THE HIGH PERFORMANCE DISCONTINUOUS FIBRE (HIPERDIF) METHOD FOR THE REMANUFACTURING OF MIXED LENGTH RECLAIMED CARBON FIBRES

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ABSTRACT

The wide spread of carbon fibres reinforced polymers in various engineering and industrial sectors over the last decades poses the challenge of dealing with production waste and end-of life products. In the case of the thermosetting-based composites, recycling is a two-step process: a reclamation stage, where the fibres are retrieved by degrading the matrix, and a remanufacturing stage to produce a reusable material. Typically, reclamation processes deliver fibres that are fragmented in short length, moreover, these often present a distribution of length and physical or mechanical properties. The HiPerDiF technology allows to deliver commercially valuable and high performance recycled composite materials by remanufacturing the reclaimed fibres into highly aligned discontinuous fibre composites. This paper demonstrates the possibility of simultaneously remanufacture fibres with different lengths. The mechanical properties of the obtained material are characterised with a novel tensile test methodology based on interlaminated hybrid specimens.

1 INTRODUCTION

1.1 Carbon Fibre Reinforced plastic recycling

The wide spread of composite material, and particularly carbon fibre reinforced plastics (CFRPs), in various engineering sectors over the last decades poses the challenge of dealing with production waste and end-of life products. Strict legislations thwart their disposal in landfill by making it uneconomical [1, 2]. However, considering the increasing carbon fibres demand, barely met by the supply, and their high production costs, well-established CFRPs recycling processes would lead to a profitable re-introduction in the market of a raw material that otherwise would represent an expensive waste.

An overview of the fibre reinforced polymers recycling state of the art was proposed by Oliveux et al in [3]. Pimenta and Pinho presented a detailed review of CFRPs recycling technologies and of the commercialisation and potential applications of recycled products [4]. The recycling process of thermosetting based CFRPs can be divided in two stages: the fibre reclamation, i.e. the extraction of the fibres by the degradation of the matrix, and the fibre remanufacturing to obtain an intermediate material or finite products. The fibres can be reclaimed by degrading the matrix with thermal (e.g. pyrolysis [5] and fluidised bed oxidation [6]) or chemical (e.g. solvolysis [7, 8] and supercritical fluids [9-12]) processes.

Of greater interest for the presented work is, independently from the fibre recovery process, the remanufacturing of the reclaimed fibres. When the recycling process preserves the reinforcement architecture of the waste this can be used as it is [13]. However, size-reduction of CFRP waste before reclamation (e.g. for ease of transport or for the separation and extraction of other materials), fibre breakage during reclamation and post-reclamation fibres chopping lead to reclaimed fibres that are usually fragmented in short length. This makes direct moulding techniques (e.g. injection moulding [14] and bulk moulding compound compression [15]) and the compression moulding of intermediate random [16] or aligned mats [17] the most readily applicable remanufacturing techniques. However, to deliver improved recycled materials a high fibre alignment is the key factor to increase the fibre volume fraction, and consequently the performances and value of recycled composites [18, 19]. A modified papermaking technique was developed by Pickering [20], Turner et al. [17] and Warrior et al. [21] reaching 80 % of the theoretical alignment value and a fibre volume of 45 % with a moulding pressure of 100 bar. Wong et al. [22] presented a centrifugal alignment rig, which uses a dispersion of fibres in a viscous media accelerated through a convergent nozzle installed in a rotating drum, capable to process 5 mm long fibres and achieve an alignment level of 90 %. The same authors [22] worked on a hydrodynamic spinning process of a viscous fibre suspension. Janney et al. [23] developed the Three Dimensional Engineered Preform Process (3-DEP) adding multiple motions control to a pulp moulding process tool to control fibre areal weight and orientation. One of the most effective processes able to remanufacture reclaimed fibres is the HiPerDiF method [24].

1.2 The HiPerDiF Methods

The HiPerDiF method (Figure 1), invented at the University of Bristol [24], has proven to be an effective way to manufacture discontinuous fibre composites with high levels of alignment from fibres between 1 and 12 mm in length. The fibres are suspended in water, accelerated through a nozzle and directed in a gap between two parallel plates. The fibre alignment mechanism relies on a sudden momentum change of the fibre-water suspension at the impact with the furthermost plate. The fibres then fall on a conveyor stainless mesh belt where the water is removed by suction. The aligned fibre preform is dried with infrared radiation to allow the resin impregnation process. The dry aligned fibres preform is finally coupled with a resin film and partially impregnated through the application of heat and pressure.

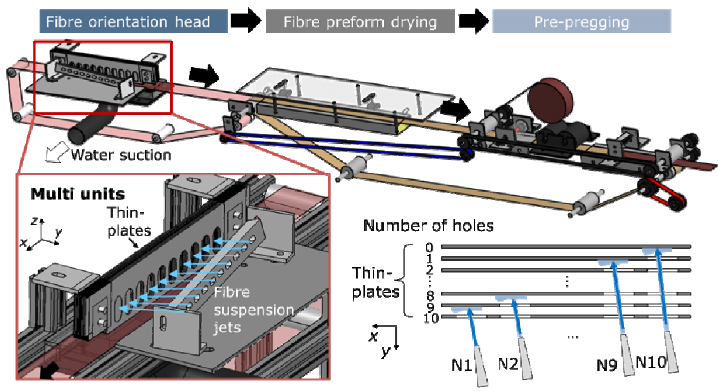

Figure 1: The HiPerDiF fibre alignment machine.

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 [25]. Different types of fibres can be mixed in the water suspension to obtain highly intermingled hybrid composites: glass and carbon fibres were coupled to achieve pseudo-ductile behaviour [26], virgin and reclaimed carbon fibres to control the composite failure properties [27].

The HiPerDiF method is ideally placed in the composite material recycling process as it is capable to remanufacture reclaimed carbon fibres, typically fragmented in short length, filamentised and randomly oriented, into high-performance highly-aligned discontinuous fibre composite. The HiPerDiF has been used to manufacture intermingled reclaimed/virgin carbon fibre composites into high performance materials and interlaminated carbon-glass hybrids with pseudo-ductile behaviour

[28]. Moreover, it has been demonstrated the possibility to use the use the HiPerDiF method to remanufacture multiple times reclaimed carbon fibre in a closed loop recycling process [29].

However, all the previous HiPerDiF research work was conducted using a single fibre length. This is not representative of the real reclaimed carbon fibres feedstock form that is constituted of discontinuous fibres with a variable length distribution. In this paper, the possibility to process carbon fibres of different length with the HiPerDiF method is investigated: intermingled length hybrids, with 3 and 6 mm fibres, are manufactured and tested in tension with the interlaminated specimens methodology presented in [30].

2 MATERIAL & METHODOLOGY

2.1 Materials

As the length distribution of reclaimed carbon fibres is hardly measurable and controllable, chopped high tensile strength virgin carbon fibre (C124, TohoTENAX) are used. As in [30], the aligned carbon fibre preforms were coupled with S-glass epoxy prepreg (SG913, Hexcel). The mechanical properties of the used materials are summarised in Table 1.

Properties		Virgin Carbon Fibres	Continuous Glass Prepreg
Diameter	[μm]	7	-
Length	[mm]	3	-
E_{11}	[GPa]	225	46
Failure σ_{11}	[MPa]	4350	1900
Failure ε_{11}	[%]	1.8	3.7
Ply Thickness	[mm]	~0.07	~0.13

Table 1: Materials properties:

The aligned carbon fibres preforms are impregnated with a 43 gsm resin film (K51, SK Chemicals).

2.2 Specimen Design

The reason for using interlaminate hybrid specimens to test the length hybrids behaviour is to avoid the stress concentration caused by the end-tabs and to be able to better define the failure strain of the internal layer of discontinuous carbon fibres [30]. Damage Mode Maps (DMM), proposed conceptually in [31] and further developed analytically in [32, 33], are an efficient design tool to tailor the material response and customise the stress-strain curve shape of interlaminated hybrid specimens. In this case, the DMM of Figure 2 is drawn to define the ratio between the length hybrid carbon fibres layer and the continuous S-glass layer that allows a single carbon failure and delamination.

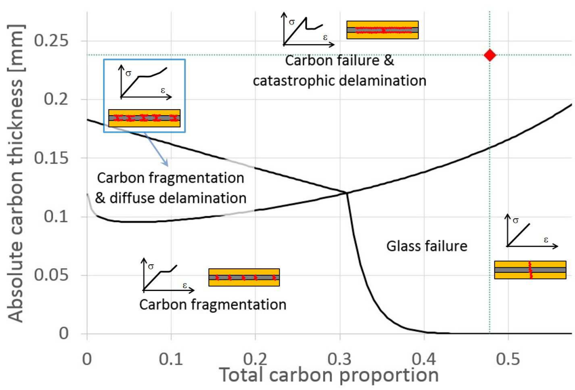

Figure 2: Damage Mode Map for continuous S-glass / discontinuous carbon fibres

From Figure 2 and Table 1 it is possible to select the discontinuous carbon absolute thickness, i.e. the number of dry preform that constitutes the core of the interlaminated hybrid specimen, and the total proportion of carbon, i.e. the number of outer continuous S-glass layer. This approached has been proposed by Czél et al. as a way to suppress the stress concentrations at the grips and protect the central carbon/epoxy plies from premature failure [34]. In this case the $[SG_1/C_4/SG_1]$ lamination sequence, identified on the DMM by the red dot, allows to obtain a single carbon failure followed by delamination.

2.3 Specimen Manufacturing

The glass prepreg plies and dry carbon fibre preforms were laid up with the stacking sequence defined above and placed in a semi-closed mould. This was autoclave cured in a vacuum bag for 135 minutes at a temperature of 135°C and a pressure of 6 bar. After the curing process, the specimens were removed from the mould and burrs at all edges were removed. GFRP end-tabs were bonded with Huntsmann Araldite 2014-1 to obtain the tensile test specimen shown in Figure 3.

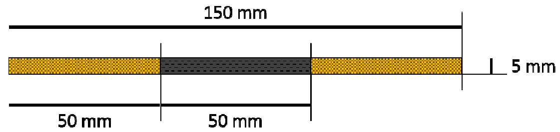

Figure 3: Tensile test specimen geometry.

Five batches of specimens were manufactured with different 3 and 6 mm fibre length ratios: 100% 3 mm, 75% 3mm - 25% 6mm, 50% 3mm - 50% 6mm, 25% 3mm - 50% 6mm and 100% 6mm.

2.4 Mechanical testing

Tensile tests were performed with an electro-mechanical testing machine at a cross-head displacement speed of 1 mm/min. The load was measured with a 10 kN load cell and the strain was measured with a video extensometer. A white speckle pattern over a black background was spray painted on the specimens to allow the strain measurement with a video extensometer.

3 TEST RESULTS

Stress-strain curves representative of the specimens' behaviour with different fibre length ratios are shown in Figure 4.

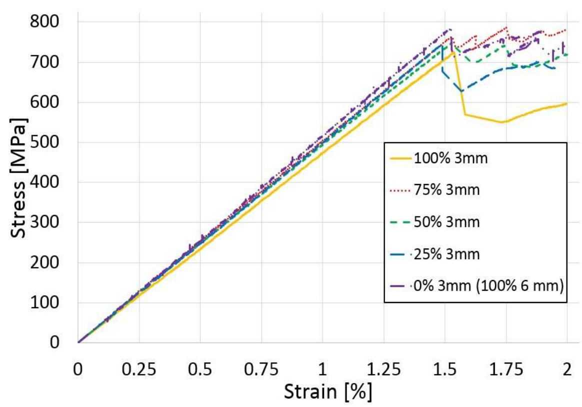

Figure 4: Representative stress-strain curves

It can be observed that the specimens failed as predicted with the DMM. It is therefore possible to unequivocally identify the failure strain of the aligned discontinuous carbon fibres layer. The stiffness and failure strain obtained from the tensile test are presented in Figure 5.

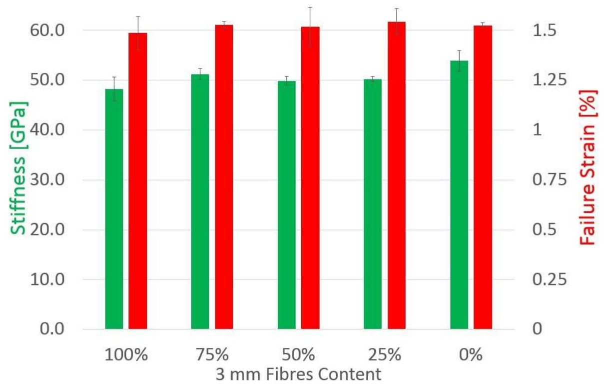

Figure 5: Stiffness and Failure Strain for different fibre length ratios

From Figure 5 it can be observed that the different sets of specimens present the same stiffness and failure strain. This allows to conclude that the specimens have the same fibre volume fraction and therefore fibres alignment level.

4 CONCLUSIONS & FUTURE WORKS

Interlaminated hybrid specimens have been designed and tested to investigate the mechanical properties of aligned discontinuous carbon fibres composites manufactured with fibres of different length. This type of specimens allowed to clearly identify the failure strain for the material and investigate the possibility to process at the same time fibres with different length. The mechanical properties of the manufactured material are independent from the fibre length ratio. This demonstrate that the HiPerDiF technology is compatible with reclaimed fibre feedstocks currently available on the market.

Further investigations, e.g. microscopy and CT scanning, will be carried out to quantify the fibre alignment level and, along with resin burn-off, to directly measure the fibre volume fraction. Moreover, wider and more complex fibre length distributions will be investigated.

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REFERENCES

[1] http://ec.europa.eu/eurostat/web/waste/key-waste-streams/elvs

[2] http://ec.europa.eu/environment/waste/landfill_index.htm

[3] G. Oliveux, L.O. Dandy, G.A. Leeke, Current status of recycling of fibre reinforced polymers: Review of technologies, reuse and resulting properties, Progress in Materials Science, Vol. 72 pp. 61-99, 2015,.

[4] S. Pimenta, S.T. Pinho, Recycling carbon fibre reinforced polymers for structural applications: Technology review and market outlook, Waste Management, Vol. 31, pp. 378-392, 2011.

[5] L.O. Meyer, K. Schulte, E. Grove-Nielsen, CFRP-Recycling Following a Pyrolysis Route: Process Optimisation and Potentials, Journal of Composite Materials, Vol. 43(9), pp. 1121-1132, 2009.

[6] S.J. Pickering, R.M. Kelly, J.R. Kennerley, C.D. Rudd, N.J. Fenwick, A fluidised bed process for the recovery of glass fibres from scrap thermoset composites, Composites Science and Technology, Vol. 60, pp. 509-523, 2000.

[7] R.E. Allred, J.M. Gosau, J.M. Shoemaker, Recycling process for carbon/epoxy composites, SAMPE 2001 Symposium & Exhibition, SAMPE, Longbeach, CA, USA, 2001.

[8] M. Nakagawa, K. Shibata, H. Kuriya, Characterization of CFRP using recovered carbon fibers from waste CFRP, Second International Symposium on Fiber Recycling, The Fiber Recycling 2009 Organizing Committee, Atlanta, Georgia, USA, 2009.

[9] R. Pinero-Hernanz, C. Dodds, J. Hyde, J. Garcia-Serna, M. Poliakoff, E. Lester, M.J. Cocero, S. Kingman, S.J. Pickering, K.H. Wong, Chemical recycling of carbon fibre reinforced composites in nearcritical and supercritical water, Composites Part A, Vol. 39, pp. 454-461, 2008.

[10] R. Pinero-Hernanz, J. Garcia-Serna, C. Dodds, J. Hyde, M. Poliakoff, M.J. Cocero, S. Kingman, S.J. Pickering, E. Lester, Chemical recycling of carbon fibre composites using alcohols under subcritical and supercritical conditions, Journal of Supercritical Fluids, Vol. 46, pp. 83-92, 2008.

[11] G. Jiang, S.J. Pickering, E.H. Lester, T.A. Turner, K.H. Wong, N.A. Warrior, Characterisation of carbon fibres recycled from carbon fibre/epoxy resin composites using supercritical n-propanol, Composite Science and Technology, Vol. 69, pp. 192-198, 2009.

[12] M. Goto, Chemical recycling of plastics using sub- and supercritical fluids, Journal of Supercritical Fluids, Vol. 47, pp. 500-507, 2009.

[13] J. Meredith, The role of recycled carbon fibre composites in motorsport applications, Carbon Fibre Recycling and Reuse 2009 Conference, IntertechPira, Hamburg, Germany, 2009.

[14] K.H. Wong, S.J. Pickering, T.A. Turner, N.A. Warrior, Compression moulding of a recycled carbon fibre reinforced epoxy composite, SAMPE'09 Conference, SAMPE, Baltimore, MD, USA, 2009.

[15] S.J. Pickering, Recycling technologies for thermoset composite materials - current status, Composites Part A, Vol. 37, pp. 1206-1215, 2006.

[16] M. Szpieg, M. Wysocki, L.E. Asp, Reuse of polymer materials and carbon fibres in novel engineering composite materials, Plastics, Rubber and Composites, Vol. 38, pp. 419-425, 2009.

[17] T.A. Turner, S.J. Pickering, N.A. Warrior, Development of high value composite materials using recycled carbon fibre, SAMPE'09 Conference, SAMPE, Baltimore, MD, USA, 2009.

[18] L.T. Harper, T.A. Turner, J.R.B. Martin, N.A. Warrior, Fibre alignment in directed carbon fibre preforms-A feasibility test, Journal of Composites Materials, Vol. 43(1), pp. 57-74, 2009.

[19] K.H. Wong, T.A. Turner, S.J. Pickering, N.A. Warrior, The potential for fibre alignment on the manufacture of polymer composites from recycled carbon fibre, SAE International Journal of Aerospace, 2(1), 2009, pp. 225-231.

[20] S.J. Pickering, Carbon fibre recycling technologies: what goes in and what comes out?, Carbon Fibre Recycling and Reuse 2009 Conference, IntertechPira, Hamburg, Germany, 2009.

[21] N.A. Warrior, T.A. Turner, S.J. Pickering, AFRECAR and HIRECAR Project results, Carbon Fibre Recycling and Reuse 2009 Conference, IntertechPira, Hamburg, Germany, 2009.

[22] K.H. Wong, T.A. Turner, S.J. Pickering, N.A. Warrior, The potential for fibre alignment in the manufacture of polymer composites from recycled carbon fibre, SAE AeroTech Congress and Exhibition, SAE International, Seattle, Washington, USA, 2009.

[23] M.E.G. Janney Jr, N. Baitcher, Fabrication of chopped fiber preforms by the 3-DEP process, Composites and Polycon 2007, American Composites Manufacturers Association, Tampa, FL, USA, 2007.

[24] H.Yu, K.D. Potter, "Method and apparatus for aligning discontinuous fibres", UK patent, Patent application number 1306762.4, 2013.

[25] H. Yu, K.D. Potter, M.R. Wisnom, A novel manufacturing method for aligned discontinuous fibre composites (High Performance-Discontinuous Fibre Method), Composites Part A, Vol. 65, pp. 175-185, 2014.

[26] H. Yu, M.L. Longana, M. Jalalvand, M.R. Wisnom, K.D. Potter, Pseudo-ductility in intermingled carbon/glass hybrid composites with highly aligned discontinuous fibres, Composites Part A, Vol. 73, pp. 35-44, 2015.

[27] M.L. Longana, H. Yu, K.D. Potter, Aligned virgin and recycled short carbon fibres hybrid composites, ICCM20, Copenhagen, Denmark, 2015.

[28] M.L. Longana, H. Yu, M. Jalalvand, M.R. Wisnom, K.D. Potter, Aligned discontinuous intermingled reclaimed/virgin carbon fibre composites for high performance and pseudo-ductile behaviour in interlaminated carbon-glass hybrids, Composites Science and Technology, Vol. 143, pp. 13-21, 2017.

[29] M.L. Longana, N. Ong, H. Yu, K.D. Potter, Multiple closed loop recycling of carbon fibre composites with the HiPerDiF method, Composites Structures, Vol. 153, pp. 271-277, 2016.

[30] M.L. Longana, H. Yu, M. Jalalvand, K.D. Potter, The High Performance Discontinuous Fibre (HiPerDiF) technology for consistent quality control of reclaimed carbon fibres, ECCM17, Munich, Germany, 2016.

[31] M. Jalalvand, G. Czél, M.R. Wisnom, Numerical modelling of the damage modes in UD thin carbon/glass hybrid laminates, Composites Science and Technology, Vol. 94, pp. 39-47, 2014.

[32] M. Jalalvand, G. Czél, M.R. Wisnom, Parametric study of failure mechanisms and optimal configurations of pseudo-ductile thin-ply UD hybrid composites, Composites Part A, Vol. 74, pp. 123-131, 2015.

[33] M. Jalalvand, G. Czél, M.R. Wisnom, Damage analysis of pseudo-ductile thin-ply UD hybrid composites - a new analytical method, Composites Part A, Vol. 69, pp. 83-93, 2015.

[34] G. Czél, M. Jalalvand, M.R. Wisnom, Hybrid specimens eliminating stress concentrations in tensile and compressive testing of unidirectional composites, Composites Part A, Vol 91, pp. 436-447, 2016.