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Preparation and bending properties of three dimensional braided single poly (lactic acid) composite

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ABSTRACT

New three dimensional (3D) braided single poly (lactic acid) composites (PLA–SPCs) were obtained by combining 3D and five (5)-direction braiding technique and hot-compression technical process. 3D and 5-direction braided preforms with different braiding angles, thicknesses and fiber volume fractions were prepared. Preforms were preheated in the specially designed die system in order to make all of the fibers partially melted. In the next stage, the preforms were consolidated under a certain pressure (from 7.8 to 10 MPa) at temperatures ranging from 130 up to 150 °C. Under the controlled processing conditions, one part of fiber body formed matrix while the other part retained its fibrous form.

At the same consolidation temperature, the maximum bending stress values resulted to be substantially dependent on the fiber volume fraction of PLA–SPCs, while the bending modulus values were largely subjected to the fiber content in the length direction. The increases of consolidation pressure gave rise to better fusion of neighboring fibers with the result that the maximum stress and modulus were increased. As the consolidation temperature increases, the fusion bonding was improved, the bending failure feature was converted from plastic to brittle, both maximum bending stress and modulus values were increased. It is expected that this study could provide a new approach for the manufacture of high-performance single polymer composites (SPCs) by using thermoplastic polymer fibers.

1. Introduction

PLA is a thermoplastic, biodegradable and absorbable polymer that can be made from annually renewable resources. PLA has great potential to be used in either the industrial packaging field or the biocompatible/bioabsorbable medical device market. However, because of its unsatisfactory mechanical properties in the raw state, PLA has not yet gained full market acceptance as an engineering resin [1].

One up-and-coming approach for improving mechanical properties of polymer materials is the single polymer composites (SPCs) approach, originally proposed by Capiati and Porter [2]. SPCs are materials in which both the reinforcements (fibers) and the continuous (matrix) phases are come from the same polymer [3,4] or polymers with the same chemical composition but different chemical structures [5–8]. One of the major advantages of this composite material is that strong and continuous interfaces could be naturally formed since the two phases possesses identical chemistry. Another important advantage of SPCs is the unexceptionable end-life recyclability since it can be achieved by using the same polymer for both the fibers and matrix phases [9].

By using SPCs method, some researchers have attempted to reinforce a PLA matrix by embedding PLA fibers to meet the demands for high strength and hardness applications. Törmälä et al. [10] fabricated SPCs consisting of a PLLA matrix reinforced with highly oriented PLLA fibers, and achieved much higher strengths than a starting unreinforced PLLA material. Majola et al. [11] reported that comparing to non-reinforced PLLA materials with the same molecular weight about 145 MPa and 53 MPa respectively, the initial bending and shear strengths of PLA–SPCs were about 260 MPa and 96 MPa, respectively. Wright-Charlesworth et al. [12] in a similar research found that a PLA–SPC fabricated from oriented PLA fibers and formed by the hot-compression method had the highest initial mechanical properties. Li and Yao [13] used hot-compression moulding to prepare PLA–SPCs consisting of two amorphous PLA sheets as the matrix and a layer high-crystallinity PLA fibers, yarns or plain fabrics as reinforcement. The tensile property test results indicated that comparing to the non-reinforced PLA sheet, an improvement of about 30% in tensile strength was attained for the PLA–SPCs.

These techniques consist in the preparation of a preform either by one direction highly oriented PLA fibers, yarns or by two

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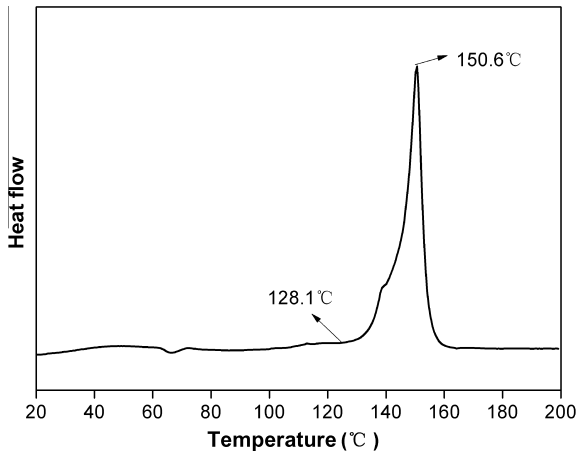

Fig. 1. The DSC thermograms of PLA fiber. A heating rate of around 20 °C/min was used in the DSC experiments.

directions fabrics interweaved by warp yarns and weft yarns. In the second step, the preform is consolidated under pressure at a suitable temperature such that the matrix melts and flows thus forming a continuous phase that bounds the reinforcing fibers. Although these methods having good strength in the fiber direction, the lack of through-thickness reinforcing fibers can be a disadvantage in terms of the mechanical properties of high stock thickness needed applications.

In this paper, we introduced a new approach for the preparation of SPCs based on 3D and 5-direction braided poly (lactic acid) fiber preforms. A specially designed die system with a thermocouple probe was employed to control the temperature balance and thickness of composites during the hot-compression process. The processing window of about 20 °C allowed us to successfully adopt a fiber surface fusion and hot consolidation process for the composites production. The effects of the preform thickness, braiding angle and consolidation temperature on the bending properties of 3D and 5-direction braided PLA–SPCs were also investigated and discussed.

2. Experimental

2.1. Materials

Composites were prepared using commercially available PLA yarns (Jiaxing Pulilai New Material Co., Ltd.). The linear density of 600 denier (1 denier = 9 g/km), 150 filaments per yarn; The diameter measured on 200 fibers results to be 18.5 ± 1.8 μm; the filaments were meltspun, with a tensile strength of approximately 95 Mpa; the melting temperature values (Tm) of the PLA yarns were 150.6 °C as measured by DSC analysis (see Fig. 1).

2.2. 3D and 5-directional braiding process

3D and 5-directional braided preforms have been developed by introducing the uniaxial reinforced yarns along the braiding direction based on the 3D and four-directional braiding process [14]. Fig. 2 illustrates the basic concept of the 3D and 5-directional braiding process in four steps method, where "O" means the braiding yarn carriers and "■" means the axial carriers. It can be seen that the axial yarns are added by insetting each axial yarn carriers between two braiding yarn carriers in rows on the machine bed. The carriers on machine bed will move just one position under each moving step, each machine cycle is accomplished by four steps: step-1, the braiding yarn carriers and the axial yarn carriers in rows move horizontally in an alternating pattern, step-2, only the braiding yarn carriers in columns move longitudinally in an alternating pattern. The step-3 and the step-4 reverse moving direction in step-1 and step-2, respectively. After these four steps movement of carriers, one-pitch-length preform will be pulled out. The relevant parameters of prepared preforms are summarized in Table 1.

2.3. Hot compacted composites preparation

As schematized in Fig. 3, PLA–SPCs were prepared in a three stages process: sample preparation, heating and compression. In the sample preparation stage, putting the preform into the die cavity and inserting the thermocouple probe into the preform from the reserved hole, after the die assembly, putting them on the lower plate of vulcanizing machine. As evidenced in Fig. 4, self-designed hot-compression die consists of three parts: concave die, terrace die and thermocouple. The design of concave die with four very thick walls is beneficial to obtaining better temperature uniformity with regard to preform surface and internal in the heating process. In order to accurately detecting temperature values of composites in the hot-compression process, a reserved hole was designed to insert the thermocouple probe into preform. The heating and compression stages were performed according to the processing scheme described in Fig. 5, where the temperature profile was experimentally determined by the thermocouple indicating values. In the heating stage, rising the lower plate of vulcanizing machine enough to make the upper plate contact with the surface

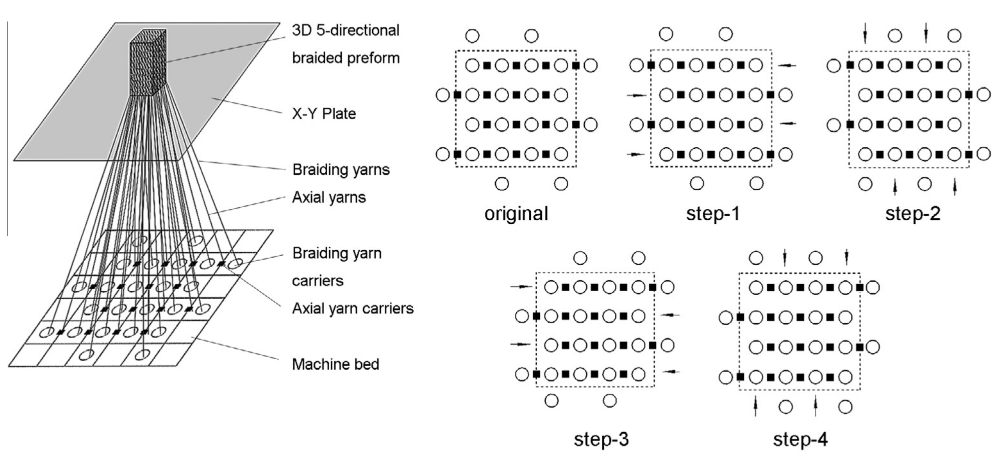

Fig. 2. Scheme of 3D and 5-directional braiding process.