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Opportunities for silk textiles in reinforced biocomposites: Studying through-thickness compaction behaviour

Darshil U. Shah *, David Porter, Fritz Vollrath

Oxford Silk Group, Dept. of Zoology, University of Oxford, South Parks Road, Oxford OX1 3PS, UK

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ABSTRACT

While it is common knowledge in natural fibre composites manufacture that plant fibre reinforcements are considerably less compactable than synthetic fibre reinforcements, the through-thickness compaction behaviour of animal-fibre silk reinforcements has not been characterised thus far. We find that not only are silk reinforcements significantly more compressible than plant fibre reinforcements, but their compactibility exceeds that of even glass fibre textiles. For instance, the fibre volume fraction (at a compaction pressure of 2.0 bar) of woven biaxial fabrics of silk, plant fibres and E-glass are 54–57%, 30–40% and 49–54%, respectively. Therefore, silks provide an opportunity to manufacture high fibre content natural fibre composites; this is a bottleneck of plant fibre textiles. Analysing the structure of silk textiles through scanning electron microscopy, we show that favourable fibre/yarn/fabric geometry, high degree of fibre alignment and dispersion, and suitable technical fibre properties enable optimal packing and arrangement of silk textiles.

1. Introduction

1.1. Liquid composite moulding

Liquid composite moulding (LCM) processes, such as vacuum infusion (VI) and resin transfer moulding (RTM), are widely used for the cost-effective production of high-performance complex-geometry large components at low-to-medium volumes (e.g. 100–10,000 parts/year) [1]. While numerous acronyms and associated process variations exist [2,3], the basic approach in any LCM process, as illustrated in Fig. 1, is to force a catalyzed thermosetting liquid resin to flow through a stationary dry, and often compacted reinforcement inside a closed mould, by creating a pressure differential (using vacuum and/or injection pressure) between the inlets and outlets.

In general, LCM processes have four stages (Fig. 1): (i) reinforcement lay-up, (ii) mould filling, (iii) post-filling, and (iv) demoulding. In particular, successful implementation of LCM processes involves understanding and optimising the mould filling stage. This stage is affected by numerous factors, including mould/part geometry; (inlet and outlet) gate location and configuration; reinforcement lay-up, orientation, compaction, and permeability; resin temperature, viscosity, and degree of cure (all of which are a function of time); pressure differential in the mould cavity; and tooling temperature. Not surprisingly, computational mould-filling simulations are widely used as a cost-effective and time-saving tool to optimise the LCM process [3]. However, accurate manufacturing process simulations require accurate data, including compaction data.

The through-thickness compaction of a reinforcement directly affects the reinforcement permeability and part fill time in the mould filling process [4]. Importantly, it also dictates the thickness and volumetric composition (i.e. fibre volume fraction) of the final part. Tight control of part thickness (and therefore weight) is a requisite for quality assurance in any composite manufacturing process. In addition, in their uncompressed state, textile reinforcements have a low fibre volume fraction (typically between 10–25% [4]). This must be increased (to up to 70%) during processing to exploit the mechanical properties of the reinforcement. Studying the relationship between compaction pressure P and fibre volume fraction v_f for a given preform also enables determining the maximum (theoretical) fibre volume fraction, which sets the upper limit of reinforcement efficiency. Consequently, compaction plays an important role in not only LCM processes but also in the stamping of textile-reinforced thermoplastic composites. Knowledge of the compaction behaviour of the reinforcement form is therefore critical.

Typically, empirical power-law relationships are used to model compaction [4,5]. However, the compaction response of a reinforcement is governed by various deformation mechanisms (depicted in Fig. 2) and hence is complex and depends on various elements, such

* Corresponding author. Tel.: +44 (0)1865271216.
E-mail addresses: darshil.shah@zoo.ox.ac.uk, darshil.shah@hotmail.co.uk (D.U. Shah).

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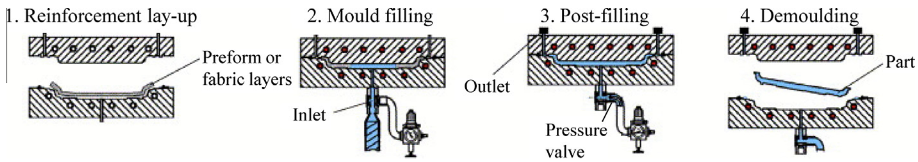

Fig. 1. Schematic of a liquid composite moulding (LCM) process, illustrating the four principal steps: (1) lay-up of the dry reinforcement (either as multiples layers of fabrics or as a prefabricated 'preform') in a mould with a rigid (metal) or semi-rigid (composite) bottom tool and a rigid (metal), semi-rigid (composite) or flexible (silicone or vacuum bag) top tool/surface; (2) compaction of the reinforcement followed by resin impregnation via drawing vacuum and/or injecting resin under pressure; (3) Removal of pressure to allow laminate thickness to equilibrate in cavity followed by curing of resin; and (4) de-moulding of the cured and stiff composite part. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

as: type and form of fibre reinforcement, fibre architecture, number of layers in the preform, preform stacking sequence, history of loading, rate of compaction, tooling temperature, and presence of lubricant (i.e. wet versus dry state) [4–9].

1.2. Natural fibre composites in LCM processes

The increasing consideration of natural fibres as next-generation sustainable composite reinforcements requires tackling the first hurdle which is composite manufacture (reviewed in [10–14]). Due to the commercial applications of natural fibre reinforced composites in principally small-part high-volume low-cycletime markets (e.g. the automotive industry), compression moulding is the widely used manufacturing technique [12]. However, LCM processes are specifically well-suited to natural fibre reinforcements for a variety of reasons [6,12,15], including:

- (i) low processing temperatures (often < 120 °C, if not ambient) avoiding thermal degradation of the fibres during composite fabrication,
- (ii) minimal fibre damage during composite processing (as opposed to injection/extrusion moulding) allowing retention of high reinforcement properties and efficiencies (i.e. length and orientation),
- (iii) use of liquid resins with typically low viscosities (0.1–1 Pas) to allow good preform impregnation with low composite void content even at low compaction/injection pressures,
- (iv) use of thermosetting resins with typically polar functional groups, which form a better interface with typically polar natural fibres (than polyolefin-based thermoplastics),
- (v) relatively low-cost (and often unsophisticated) tooling, making the process compatible with low-cost plant fibres, particularly when manufacturing in developing countries with an abundance of indigenous natural fibres, and
- (vi) LCM processes are close-moulding 'clean' processes which provide worker-friendly conditions.

Not surprisingly, researchers are increasingly investigating different aspects of the LCM process for natural fibre reinforced composites, particularly reinforcement permeability [16–21] and

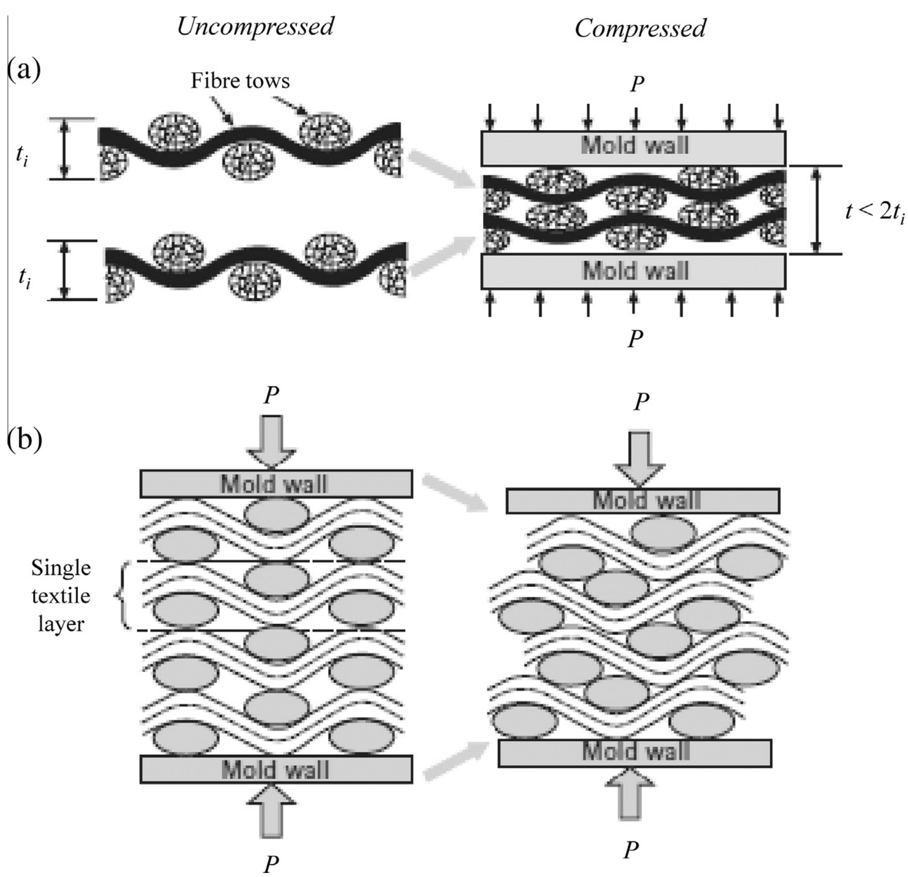

Fig. 2. Key mechanisms that drive reinforcement compaction: (a) yarn cross-section deformation and yarn flattening, and (b) yarn bending deformation, void condensation/reduction, and nesting and packing of layers. Ref. to [42] for detail.