Composites Science and Technology 143 (2017) 13–21

Contents lists available at ScienceDirect

Composites Science and Technology

journal homepage: http://www.elsevier.com/locate/compscitech

Aligned discontinuous intermingled reclaimed/virgin carbon fibre composites for high performance and pseudo-ductile behaviour in interlaminated carbon-glass hybrids

Marco L. Longana*, HaNa Yu, Meisam Jalavand, Michael R. Wisnom, Kevin D. Potter

ACCIS, University of Bristol, Bristol, BS8 1TR, UK

ARTICLE INFO

Article history:
Received 5 December 2016
Received in revised form
22 February 2017
Accepted 27 February 2017
Available online 28 February 2017

Keywords:
Recycling
Short-fibre composites
Hybrid composites

ABSTRACT

Highly aligned intermingled fibre composites are produced from reclaimed and virgin carbon fibres using the High Performance Discontinuous Fibre (HiPerDiF) method. The stiffness and strength characteristics of these materials are studied as a function of the reclaimed to virgin fibres ratio. Interlaminated hybrid composites with discontinuous carbon fibre preforms sandwiched between continuous glass fibres are designed to demonstrate pseudo-ductility and allow investigation of the effect of the mixing ratio of reclaimed and virgin carbon fibres on the nonlinear stress-strain curve shape. The pseudo-ductile behaviour is explained by adapting the Damage Mode Map to describe the failure process of interlaminated hybrid specimens with different low elongation material strength. It is concluded that the HiPerDiF method is a valuable platform to remanufacture reclaimed carbon fibres into a high performance and potentially economical value recycled composite material. The Damage Mode Maps can be used to optimise the pseudo-ductile response of the interlaminated hybrid material.

1. Introduction

The wide spread of carbon fibres reinforced polymers (CFRPs) in various engineering and industrial sectors over the last decades poses the challenge of dealing with production waste and end-of life products, particularly if we consider that carbon fibres preserve high intrinsic value. The simple disposal in landfill or incineration are increasingly discouraged by the legislation. The mechanical comminution of CFRP and the dispersion of the chopped fibres as fillers in replacement for glass fibres limit the derivable value. In order to apply the circular economy model to composite materials, recycling processes that will allow reclaiming the fibres with minimal loss of mechanical properties and remanufacturing them into high performance materials need to be developed and integrated. A complete review about the technologies to recycle CFRPs for structural applications was presented by Pimenta and Pinho [1]. Amongst the fibre reclamation processes it is worth mentioning pyrolysis, i.e. thermochemical decomposition of the matrix at elevated temperatures in an inert environment [2], oxidation in a fluidised bed, i.e. the matrix elimination at high temperature in oxygen-rich flow [3], chemical recycling in various reactive media at moderate temperature, e.g. catalytic solutions [4], benzyl alcohol [5], or at higher temperature and pressure in supercritical fluids [6–9].

Of greater interest for the presented work is, independently from the fibre recovery process, the remanufacturing of the reclaimed fibres into CFRP and their mechanical response. When the reclamation process preserves the reinforcement architecture of the waste the reclaimed fibres can be used as it is [10]. However, the size-reduction of CFRP waste before reclamation, the fibre breakage during reclamation and the chopping of the fibres after reclamation lead to fibres that are fragmented to short lengths. As a result, the only industrially relevant remanufacturing processes for reclaimed fibres so far are direct moulding techniques, e.g. injection moulding [11] and bulk moulding compound compression [12], and the compression moulding of intermediate random [13] or aligned mats [14]. However, to deliver improved recycled materials, a high fibre alignment is the key factor to increase the fibre volume fraction, and consequently the performances of recycled composites [15,16]. Various techniques, already used for the alignment of short fibres, have been taken in consideration for the remanufacturing of reclaimed carbon fibres. A modified papermaking technique was applied to reclaimed fibres from the University of Nottingham

* Corresponding author.
E-mail address: m.l.longana@bristol.ac.uk (M.L. Longana).

http://dx.doi.org/10.1016/j.compscitech.2017.02.028
0266-3538/

research group [14,17,18] reaching 80% of the theoretical alignment value and a fibre volume fraction of 45% with a moulding pressure of 100 bar. Wong et al. [19] proposed the use of a centrifugal alignment rig, which uses a dispersion of fibres in a viscous media accelerated through a convergent nozzle installed in a rotating drum, as remanufacturing technique for reclaimed carbon fibres. An alignment level of 90% was obtained using 5 mm fibres. The same authors [19] worked on a hydrodynamic spinning process of a viscous fibre suspension. Janney et al. [20] developed the Three Dimensional Engineered Preform Process (3-DEP) adding multiple motions control to a pulp moulding process tool and therefore the control of fibre areal weight and orientation.

The HiPerDiF method, developed at the University of Bristol [21], has proven to be an effective way to manufacture composite materials with high levels of alignment from discontinuous fibres. This unique fibre orientation mechanism uses the momentum change of a water-fibre suspension to align the fibres. It was previously noted that tensile modulus, strength and failure strain of aligned discontinuous fibre composites produced with the HiPerDiF method were close to those of continuous fibre composites provided that the fibres are accurately aligned and their length is sufficiently long compared to the critical fibre length [22,23]. The use of the HiPerDiF method allows the production of high performance recycled carbon fibre composites from reclaimed discontinuous carbon fibres. Therefore, this method enables the efficient recovery of value from end-of-life components and production wastes, and is well placed in the developing of a supply and processing chain of recycled carbon fibre composites and in a circular economy model, as demonstrated also by Ref. [25].

As described in Ref. [22] the HiPerDiF method can be used to produce hybrid composites with different configurations, these allowed obtaining pseudo-ductile behaviour from glass-carbon and carbon-carbon intermingled composite [23,24], this can be further tailored if intermingled composites are coupled with continuous glass fibres to generate interlaminated composites [24].

The present work is aimed at evaluating the effect of reclaimed fibres on the mechanical properties of intermingled and interlaminated hybrid composites. In a first stage, the performances of intermingled reclaimed and virgin carbon discontinuous fibre (rCF and vCF respectively) composites are assessed. A good knowledge about the mechanical properties of combined reclaimed/virgin carbon fibre composite will help to maximise the use of reclaimed carbon fibres taking account the related economic advantages. Subsequently, plies of intermingled discontinuous fibres, with different ratios of rCF/vCF, are interlayered in continuous glass/epoxy prepreg layers to study the effect on tensile behaviour of carbon/glass hybrid composites.

2. The HiPerDiF method

The HiPerDiF method is a novel technique that allows aligning discontinuous fibres [21,22]. The technique was originally developed to study the behaviour of aligned discontinuous fibre composites as a function of fibre type, length and alignment level within the HiPerDuCT (High Performance Ductile Composite Technology) project [23]. The working principle exploits the sudden momentum change of a jet of fibres suspended in water directed in a narrow gap between parallel plates as shown in Fig. 1.

In the HiPerDiF process, the fibres are dispersed in a liquid medium (water) that is accelerated through a nozzle to partially align the fibres. The fibre suspension jet is directed to the orientation head, which is comprised of parallel plates with a controllable gap. The fibres are aligned transversely to the suspension jet by a sudden momentum change of the liquid, provided that the gap is a maximum of 1/3 the fibre length. Subsequently, the fibres fall on a perforated conveyor belt that is running parallel to the narrow gap direction; a suction plate, placed underneath the belt, removes the water maintaining the fibre orientation. The aligned fibre preform is then dried with infrared radiations to allow the resin impregnation process. This method allowed obtaining highly-aligned and high fibre volume fraction discontinuous CFRPs: for composites with a 41% fibre volume fraction (v_f), 65% of fibres were in the range of ±3°to perfect alignment, and in the case of composite specimens with 55% of v_f, 67% of fibres were in the range of ±3° to perfect alignment [22]. Moreover, using high strength fibres (Young's Modulus 225 GPa, Strength 4350 MPa), mechanical properties comparable to those of continuous fibres were achieved: a Young's Modulus of 80.6 GPa and a strength of 816 MPa for 41% of v_f and a Young's Modulus of 115 GPa and a strength of 1509 MPa for 55% of v_f [22]. In addition, the HiPerDiF method enabled intimately mixing two or more different fibre types in one preform due to its intrinsic manufacturing capabilities [23,24].

One of the exceptional potentials of HiPerDiF technology is that it makes it possible to achieve high mechanical properties and a high value by remanufacturing reclaimed carbon fibres into highly-aligned, high-performances unidirectional composites [24]. These preforms have also the potential to achieve pseudo-ductile behaviour. To do so, two approaches are considered in this paper: (i) intermingled rCF/vCF composites and (ii) interlaminated hybrid composites with an embedded layer of intermingled rCF/vCF sandwiched between continuous glass fibre layers.

3. Experiment

3.1. Materials

High tensile strength virgin carbon fibres (C124, TohoTENAX, [26]) and reclaimed carbon fibres (AS4, Hexcel) from a M56 resin composite with the pyrolysis “cycle B” process defined by Pimenta and Pinho in Ref. [27] were used. The mechanical properties are summarised in Table 1.

The intermingled preforms with rCF/vCF are coupled with a MTM49-3 epoxy resin film [28] and partially impregnated by applying a pressure of 30 bar at a temperature of 60 °C. The mechanical properties of the continuous E- and S-glass composite layers used for the interlaminated hybrid specimens, measured with tensile tests conducted with the specimens shown in Fig. 2, are summarised in Table 2. Please note that these glass/epoxy composites were manufactured in a closed mould and therefore the fibre volume fraction was about 15% higher than one obtained with specimens manufactured on an open tool-plate. For the interlaminated hybrid composites, the rCF/vCF preform was impregnated during the curing process by the resin excess from the continuous glass fibre prepreg.

3.2. Specimen preparation

The specimens were prepared by vacuum bag moulding. The

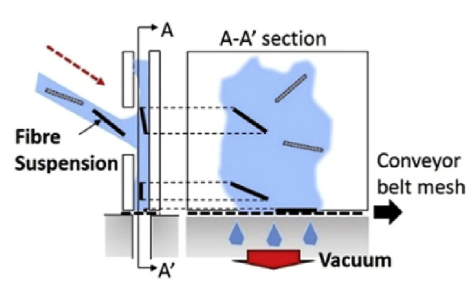

Fig. 1. HiPerDiF fibre alignment mechanism, front view and cross-section (A-A′) [22].