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Ductile steel fibre composites with brittle and ductile matrices

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ABSTRACT

Due to the intrinsic brittleness of high performance fibres, traditional structural fibre-reinforced composites have limited ductility and toughness. In the present work a new class of fibres is explored for the reinforcement of polymers: continuous stainless steel fibres that simultaneously possess a high stiffness and a high strain-to-failure. The fibres are combined with brittle and ductile matrix systems (epoxy and PA-6) to produce unidirectional and cross-ply composites. The composites are investigated in quasi static tensile tests accompanied with acoustic emission registration. The steel fibre composites are found to exhibit a 3–4 times higher strain-to-failure than typical carbon or glass fibre composites.

1. Introduction

The strain-to-failure of structural fibre-reinforced polymers like carbon or glass fibre composites is known to be low. The reason for this is the brittleness of the fibres. The composite ductility and overall toughness can be enhanced by choosing fibres that have a higher strain-to-failure. This has already been proven in such systems as metal fibre reinforced ceramics, metal fibre reinforced metals and short ductile fibre reinforced polymers [1–3]. In polymer composites reinforced with continuous fibres the choice of ductile fibres is currently limited to either polymeric fibres (i.e. polyethylene), natural fibres (i.e. silk, coconut [4,5]) or regenerated cellulose [6]. The high toughness of these fibres, however, comes at the expense of a low stiffness, which limits their use in structural applications.

Recently a new class of stiff but ductile fibres became available for application in structural composites: annealed stainless steel fibres (diameter of 5–100 μm) which exhibit both high stiffness and high strain-to-failure. The stiffness of such a steel fibre is almost as high as that of a carbon fibre (193 GPa), and the strain-to-failure is as high as that of a silk fibre (up to 20%). Moreover, the strain-to-failure of such a steel fibre can be tailored by altering its heat treatment with no effect on the stiffness.

Steel itself is not a new reinforcing material. It is successfully used in tyres and conveyor belts in the form of continuous wires to reinforce rubber [7–12] and in the form of cords and filaments for reinforcement of concrete [13–15]. In these applications, steel wires or filaments with a diameter of about 150 μm or higher are typically made of high carbon steel that has a high strength but limited ductility in the as-drawn state. The benefit of steel in these applications is in increasing the stiffness and strength of the base material, namely rubber or concrete.

An example, in which steel cords are used for their ductility, is the EASI (Energy, Absorption, Safety, Integrity) material [16,17], developed by Bekaert NV (Belgium). In the EASI concept, steel cords are used to reinforce glass fibre thermoplastic composites used in structural crash components such as car bumpers. Similarly to the previous examples, steel wires used in this application have a large diameter that is typically above 100 μm.

Continuous stainless steel fibres with a diameter below 100 μm are not yet commercially used as reinforcement in polymer composites. Currently, their use is limited to other applications. For example, they are employed in filters for liquid filtration [18,19], as a heat resistant separation material in the process of glass shaping for automobile windows [20,21] and as anti-static or cut-resistant textiles [22–25] (Bekinox multifilament yarns). Steel fibres can also be incorporated inside plastics for EMI shielding (Bekishield [26]). Thus, continuous steel fibres are mainly exploited for their thermal/electrical/magnetic properties.

The scientific literature that describes the use of steel fibres as a reinforcing material in polymer composites is very limited. In the case of short-fibre reinforced composites, Sabino-Netto et al. [27] reported the friction properties of short steel fibre/epoxy composites. Steel fibres used in their research were 45 μm in diameter and on average 455 μm in length, the type of steel used was not men-

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tioned. Zou et al. [28] investigated mechanical properties of HA–$ZrO_2(CaO)$ ceramic biomaterial reinforced with stainless steel fibres of 40–50 μm in diameter and 0.8–2 mm in length. The authors reported an increase in toughness with an increase in the fibre volume fraction. In the case of continuous steel fibre composites, Ahmed [29] reported an improved impact performance when stainless steel fibres (100 μm in diameter) were added to a glass fibre/epoxy laminate. An improved impact performance was also reported in Clemens [30] where stainless steel fibres (30 μm in diameter) were combined with different matrix systems. In Callens et al. [31–35] authors of the current work reported preliminary results on the tensile properties of steel fibre reinforced composites.

The current study focuses on the tensile behaviour of composites made of ductile continuous aligned stainless steel fibres. The steel fibres are impregnated with matrices of different ductility and their tensile behaviour is investigated for uni-directional (UD) and cross-ply laminates. The failure behaviour of these composites is of particular interest.

2. Materials and methods

2.1. Raw materials

The reinforcement is a quasi UD woven structure consisting of steel fibre warp yarns (each containing 550 untwisted fibres) and thin polyethylene terephthalate (PES) weft yarns (Fig. 1). The areal density of the fabric is 1905 g/m^2. The reinforcement is supplied by NV Bekaert SA. The steel fibres have a diameter of 30 μm and are made of a 316 stainless steel alloy. The steel fibres are produced using a bundle drawing technique, in which multiple steel wires are combined in a copper matrix and subsequentally drawn to smaller diameters [36]. Mechanical properties of the steel fibre are reported in Table 1, along with a representative tensile stress–strain curve (Fig. 2a) (sourced by NV Bekaert SA). The fibres were annealed at >800 °C to ensure a high strain-to-failure.

Two matrix systems that differ in ductility are chosen for the study. The brittle system is an Epikote 828LVEL (a Bisphenol-A type) epoxy, with a 1,2-diaminocyclohexane (Dytek DCH-99) as hardener in weight ratio 100 and 15.2 respectively. Its mechanical properties are presented in Table 1 along with the tensile stress–strain curve in Fig. 2b. The ductile matrix system is a polyamide 6 from EMS-Griltech (Grilon ELX 50HNZ) with a melting point of 220 °C (Table 1 and Fig. 2b).

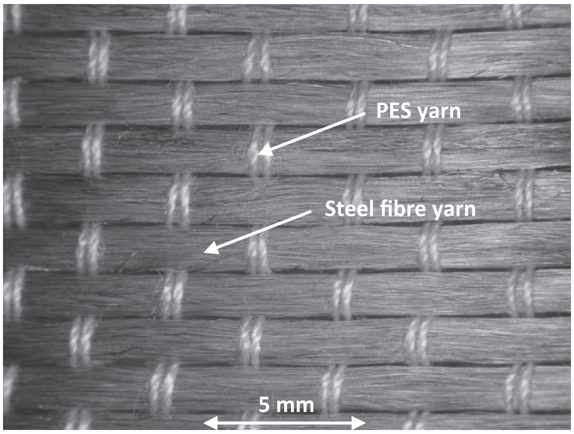

Fig. 1. Photograph of the quasi UD woven steel fabric.

Table 1
Mechanical properties of the annealed stainless steel fibres and the matrix systems.

	Fibre	Matrix	
	Stainless steel	Epikote 828LVEL	Polyamide 6
Young's modulus, E	193 GPa	2.9 GPa	0.7 GPa
Strength, σ	660 MPa	75 MPa	22 MPa
Strain-to-failure, ε	17%	4%	250%
Yield strength (0,2%), ε_{yield}	365 MPa		
Weibull modulus	29		
Weibull scale parameter	674 MPa		

2.2. Production of the composite plates

Composite plates with the epoxy matrix were produced using the vacuum assisted resin infusion technique. Three layers of the quasi UD steel fibre fabric were stacked for the UD laminate. Four layers were stacked for the cross-ply laminate in $(0.90)_s$ configuration, in order to realise a symmetric laminate. In the case of the epoxy matrix, the impregnation was done at 40 °C, curing at 70 °C for 1 h and post-curing at 150 °C for 1 h. The composite plates with the polyamide 6 matrix were produced using the compression moulding technique. For both the UD and cross-ply PA-6 laminates, four layers of the quasi UD steel fibre fabric were stacked with a 300 μm thick PA-6 film in between the fabric layers (three in total). The impregnation was done at 260 °C under pressure of 7 bar for 5 min. The plates were cooled under pressure (±50°/min). These production conditions are not expected to alter the microstructure of the steel fibres as they were annealed at a temperature above 800 °C.

After production a quality control of the composites was performed. Due to the difficult handleability of the fabric, the steel fibre yarns were found to be slightly misoriented during lay-up. The misalignment was measured on the surface for all specimens and is reported together with the results. Examination of the composite cross-sections, using optical microscopy (OM), showed no voids, dry areas or residual cracks (Fig. 3).

The fibre volume fraction of the UD epoxy laminate was estimated using three procedures: (1) a matrix burn-off test according to ASTM D2584 standard, (2) image analysis and (3) calculations based on the fabric areal density and the composite thickness. Good correlation between these techniques was found (Table 2). The fibre volume fraction for all other composites was determined using the third approach (Table 2).

The steel fibres remain in bundles after impregnation. The fibres fit into each other like puzzle pieces, resulting locally in very high fibre volume fractions (Fig. 3b). The average fibre volume fraction measured inside yarns, using image analysis, ranges between 55% and 65%. As shown in Fig. 3, the fibres have irregular hexagonal cross-sections. Being drawn in bundles, they plastically deform to fit an approximate hexagonal packing. Using SEM it could be confirmed that even closely packed fibre bundles were well impregnated with no sign of voids or dry areas (Fig. 4).

2.3. Experimental methodology

The produced composites were tested under quasi static tensile loading. The tests were performed according to ASTM D3039 on an Instron 4505 machine. The displacement was applied at 2 mm/min, the load was recorded using a 100 kN load cell and the strain was measured using an extensometer. The strain interval for calculation of the composite stiffness was chosen differently than recommended in the standard. This adjustment was done because of the low yield strain of the composite (0.4%). An interval within