0	4.5 ± 0.3
Hybrid: steel inside	2500	8.3 ± 0.7	21.2 ± 1.1	56.1 ± 4.7	4.5 ± 0.7
Reference SRPP	900	4.5 ± 0.4	19.3 ± 3.1	161.8 ± 9.5	10.4 ± 0.7

The specific tensile strength of steel fibre/PP is lower than SRPP, as the tensile strength of the reference materials is similar, while the density is four times higher. The specific tensile strength of the hybrids is therefore approximately three times lower than that of SRPP. The situation is similar for the specific energy, which is approximately two times lower for the hybrids than for the SRPP. The specific yield stress however remained nearly constant.

The hybrids all follow similar trends with tensile properties that are statistically the same. The modulus after the yield point is, however, significantly higher than the value obtained from the linear rule-of-mixtures. This linear rule-of-mixtures is based on iso-strain assumptions and corresponds to volume averaging of the stress-strain curves of the reference non-hybrids. According to the general definition in Swolfs et al. [22], one could state that this is a positive hybrid effect, as the hybrids are performing better than the linear rule-of-mixtures. It should however be noted that attributing this to synergies between the two constituent materials depends on how advanced the reference model was. In the case here, the linear rule-of-mixtures is relatively simple. The model described in “3.2 Non-linear model” was therefore used in an attempt to better understand and explain the behaviour of the hybrids. Only the “hybrid: steel inside” will be plotted, as the modelling predictions are not affected by the layup.

The initial modelling predictions for the hybrid using a modified CLT show a better fit with the experimental curves than the linear rule-of-mixtures (see Fig. 4). This can be explained based on the Poisson contractions of the layers. The Poisson’s ratio of the cross-ply steel fibre/PP was calculated to be 0.0020, 0.0011 and 0.0008 for strains of 5%, 9% and 12%, respectively. These low values are attributed to the fact that the stiff 90° steel fibres nearly completely prevent the contraction that the 0° steel fibres want to develop. This also implies that those 90° steel fibre plies prevent the Poisson contraction of the SRPP layers. This creates a biaxial stress state in both materials, which causes the hybrid to behave stiffer than the linear rule-of-mixtures. The observed effect is hence attributed to differences in the Poisson’s ratio. Whether this can rightfully be called a hybrid effect is a difficult discussion, as it depends on how advanced the model is that you use as reference.

Figure 4: The stress level and slope of the hybrid composite are underestimated when the measured variation in the Poisson's ratio for SRPP is taken into account (see Figure 5). A better prediction is achieved when the Poisson's ratio for SRPP is set to a constant value of 0.225. The model predictions are in dashed lines, and were calculated for strains of 5%, 9% and 12%. For the reference composites, the Poisson contraction does not affect the predictions.

The modified CLT-based model with the measured Poisson's ratio of SRPP did not yet satisfactorily describe the stress-strain behaviour of the hybrid: the slope of the diagram and the overall stress were underestimated. This is likely to be due to inaccuracies in the Poisson's ratio of the SRPP. The changing Poisson's ratio of the SRPP, which was used in the initial modelling prediction, is plotted in Fig. 5. The Poisson's ratio decays as a function of the longitudinal strain. The part of the diagram before 1% strain is shown for completeness, but actually should be disregarded. Calculating the Poisson's ratio at such low deformations is numerically unstable, as it requires division of two small numbers.

Figure 5: Experimental measurement of the SRPP Poisson's ratio as a function of the longitudinal strain. The constant Poisson's ratio assumption in the model is added to facilitate comparison.

The transverse SRPP deformation was not constrained in the experimental measurements on laminates with only SRPP layers, as there were no steel fibres present to constrain the SRPP. In the hybrids, however, the stiff steel fibre layers prevent the transverse contraction and affect the contraction in the thickness direction. The Poisson contraction inside the hybrids is

therefore a complicated matter and there is significant doubt to which value should be used. To gauge the effect of the Poisson contraction, it was set to a constant value (see Fig. 5). A value of 0.225 was chosen, as this is a realistic value for low longitudinal strains (0.5-5%). This constant value indeed significantly improved the fit with the experimental data (see Fig. 4), which highlights the importance of the Poisson effect in increasing the stress level in these hybrids. It also indicates that more refined measurements of this Poisson's ratio would be useful. There are, however, experimental challenges in achieving this.

It should be noted that the predictions for the reference composites do not depend on the assumption for the Poisson contraction (see Fig. 4). The Poisson contraction is the same in all layers, and they can hence freely contract without causing an increased longitudinal stress.

The stress level after yielding was higher than predicted by the linear rule-of-mixtures. According to the general definition in Swolfs et al. [22], this effect can be considered as a positive hybrid effect. This effect can however be captured with the more refined predictions of CLT. Whether this can rightfully be called a hybrid effect is therefore open to debate.

4.2 Impact resistance

The absolute penetration impact resistance is summarised in Fig. 6a. The reference steel/PP has an excellent impact resistance of 68 J/mm. This value is much higher than the 28 J/mm for SRPP, which is still a rather high value. The hybrids have an intermediate impact resistance, with the “hybrid: steel outside” hybrid having the highest one. This difference between “hybrid: steel distributed” and “hybrid: steel inside” is statistically significant with a p-value of 4%, but not statistically significant with a p-value of 13% “hybrid: steel distributed” and “hybrid: steel outside”.

It should be noted that the literature on hybrid composites has found that placing the high elongation plies more towards the outside of the laminate improves the penetration impact resistance [22]. This finding however does not directly apply to the hybrids under investigation here, as their tensile failure strains are nearly the same. The statement can therefore be refined to: “placing the toughest plies more towards the outside of the laminate improves the penetration impact resistance”. With this way of phrasing it, the statement applies to the experimental results (see Fig. 6a).

The global picture changes when the absolute penetration impact resistance is divided by the material density. This specific penetration impact resistance was 16 MJ.mm²/kg for the steel fibre composites, whereas the corresponding value for SRPP was 31 MJ.mm²/kg. The “hybrid: steel outside” outperformed the reference steel/PP. Due to the large standard deviation, this difference was not statistically significant with a p-value of 25%.

Figure 6: The penetration impact resistance of reference materials and their hybrids: (a) in absolute terms, and (b) in specific terms. The error bars indicate the 95% confidence intervals.

The question arises where these layup-dependent differences in the impact resistance are coming from. This was investigated by analysing the failure surfaces of the impacted samples (see Fig. 7). This analysis revealed clear differences, not only between the reference materials but also between the hybrids. Steel fibre/PP absorbs a large amount of energy due to the large plastic deformation of its fibres (see Fig. 7a). SRPP on the other hand absorbs energy through tape debonding and fibrillation (see Fig. 7e) [5].

Figure 7: Photographs of the fracture surface of the impacted samples: (a) Reference steel/PP, (b) hybrid: steel distributed, (c) hybrid: steel outside, (d) hybrid: steel inside, and (e) reference SRPP.

The hybrids absorb energy through a combination of plastic deformation of the steel fibres and tape debonding/fibrillation. The relative importance of these contributions however changes depending on the layup. The “hybrid: steel inside” limits the plastic deformation of the steel fibres, as the inner steel/PP layers are closer to the neutral line and are constrained by the outer SRPP layers (see Fig. 7e). This limits the energy absorption of the plastic fibres and hence that of the hybrid in general. Placing the SRPP plies on the inside can also lower the energy absorption potential of those plies in the “hybrid: steel outside”. However, the steel/PP layers have a larger energy absorbing potential (68 J/mm) than SRPP layers (28 J/mm), implying that placing steel/PP on the outside leads to a higher energy absorption in a hybrid. This is confirmed by the experiments (see Fig. 6).

The “hybrid: steel distributed” is in between both behaviours (see Fig. 7b). This hybrid reveals more plastic deformation than the “hybrid: steel inside” hybrid, but not as much as for the “hybrid: steel outside” hybrid. Nevertheless, it absorbed the least energy of the three hybrid layups (see Fig. 6). The SRPP layers prevent the steel fibres from using their full plastic deformation potential, whereas the steel fibre/PP layers hamper the delamination of the SRPP layers and fibrillation of the PP tapes. These effects are the strongest when the layers are distributed the most. This explains the lower impact resistance of the “hybrid: steel distributed”, as it has the most intimate dispersion of the layers.

5 Conclusion

The first hybrid composite consisting of two ductile materials was investigated by hybridising steel fibres with SRPP. By adding steel fibres, the SRPP stiffness and yield stress was increased by a factor of 5 and 3, respectively. Despite the high steel fibre density, the specific modulus and tensile strength were still increased by a factor of about 2. The layup had a limited influence on the tensile behaviour of the hybrids. The hybrids displayed a stress level and slope after yielding that was higher than predicted by volume averaging using the linear rule-of-mixtures. This effect was explained and predicted based on the difference in Poisson contractions of both materials.

The penetration impact resistance of the hybrids was improved compared to SRPP, but only if the steel fibres were on the outside of the layup. In this configuration, the full plastic potential of the steel fibres could be exploited. The specific penetration impact resistance of the hybrids was close to that of the steel fibre/PP reference, but about 2 times lower than that of the SRPP reference.

Future work should include studying the flexural and fatigue behaviour. The potential improvements in flexure are even larger than in tension and impact. This hybrid composite could also possess excellent fatigue properties, but this has not even been reported for the steel fibre composite on its own.

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7 References

- [1] De Greef N, Gorbatiikh L, Godara A, Mezzo L, Lomov SV, Verpoest I. The effect of carbon nanotubes on the damage development in carbon fiber/epoxy composites. *Carbon*. 2011;49(14):4650-4664.
- [2] Li L, Lomov SV, Yan X. Correlation of acoustic emission with optically observed damage in a glass/epoxy woven laminate under tensile loading. *Composite Structures*. 2015;123:45-53.
- [3] Tang YH, Ye L, Zhang Z, Friedrich K. Interlaminar fracture toughness and CAI strength of fibre-reinforced composites with nanoparticles - A review. *Composites Science and Technology*. 2013;86:26-37.

- [4] Hsieh TH, Kinloch AJ, Masania K, Lee JS, Taylor AC, Sprenger S. The toughness of epoxy polymers and fibre composites modified with rubber microparticles and silica nanoparticles. *Journal of Materials Science*. 2010;45(5):1193-1210.
- [5] Swolfs Y, Van den fonteyne W, Baets J, Verpoest I. Failure behaviour of self-reinforced polypropylene at and below room temperature. *Composites Part A: Applied Science and Manufacturing*. 2014;65:100-107.
- [6] Ward IM, Hine PJ. The science and technology of hot compaction. *Polymer*. 2004;45(5):1413-1427.
- [7] Swolfs Y, Zhang Q, Baets J, Verpoest I. The influence of process parameters on the properties of hot compacted self-reinforced polypropylene composites. *Composites Part A: Applied Science and Manufacturing*. 2014;65:38-46.
- [8] Callens MG, Gorbatiikh L, Bertels E, Goderis B, Smet M, Verpoest I. Tensile behaviour of stainless steel fibre/epoxy composites with modified adhesion. *Composites Part A: Applied Science and Manufacturing*. 2015;69:208-218.
- [9] Callens MG, Gorbatiikh L, Verpoest I. Ductile steel fibre composites with brittle and ductile matrices. *Composites Part A: Applied Science and Manufacturing*. 2014;61:235-244.
- [10] Allaer K, De Baere I, Lava P, Van Paepegem W, Degrieck J. On the in-plane mechanical properties of stainless steel fibre reinforced ductile composites. *Composites Science and Technology*. 2014;100:34-43.
- [11] Callens MG, De Cuyper P, Gorbatiikh L, Verpoest I. Effect of fibre architecture on the tensile and impact behaviour of ductile steel fibre polypropylene composites. *Composite Structures*. 2014;119:528-533.
- [12] Czél G, Wisnom MR. Demonstration of pseudo-ductility in high performance glass/epoxy composites by hybridisation with thin-ply carbon prepreg. *Composites Part A: Applied Science and Manufacturing*. 2013;52:23-30.
- [13] Dong C, Sudarisman, Davies IJ. Flexural Properties of E Glass and TR50S Carbon Fiber Reinforced Epoxy Hybrid Composites. *Journal of Materials Engineering and Performance*. 2013;22(1):41-49.
- [14] Pandya KS, Veerajulu C, Naik NK. Hybrid composites made of carbon and glass woven fabrics under quasi-static loading. *Materials & Design*. 2011;32(7):4094-4099.
- [15] Enfedaque A, Molina-Aldareguia JM, Galvez F, Gonzalez C, Llorca J. Effect of Glass Fiber Hybridization on the Behavior Under Impact of Woven Carbon Fiber/Epoxy Laminates. *Journal of Composite Materials*. 2010;44(25):3051-3068.
- [16] González EV, Maimí P, Sainz de Aja JR, Cruz P, Camanho PP. Effects of interply hybridization on the damage resistance and tolerance of composite laminates. *Composite Structures*. 2014;108:319-331.
- [17] Fernando G, Dickson RF, Adam T, Reiter H, Harris B. Fatigue behavior of hybrid composites Part 1 Carbon-kevlar hybrids. *Journal of Materials Science*. 1988;23(10):3732-3743.
- [18] Sayer M, Bektas NB, Callioglu H. Impact Behavior of Hybrid Composite Plates. *Journal of Applied Polymer Science*. 2010;118(1):580-587.
- [19] Fiore V, Valenza A, Di Bella G. Mechanical behavior of carbon/flax hybrid composites for structural applications. *Journal of Composite Materials*. 2012;46(17):2089-2096.
- [20] Dhakal HN, Zhang ZY, Guthrie R, MacMullen J, Bennett N. Development of flax/carbon fibre hybrid composites for enhanced properties. *Carbohydr Polym*. 2013;96(1):1-8.
- [21] Kretsis G. A review of the tensile, compressive, flexural and shear properties of hybrid fibre-reinforced plastics. *Composites*. 1987;18(1):13-23.

- [22] Swolfs Y, Gorbatiikh L, Verpoest I. Fibre hybridisation in polymer composites: a review. *Composites Part A: Applied Science and Manufacturing*. 2014;67:181-200.
- [23] Hayashi T. On the improvement of mechanical properties of composites by hybrid composition. *Proc 8th Intl Reinforced Plastics Conference*. 1972:149-152.
- [24] Zweben C. Tensile strength of hybrid composites. *Journal of Materials Science*. 1977;12(7):1325-1337.
- [25] Swolfs Y, McMeeking RM, Gorbatiikh L, Verpoest I. The effect of fibre dispersion on initial failure strain and cluster development in unidirectional carbon/glass hybrid composites. *Composites Part A: Applied Science and Manufacturing*. 2015;69:279-287.
- [26] Pegoretti A, Fabbri E, Migliaresi C, Pilati F. Intraply and interply hybrid composites based on E-glass and poly(vinyl alcohol) woven fabrics: tensile and impact properties. *Polymer International*. 2004;53(9):1290-1297.
- [27] Swolfs Y, Meerten Y, Hine PJ, Ward IM, Verpoest I, Gorbatiikh L. Introducing ductility in hybrid carbon fibre/self-reinforced composites through control of the damage mechanisms. *Composite Structures*. 2015;131:259-265.
- [28] Swolfs Y, Crauwels L, Van Breda E, Gorbatiikh L, Hine P, Ward I, et al. Tensile behaviour of intralayer hybrid composites of carbon fibre and self-reinforced polypropylene. *Composites Part A: Applied Science and Manufacturing*. 2014;59:78-84.
- [29] Verpoest I, Lomov S, Swolfs Y, Jacquet P, Michaud V, Manson J-A, et al. Advanced materials enabling high-volume road transport applications of lightweight structural composite parts. *Sampe J*. 2014;50(3):30-37.
- [30] Swolfs Y, Shi J, Meerten Y, Hine P, Ward I, Verpoest I, et al. The importance of bonding in intralayer carbon fibre/self-reinforced polypropylene hybrid composites. *Composites Part A: Applied Science and Manufacturing*. 2015;76:299-308.
- [31] Múgica JI, Aretxabaleta L, Ulacia I, Aurrekoetxea J. Impact characterization of thermoformable fibre metal laminates of 2024-T3 aluminium and AZ31B-H24 magnesium based on self-reinforced polypropylene. *Composites Part A: Applied Science and Manufacturing*. 2014;61:67-75.
- [32] Carrillo JG, Cantwell WJ. Mechanical properties of a novel fiber-metal laminate based on a polypropylene composite. *Mechanics of Materials*. 2009;41(7):828-838.
- [33] Mosse L, Compston P, Cantwell WJ, Cardew-Hall M, Kalyanasundaram S. The effect of process temperature on the formability of polypropylene based fibre-metal laminates. *Composites Part A: Applied Science and Manufacturing*. 2005;36(8):1158-1166.
- [34] Iriondo J, Aretxabaleta L, Aizpuru A. Characterisation of the elastic and damping properties of traditional FML and FML based on a self-reinforced polypropylene. *Composite Structures*. 2015;131:47-54.
- [35] Debruyne R. Bundle drawn metal fibers. *Advanced Materials & Processes*. 1995;147(6):33-34.
- [36] Swolfs Y, Crauwels L, Gorbatiikh L, Verpoest I. The influence of weave architecture on the mechanical properties of self-reinforced polypropylene. *Composites Part A: Applied Science and Manufacturing*. 2013;53:129-136.
- [37] Wolfrath J, Michaud V, Modaressi A, Manson JAE. Unsaturated flow in compressible fibre preforms. *Composites Part A: Applied Science and Manufacturing*. 2006;37(6):881-889.
- [38] Lomov SV, Verpoest I, Cichosz J, Hahn C, Ivanov DS, Verleye B. Meso-level textile composites simulations: Open data exchange and scripting. *Journal of Composite Materials*. 2014;48(5):621-637.