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Manufacturing characteristics of the continuous tow shearing method for manufacturing of variable angle tow composites

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ABSTRACT

Automated fibre placement (AFP) is well-known as a cutting-edge technology for manufacturing variable angle tow (VAT) composites with tailored fibre paths. However, its process-induced defects prevent the wide application of VAT composite structures. As an alternative manufacturing method, the continuous tow shearing (CTS) technique, utilising the ability to shear dry tows, has been developed. It was shown that CTS could significantly reduce process-induced defects such as fibre wrinkling, resin rich areas and fibre discontinuities. In this paper, its manufacturing characteristics such as material characteristics, layup accuracy, and thickness variation are investigated experimentally.

1. Introduction

With the dramatic increase in the usage of composite materials for aircraft structures, variable angle tow (VAT) composites are being widely studied to achieve ultra-high structural efficiency, which is even greater than that obtained by the inherent high specific stiffness of composites, by adopting curved fibre paths and customising stress distributions [1–4]. The automated fibre placement (AFP) process that can steer fibre paths using cutting-edge robotics is considered to be a key enabling technology to manufacture VAT composites. However, in the tow steering process, it generally produces manufacturing defects such as local fibre buckling, resin pockets, fibre discontinuity due to tow drops, and local thickening due to tow overlaps [5–11]. Researchers have been trying to investigate the detrimental effects of the defects and consider the resulting reduction of the structural performance during design and analysis processes. The negative effect of a gap width on the compressive strength of notched and unnotched specimens has been explored [12]. Local buckling of the slit-tape during the conventional AFP process has been studied to determine the minimum steering radii for different tow widths [13]. The effects of tow gaps and overlaps on tensile, compression, and in-plane shear strengths have been widely investigated [14]. A numerical analysis has demonstrated that damage can be initiated at tow drop locations and the influence of tow drop areas should be taken into account by reducing the values of material allowables [15]. A modelling method to reflect the stiffness reduction in finite elements, including a tow gap or overlap, has been developed [16,17]. Some researchers have applied stagger and interweaving techniques in order to smooth tow overlaps [18].

As a novel alternative to the conventional AFP process, the continuous tow shearing (CTS) technique using the ability to deform dry tows in shear has been developed recently [19,20]. In previous research, it was shown that CTS could significantly reduce process-induced defects such as fibre wrinkling, resin-rich areas and fibre discontinuities by using the in-plane shear deformation of dry tows. In this technique, tow cuts, gaps and overlaps are not required theoretically in the shifting method where identical reference paths are simply shifted along a specific direction. The design process is simplified by eliminating complicated models for capturing process-induced defects, noting that the thickness change with respect to the tow shear angle is the only consideration of interest.

In this paper, we report on manufacturing characteristics of the CTS including impregnation characteristics, layup accuracy, and thickness variation that have been investigated experimentally through layup tests. After these layup tests, we discuss VAT prepregs that were produced with the same machine settings and a VAT composite laminate that was cured using manual stacking with an autoclave cure. Finally, its impregnation quality and dimensions are discussed having been evaluated using CT scanning.

2. Continuous tow shearing (CTS)

The key mechanism of CTS is the applied in-plane shear deformation of the semi-impregnated tow material that is continuously

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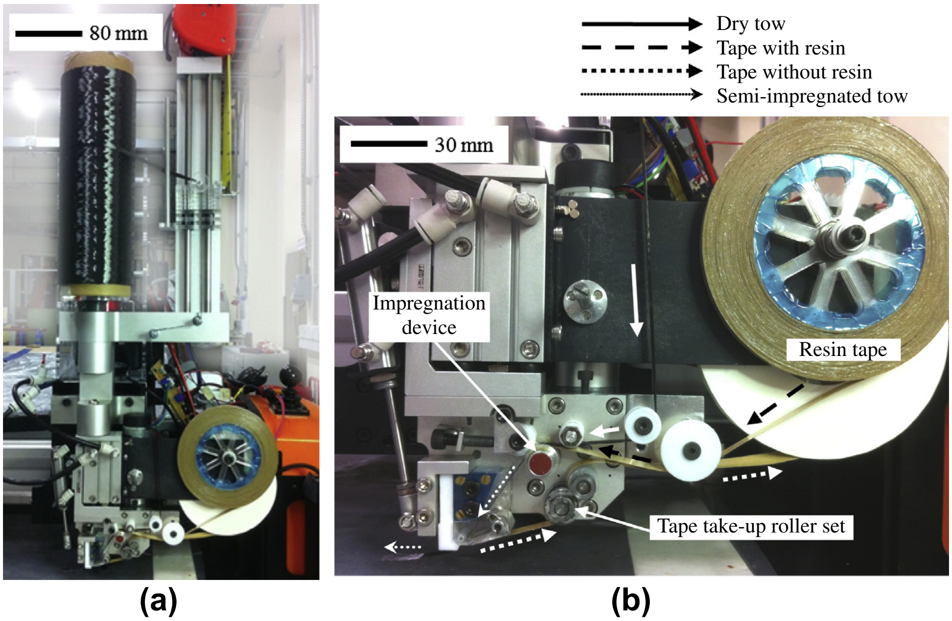

Fig. 1. Continuous tow shearing head: (a) attached to the ply cutting machine and (b) close view. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

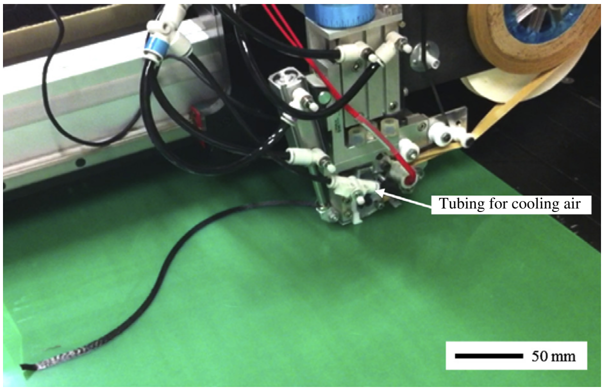

Fig. 2. Continuous tow shearing head laying up a single tow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

fed into a small shearing gap [19]. When the tow material impregnated with a constant resin content is sheared keeping fixed boundaries, the tow thickness increases. The thickness can be calculated readily as

$$t = t_0 / \cos\theta \qquad (1)$$

where t_0 and θ are the original tow thickness and the shear angle, respectively [19].

As the fibre angle and the ply thickness are coupled, the layup accuracy is an important consideration in CTS. Also, the amount of resin for tow impregnation should be held constant to make the thickness variation follow the simple relation with the shear angle. All these factors combine to give the manufacturing characteristics of the CTS process.

In order to investigate the manufacturing characteristics, the CTS prototype head module was developed as shown in Fig. 1. The head module was attached to the moving body of a commercial CNC ply cutting machine, and repeated layup tests were performed as shown in Fig. 2. Although the mechanism was almost the same as the previous prototype [19], there was a difference in that the paper take-up speed was precisely synchronised with the tow-feed speed measured by an additional encoder. A tow dispenser with tensioning and redirecting parts as well as a large-capacity resin tape dispenser was installed. A commercial bobbin of 24 K dry carbon tow (Tenax-E IMS65, Toho Tenax Co. Ltd., EU) was used as it is produced without a rewinding process. The 80 gsm resin film (MTM49-3, ACG, UK) was slit into 8 mm wide tapes and mounted on the head. For the in situ impregnation, the dry tow combined with resin film was fed through the precise gap between the PTFE compaction roller and the hot roller heated by a PTC (Positive temperature coefficient) heater. The temperature of the hot roller was kept at approximately 70 °C, and the impregnated tow was cooled down by shooting cold air through a pneumatic tubing, which is shown in Fig. 2, immediately after it passed through the impregnation device. (The tubing for cooling was detached to show other components better in Fig. 1.) The CNC (Computer Numerical Control) code for the ply cutting machine was adjusted to synchronise the tow feed speed and the head moving speed at 5 mm/s.

3. Experiments and analysis

3.1. Microscopic observation

The cross-section and top surface of the impregnated tow were observed using a microscope in order to investigate the impregnation quality. They were compared with those of a commercial prepreg, and the cross-sectional area was measured to calculate the fibre packing factor. Both materials were cured at room temperature for more than a month so as not to cause resin flow and fibre movement during sample preparation. In order to investigate the cross-section, the cut tow and prepregs were potted in highly viscous and room temperature curable epoxy to prevent the potting material from infiltrating into the void area.

3.2. Tow path tracing using image analysis

In order to investigate the layup accuracy, an image analysis method was used. Firstly, several tows with different paths were