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Effect of fibre architecture on the tensile and impact behaviour of ductile stainless steel fibre polypropylene composites

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ABSTRACT

The high stiffness (∼193 GPa) and high strain-to-failure (∼20%) of annealed stainless steel fibres present an opportunity to design ductile structural composites. In this research, the effect of the weave architecture on the tensile and impact behaviour of ductile stainless steel fibre/PP composites is investigated. Composites with three different weave architectures are compared: a quasi-unidirectional weave, a basket weave and a satin weave. The tensile test results show that all weave architectures show the same composite strain-to-failure, despite the difference in crimp. The composite with the basket weave (high crimp) has much lower stiffness and yield stress in comparison with the other two composites. This is attributed to significant out-of-plane deformations observed during the tensile test. The penetration impact results show that the high ductility of stainless steel fibre composites in tensile tests is transferred into excellent impact performance.

1. Introduction

The strain-to-failure of polymer composites reinforced with continuous fibres is intrinsically dependent on the deformation of the fibres. Composites can be made tougher by using more ductile fibres. Traditional fibres like carbon and glass fibres, however, have limited ductility: their strain-to-failure is in the range of 1.5–4%. Other fibres like polymeric [1,2] and natural fibres (i.e. silk, coconut [3,4]) can offer higher strain-to-failure (15–30%) but at the expense of much lower stiffness (<30 GPa), which limits their use in structural applications.

When both high stiffness and high ductility are targeted, stainless steel fibre has no equal. Its strain-to-failure can be altered with a heat treatment without affecting its stiffness. The stiffness of stainless steel fibre is around 193 GPa, which is close to the stiffness of carbon fibre, while its strain-to-failure can be increased till 20%, which is 10 times higher than the strain to failure of carbon fibre. Previous research [5–7] showed that stainless steel fibre composites also have a high strain-to-failure (±7%) even when they are combined with brittle matrices like epoxy. The strain-to-failure can be further increased to ±13% by choosing a more ductile matrix [5]. The density of steel fibres is, however, much higher than the density of carbon or glass fibres. From simple calculations, one can estimate that in terms of the specific stiffness steel fibre composites would be comparable to glass fibre composites, but in no competition to carbon fibre composites, unless the added value of their high ductility is also taken into account. In weight sensitive applications hybrids of carbon and steel fibres could provide a solution to add the ductility with a limited density increase.

The research on stainless steel fibre composites up to now dealt only with unidirectional (UD) and cross-ply composites [5–7]. However, fibre architecture can have a major influence on the composite performance. It may change processing performance such as drapability and permeability, but also mechanical performance such as impact resistance, damage tolerance and fatigue life. When comparing a UD fibre architecture with a woven fibre architecture, the main differences are the crimp of the fibres and the interweaving of the yarns. The presence of the crimp is expected to reduce the composite stiffness due to the local fibre mis-orientation and the interweaving of the yarns may change the damage behaviour, both in tensile [8,9] and impact tests.

A higher strain-to-failure of a composite in a quasi-static tensile test is often an indication of better impact properties. The impact performance can be understood and characterized in different ways: as damage tolerance (residual strength after impact), damage resistance (impact energy needed to induce damage) and energy absorption during penetration. Two review papers on impact properties of composites [10,11] state that the ability of the fibres to store energy appears to be the fundamental parameter in determining penetration impact resistance of a composite. Thus, fibres with a large area under the stress–strain curve and hence a

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large energy-to-failure should offer excellent energy absorption during penetration. In the case of stainless steel fibre, this area is more than three times higher than for carbon fibre.

The effect of the fibre architecture on the impact performance of conventional carbon and glass fibre-reinforced composites has been extensively studied. Vallons et al. [12] compared the impact and post-impact behaviour of composites with woven and non-crimp fabrics. It was found that the damage area after the drop weight impact was more localized in the composite with the woven fabric. This was attributed to the crimp of the fibres, where it is known that more energy is required to propagate delaminations during impact due to a wavy crack path and crack deflections. Because of the smaller damage area, the composite with the woven fabric performed better in a post-impact tensile–tensile fatigue test. It was, thus, concluded that the damage resistance could be increased by using a fabric with a higher crimp.

Shyr et al. [13] investigated energy absorption during penetrating impact for composites with non-crimp and woven fabrics. A higher energy absorption was reported for the non-crimp fabric. Thus, for energy absorption during penetration, a fabric with a lower crimp or no crimp is preferred.

In the present work, the tensile and impact behaviour of composites with novel stainless steel fibres in combination with polypropylene matrix are investigated. Three different stainless steel fibre architectures with three levels of crimp are chosen: a quasi-unidirectional (Q-UD) structure stacked in (0,90)s, a satin weave structure and a basket weave. The goal of this research is to understand the influence of the fibre architecture on the mechanical properties in both a quasi-static tensile test and a drop weight impact test. The latter focuses only on energy absorption during penetration, since the ductility of the stainless steel fibres is most used in this case.

2. Materials and methods

2.1. Raw materials

Three stainless steel fibre architectures were chosen for the study: a quasi-unidirectional structure consisting of stainless steel fibre weft yarns and thin polyester warp yarns (to be referred as Q-UD weave); a 2×2 basket weave and a satin weave (see Table 1). These materials were supplied by NV Bekaert SA (Belgium) with the same type of annealed stainless steel fibre as in [5]. Areal densities and additional information about the materials are provided in Table 1. An important difference between the architectures is the weave pattern and thus the amount of crimp. The basket weave has a very high crimp (i.e. the length of the yarn is ±5% longer than the length of the unit cell), the satin weave has a lower crimp (±0,5%) and the Q-UD has no crimp. As a result, the basket weave has the highest stability and the Q-UD the lowest. The polypropylene (PP) matrix was supplied in films of 50 µm thickness (Ineos 100-GA02).

2.2. Composite production

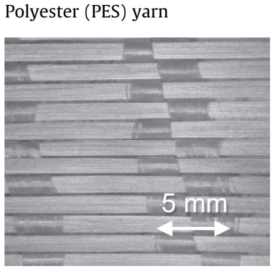
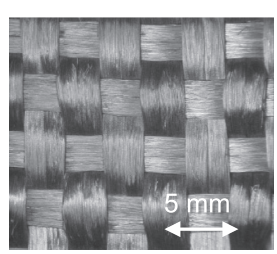
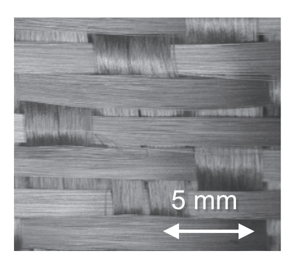
All composites in the study were produced using hot pressing. Stainless steel fibre fabrics and PP films were alternately stacked. The number of fabric layers and PP films are listed in Table 2. The lay-up is fed into a heated press and compacted with a pressure of 50 bar during 5 min at 186 °C. During this process, stainless steel fibres are impregnated with PP. After compaction, the laminates are cooled at 40 °C/min under 50 bar pressure. Table 2 provides additional information about the composites produced. The stainless steel fibre volume fraction was determined using two approaches: (1) calculated based on the laminate thickness and the fabric areal density and (2) measured using a matrix burn-off test according to ASTM D2584 standard. The quality of the produced laminates was investigated using optical microscopy. All laminates were found to have high quality impregnation with no voids or other defects detected (Fig. 1).

2.3. Experimental methodology

The composites were tested under quasi static tensile loading. The tests were performed according to ASTM D3039 on an Instron 4505. The displacement was controlled (2 mm/min) and the loading was measured using a 100 kN load cell. The strains were measured using an extensometer. The sample width and gauge length were 25 mm and 150 mm, respectively. No end tabs were used.

The stiffness was measured from 0% till 0,1% of strain, not as required by the standard (between 0,1% and 0,3%). This was done because of the early yielding of the stainless steel fibres. At 0,4% of the measured strain they already showed 0,2% of plastic strain.

Table 1
The three different fibre architectures investigated in this research.

	Q-UD weave	Basket weave	Satin weave
Areal weight	1425 g/m^2	2480 g/m^2	1455 g/m^2
Weft yarn	275 stainless steel fibres	2×275 stainless steel fibres	275 stainless steel fibres
Warp yarn	Polyester (PES) yarn	2×275 stainless steel fibres	275 stainless steel fibres
Image			
WiseTex model