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A novel manufacturing method for aligned discontinuous fibre composites (High Performance-Discontinuous Fibre method)

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ABSTRACT

The High Performance-Discontinuous Fibre (HiPerDiF) method is a new high speed process to produce discontinuous fibre architectures with high volume fraction. It allows the manufacture of tow or tape type prepregs with highly aligned reinforcements directly from short fibres rather than from pre-existing tows.

This paper introduces the principle of this unique short fibre alignment method and describes the improved orientation head design for obtaining tape type preforms with high productivity. Using this HiPerDiF method, tensile specimens with 67% of the fibres aligned within the range of ±3° were successfully produced from tape type preforms with 3 mm long carbon fibres. Tensile modulus and strength in the fibre direction of specimens with a fibre volume fraction of 55% were 115 GPa and 1509 MPa, respectively, significantly higher than those of aligned short fibre composites made by conventional methods.

1. Introduction

High specific stiffness and strength of composites are generally obtained by having a high level of fibre alignment, which allows a high fibre volume fraction to be attained. Although high performance composites are typically made of continuous fibres embedded in a polymer matrix, these tend to fail in a catastrophic way as cracks initiate where the reinforcements penetrate the composite surface [1,2]. As an alternative, highly aligned discontinuous fibre reinforced composites began to attract attention since they can also achieve high performance provided the aspect ratio is sufficiently high to support load transfer [3,4]. Discontinuous fibre reinforced composites not only offer a significant advantage over continuous fibre reinforced composites in manufacturing complex structural parts because of their superior formability, but also provide scope to create a ductile or pseudo-ductile response under loading by deformation and slip at the discontinuities [5–7].

The aim of this research was to develop a new method to manufacture highly aligned discontinuous preforms directly from short fibres rather than from pre-existing tows. Also, it was to make the process applicable for different types and length of fibre (up to 5 mm) with a fast and continuous process.

Several techniques using electrical, magnetic and pneumatic means have been tried in the past to orient fibres in a preferred direction while processing discontinuous fibre composites [8,9]. However, these methods are limited to specific types of fibre or a particular length of fibre. Electric or magnetic field methods strongly rely on the electrical or magnetic conductivity of fibres although the fibre alignment level is largely unaffected by fibre length. Pneumatic methods are more productive and simpler. They have previously been used to produce glass-mat reinforced thermoplastics (GMT) by supplying 25 mm long bindered glass strands onto orientation plates at the end of fibre delivery tubes. Although these methods enabled a significant reduction in the manufacturing time, the degree of alignment was generally low compared to the hydrodynamic techniques described below. Alignment from electric field methods typically resulted in only 70% of fibres within the range of ±20° [10], and the alignment performance of pneumatic means was even lower, with the majority of fibres oriented between ±52°.

On the other hand, hydrodynamic or flow-induced alignment techniques have achieved some success with a superior fibre alignment level. The degree of alignment attained by typical wet processing methods with a rotating vacuum drum is such that 60% of fibres are in the range of ±3° in cured composites [11]. Conventional flow-induced alignment methods [11–19] can be divided into 3 main operations; fibre dispersion, alignment and liquid medium separation. Fibres are typically suspended in a highly viscous liquid such as glycerine to induce high shear stress within the liquid medium. In order to achieve a high degree of fibre alignment, the carrier liquid is accelerated through a converging nozzle

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or channel forcing the fibres to follow the fluid streamlines. The high viscosity of liquid is essential for achieving good fibre dispersion and alignment in conventional methods. However, it turned out to be the main factor limiting the productivity. In addition, the carrier liquid (glycerine) removal should be completed by washing with a gentle water mist spray, which leads to an economically unacceptable production rate. The flow-induced alignment method has the potential to achieve the research aim, but significant reduction in fabrication times or costs needs to be achieved.

Recently, by analysing the limitations of conventional flow-induced discontinuous fibre alignment methods with Axiomatic Design theory, a new method with a unique fibre orientation mechanism has been developed at the University of Bristol, with the initial concept outlined in Refs. [20,21]. As a novel way of solving the problems mentioned above, the new method utilised momentum change of a fibre suspension to align the fibres. This enabled a fast and continuous process producing highly aligned tow type preforms because the suspension is a low viscosity fluid such as water. A prototype module was set up to verify the design concept, and a thin tow type preform with highly oriented short fibres was obtained (80% fibres in the range of ±3°) [20,21].

This paper gives full details of a new design with significant improvement and scale-up of the orientation head by integrating multiple tow type aligned preforms to form a tape-like discontinuous fibre preform, which leads to high productivity. Short fibre aligned carbon/epoxy composites by the improved HiPerDiF method were successfully produced and their mechanical performance is compared with that of continuous fibre composites. Experimental results such as the fibre orientation level, fibre volume fraction, and mechanical properties of composite samples are presented to demonstrate the potential of this newly developed short fibre alignment method.

2. Experimental methodology

2.1. Method and equipment design

The design concept for producing highly aligned tow type preforms, as shown in Fig. 1, is comprised of the following steps [20,21],

(a) Dispersing the fibres in a liquid dispersion medium (water).
(b) Accelerating the dispersion medium through a nozzle to partially align the fibres.
(c) Shooting the fibre suspension jet onto the orientation plate and aligning the fibres transversely to the suspension jet.
(d) Removing the liquid medium by a suction plate through the moving perforated belt whilst maintaining the fibre orientation.
(e) Drying the aligned fibre preform before resin impregnation.

As shown in Fig. 2(a), the original fibre orientation mechanism is that the fibres in the suspension hit the inclined plate and then their orientation is changed transversely to the water jet direction, provided that the distance d between the two inclined plates is less than the discontinuous fibre length. When the slit width of the suction plate connected with the vacuum source is the same as the distance d between the two inclined plates, it allows the fibre alignment to be maintained.

This orientation mechanism can be simplified by understanding the roles of the inclined plates of the orientation head; an inclined plate changes the momentum of the fibre suspension and a second inclined plate is used as a guide to prevent an overflow that would cause misaligned fibres. The fibre orientation mechanism can be therefore replicated with two parallel plates; the second plate has a lower height so that the fibre suspension jet can be directed onto the first plate over the second plate. The major difference from the initial concept is in the simplified concept of the head using parallel plates that the orientation of the fibres is in part changed parallel to the first plate plane in steps 1–2 of the process and then the fibre are aligned along the movement direction of the conveyor belt in steps 3–4 by colliding with the conveyor belt as shown in Fig. 2(b).

This simplified concept can be extended to an array of multiple heads. A new orientation head has been designed that consists of two parallel plates staggered with the gap d between them which is controllable. As shown in Fig. 3(a), the fibre suspension jet from the nozzle is inclined downwards from the horizontal and oriented at an oblique angle (θ) to the $x-y$ plane to ensure the jet is fully captured within the channel. This is referred to as a single unit of the orientation head. In a 3D system the orientation head size

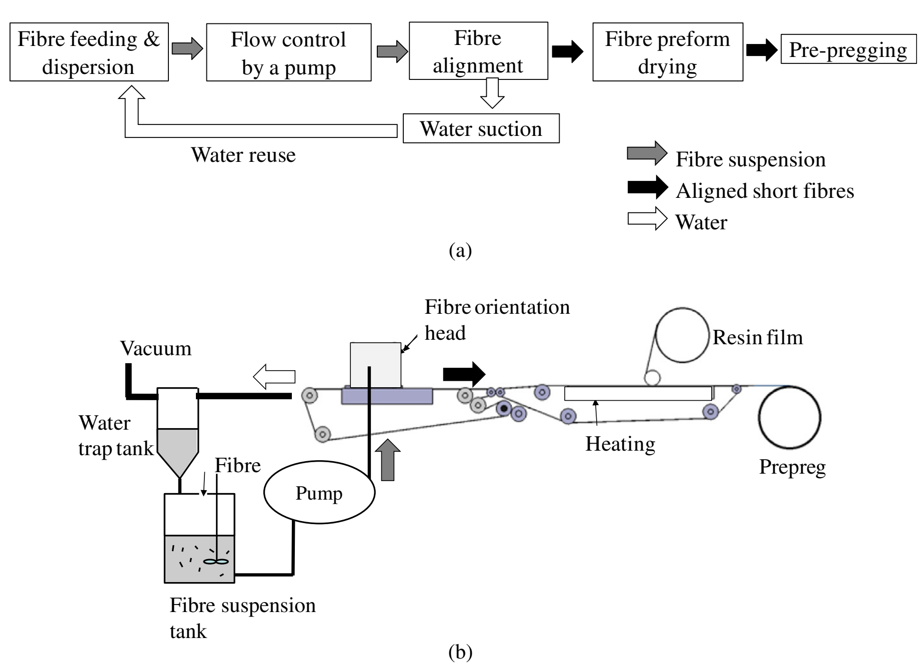

Fig. 1. (a) Flow chart and (b) schematic diagram of the discontinuous fibre alignment process.