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CT Scan Generated Material Twins for Composites Manufacturing in Industry 4.0

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Chapter 1
Introduction

1.1 Background

The availability of adequate materials has been a significant factor in the advancement of human civilization and technological breakthroughs. Throughout the ages, the constant improvements in the mechanical, electrical and thermal properties of materials have been pushing the limits of technology. In these advancements, composite materials represent a giant leap with promising characteristics for high performance, lightweight and multifunctional applications. The design and manufacturing of composite materials and structures has been pursued in evolutionary as well as revolutionary ways during the past few decades [1]. Constant progress is being made in the development of existing techniques through research and experiments, as well as new ideas that are being presented. These efforts aim at reducing the manufacturing cost and complexity, enhancing the quality of parts produced and minimizing environmental impacts.

A composite material is a material made from two or more constituent materials with significantly different physical or chemical properties that, when combined, produce a material with characteristics different from the individual components. The individual components remain separate and distinct within the final part. Fiber Reinforced Polymer Composite (FRPC) is a class of composite materials that consists of a polymer matrix reinforced with high-strength natural or synthetic fibers. The reinforcing fiber adds rigidity and is the main load-bearing component of the composite materials. While high performance composites are dominated by synthetic glass, carbon and aramid fibers, a wide range of natural fibers is also gaining popularity. The matrix binds the fibers together, transmits applied loads to the fibers, prevents propagation of cracks and protects the fibers from damage. Polymer matrices are classified as thermoplastic or thermosetting resins. A thermosetting polymer is irreversibly-cured from a soft solid or viscous liquid, whereas a thermoplastic polymer becomes pliable or moldable above a specific temperature and solidifies upon cooling.

The advantages of FRPC over other materials have attracted many industries such as aerospace, automobile, infrastructure, sports and marine to explore and increase their usage. FRPC materials have been used extensively in a wide variety of aerospace applications, ranging from commercial airliners to deep space vehicles. World-leading organizations in aerospace such as National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), Boeing, Airbus, Bombardier etc. are investing intensively in developing such materials. The commercial airliners, the Boeing 787 and the Airbus A350 are excellent examples, where more than 50% of the structure is comprised of fiber reinforced composites. NASA recently achieved a major milestone in the advancement of space technology by successfully testing a pressurized, large cryogenic propellant tank made entirely out of fiber reinforced composite materials. In automobile manufacturing, FRPC materials offer major advantages over steel and similar metals in producing lighter, safer and more fuel-efficient vehicles. FRPC materials are now being used in automobile body, chassis, interiors and engine components. Recently, several high value vehicles, such as the BMW M, and the i-series have used carbon fiber reinforced composites as primary structures. Apart from these two major industries, fiber reinforced composites have been the focus of many other industries, such as marine, defense, sports and energy sectors. For example, entire wind turbine blades are being manufactured using advanced composite manufacturing techniques. Sport items such as, tennis rackets, snow skis, sail boats, kayaks, helmets, shoe soles, hockey sticks, etc. are also being manufactured from fiber reinforced polymer composites.

1.2 Manufacturing of Fiber Reinforced Polymer Composites

Fiber reinforcements are typically in the form of random mats, woven reinforcements, unidirectional or non-crimp stitched reinforcements, knits, braids, or 3D woven reinforcements [2]. Such types of reinforcement are developed into composite parts through various composite manufacturing techniques. The quality of the composite material and the resulting part depends on the manufacturing process, since it is during the manufacturing process that the matrix material and the fiber reinforcement are combined and consolidated to form the composite part. The process depends on the type of resin and reinforcement used. In this book, the focus is mainly on composites manufacturing process characterization which can be used in autoclave and Out-of-Autoclave (OoA) manufacturing techniques. In the autoclave process, the fiber reinforcements are used in the form of prepregs. The prepregs are cut and formed into the desired shape and placed on a rigid mold in the desired position, orientation and sequence to form a layup. The layup, sealed with vacuum bag, is then placed into the autoclave and the curing process is performed according to the prescribed temperature-pressure-vacuum-time cycle inside the autoclave. The process is very versatile and gives a very uniform quality, as pressure and heat can be regulated

very precisely. On the other hand, it is very costly due to high capital cost and time consuming due to long layup and curing time. The Out-of-Autoclave manufacturing includes processes such as vacuum bag only (VBO) and liquid composite molding (LCM). The main advantage of OoA processing techniques is the low capital cost. LCM techniques are attractive as they provide excellent control over part thickness hence, excellent mechanical properties are possible. However, the process characterization and quality control tools are still under development and require considerable research to achieve repeatable part quality. This book will focus on new LCM reinforcement characterizations (compaction response and permeability) techniques based on micro CT imaging.

1.2.1   Liquid Composite Molding

Liquid composite molding (LCM) processes involve impregnation of a reinforcement using a liquid resin with "injectable" viscosity. A generic LCM process utilizes a mold cavity that is in the shape of the part to be manufactured. The fiber reinforcement is placed inside the mold cavity and the mold is closed. A reactive (thermoset) resin is then injected into the mold cavity under pressure, until complete saturation of the reinforcing material is achieved. The resin is then allowed to cure, after curing, the part is de-molded to yield the finished product. These steps are illustrated in Fig. 1.1.

Liquid composite molding process has several variants with minor differences. Some of these variants of LCM processes are shown in Fig. 1.2. Resin Transfer
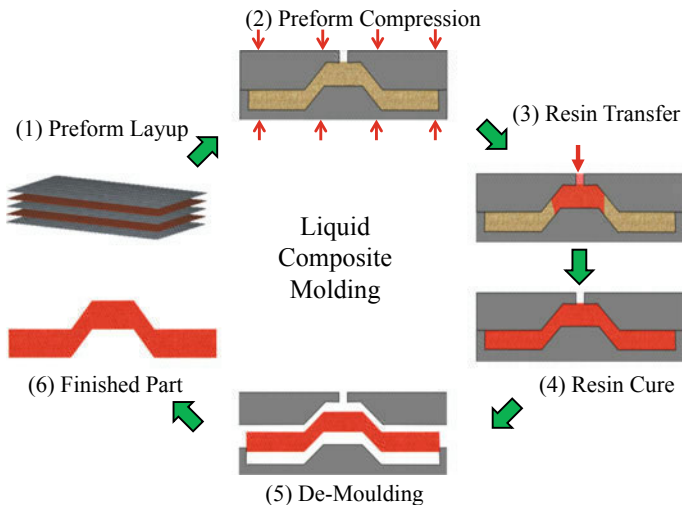
Fig. 1.1   Schematic illustration of various steps involved in manufacturing of composite parts using liquid composite molding process

Fig. 1.2 Various variations
of liquid composite molding
technique
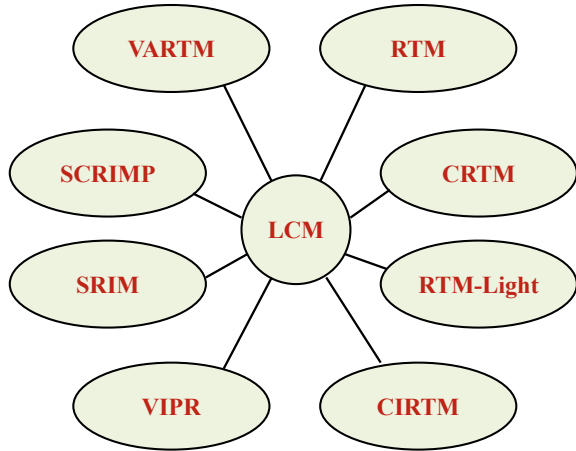
Molding (RTM) and Compression Resin Transfer Molding (CRTM) employ two
rigid molds that enable a high compaction force to be applied with minimal mold
deflections. RTM-light uses semi-flexible plastic or composite molds, providing a
medium level compaction while minimizing mold deflections at a much reduced
cost.

The Vacuum Assisted Resin Transfer Molding (VARTM) and Seemann's
Composite Resin Infusion Molding Process (SCRIMP) are slight modifications of
the process where the top half of the mold is replaced by a vacuum bag. In SCRIMP,
a highly permeable layer is introduced at the top or the bottom of the reinforce-
ment to facilitate rapid distribution of the resin throughout the part. Both VARTM
and SCRIMP rely on drawing the resin from a container at atmospheric pressure
through the fibrous bed by creating a vacuum. These processes have replaced RTM
for many applications due to their simplicity, low initial capital investment and the
ability to manufacture large structures. The cost is low due to low pressures used
in the manufacturing process and the curing reactions being carried out mostly at
room temperature. The process requires only a single tool surface, while the top
surface is covered with a vacuum bag which also cuts down on tooling costs. The
disadvantages of VARTM process is rough surface finish on the bag side, the time
required in material preparation, inconsistent dimensional tolerances and the lack of
automation.

1.3 Reinforcement Characterization

During the LCM process, reinforcement compaction inside the mold cavity and
successful injection of the resin plays an important role to ensure part quality.
These two steps are primarily dependent on the reinforcement compressibility and
permeability. Hence, for better process optimization and modeling, the compaction

response and permeability of the reinforcement need to be determined. These two characteristics are considered vital processing parameters in LCM.

1.3.1   Reinforcement Compaction Response

In an LCM process, once a dry fiber reinforcement is placed inside the mold cavity, the mold is closed using either a hydraulic press or vacuum bag. The behavior of a reinforcement subjected to a applied force normal to its plane has important consequences on the mold design and equipment specifications for all processes using fiber reinforcements. For example, in VARTM, the clamping force is applied using vacuum pressure under a flexible tooling, while in the RTM process, the reinforcement is compacted between two rigid molds. In either case, the reinforcement compaction response influences the mold clamping force, part thickness and fiber volume fraction, as result, affecting the reinforcement permeability. The compaction step is vital since, prior to manufacture, the fibrous material is not yet at the desired fiber volume fraction. The compaction decreases reinforcement thickness and increases fiber volume fraction. Furthermore, in some cases, the reinforcements are intentionally subjected to transverse compaction in order to "de-bulk" to a high fiber volume fraction [3]. The reinforcements can be subjected to single-cycle, multi-cycle or multi-stage compaction [4]. Moreover, during the resin injection, the reinforcement is not only subjected to the mold clamping force provided by the press, but also to the fluid pressure generated as a result of resin injection. The total stress acting on the reinforcement is governed by Terzaghi's law which states that the total stress carried by the reinforcement is equal to the sum of the compaction stress taken by the fibers and fluid pressure [5–8]. Due to the compaction stress, the internal architecture of the reinforcement also changes, i.e. the tows flatten, the spaces between the fiber tows decrease, the tows undergo bending while at the micro-scale, the gaps between individual fibers also decrease. The compaction of multiple layered reinforcements (a stack of a number of 2D textiles) possess additional complexity of nesting, interlayering and packing. Hence, during manufacturing of composite parts via LCM process, the transverse compaction is important and it is essential to characterize the compaction response of the reinforcing fabric.

In any reinforcement compaction characterization, two major attributes need to be investigated; (1) the relationship between applied load and the resulting thickness or fiber volume fraction (V_f) and, (2) microscopic geometrical changes of the tows and fibers. The relationship between applied stress and/or resulting thickness (fiber volume fraction) is presented as a stress relaxation curve. The standard stress relaxation curve is a plot of applied stress versus time or fiber volume fraction (V_f). Typically, the compaction of reinforcement consists of two parts, i.e. dynamic, non-linear compression stage and stress relaxation. The compaction depends on the reinforcement architecture, speed, dry/wet state, and number of reinforcement layers used. The second objective of a compaction study is to document tow deformations and

the inter-tow gap reduction as a result of decreasing thickness, this is achieved by microscopic investigation either in-situ or ex-situ.

1.3.2 Reinforcement Permeability

In the LCM process, the impregnation of reinforcement with resin is considered as flow through porous medium phenomena, and the permeability of the reinforcement dictates the "ease" of advancement of the resin flow front through the open channels therefore, influencing mold filling time. As the Reynolds number of the resin flow is considered very low due to low flow velocities, the resin flow through the reinforcement is assumed to be governed by Darcy's law. The Darcy's law relates the volume flow rate of a Newtonian fluid through a porous media of given cross-sectional area and the pressure gradient along the flow direction. The parameters included in Darcy's law are illustrated in Fig. 1.3a. Mathematically, Darcy's law is given as,

$$Q = -K \frac{A}{\mu} \frac{P_i - P_o}{L} = -K \frac{A}{\mu} \frac{\Delta P}{L} \tag{1.1}$$

where Q is the volume flow rate of the fluid, K is the permeability tensor, μ is the dynamic fluid viscosity, $P_i - P_o$ is the pressure gradient or the pressure difference, A is the cross-sectional area, and L is the length of the medium across which the fluid flows. The permeability is a measure of the ability of a porous material to allow fluid to pass through it and is also related to its porous structure and the connectivity of the pores. The Permeability is a directional quantity, described by a tensor in three dimensions. The 3D permeability tensor K can be expressed in Cartesian coordinates as,
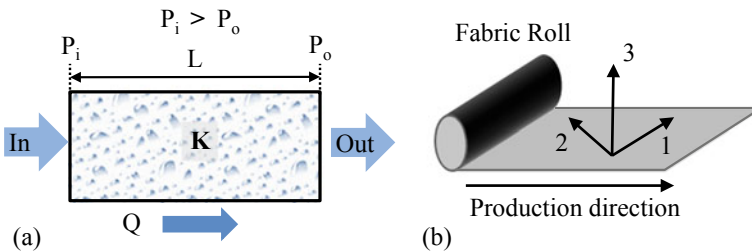
Fig. 1.3 Illustration of **a** flow through a porous medium with relevant parameters and **b** principle permeability directions for a typical reinforcement

$$K = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zy} & K_{zy} & K_{zz} \end{bmatrix} \tag{1.2}$$

In case of symmetry, the off-diagonal terms are usually taken equal. If the coordinate system is oriented in the principal directions, the off diagonal elements are taken as zero, and the remaining terms are known as principal permeability values i.e. K_{11}, K_{22} and K_{33}. For fibrous reinforcement, they are divided as the in-plane, K_{11} and K_{22}, and through-thickness or transverse, K_{33}, permeabilities. The principal directions for a typical fibrous reinforcement are illustrated in Fig. 1.3b.

The reinforcement permeability is primarily a function of the reinforcement architecture and its fiber volume fraction (V_f) [9]. Incorrect compaction and permeability predictions may lead to an inefficient process design through incorrect fiber volume fractions and mold filling time, dry spots and defects in the manufactured parts [3]. The permeability characterization of fiber reinforcements is important for liquid composite molding process modeling and simulations. The permeability dictates the time taken to fill the mold, the degree of fiber wetting by the resin and flow patterns generated as a result of resin flow.

1.4 State-of-the-Art

Existing reinforcement characterization techniques focus on compaction response and permeability characterization separately. A number of analytical, experimental and numerical methods exist for the prediction of both the compaction behavior and permeability of reinforcement as described below.

1.4.1 Compaction Characterization

1.4.1.1 Theoretical Compaction Models

Available theoretical models for reinforcement compaction response relate the compaction stress to fiber volume fraction using an algebraic relationship. There are a number of such models which are derived from micro-, meso- or macro-scale compaction behavior. At the micro-scale, micro-mechanical models based on the elastic beam theory have been developed. Another commonly applied approach is the use of a semi-empirical model based on compaction characterization experiments. In this empirical approach, the compaction behavior is modelled using one or multiple non-linear elastic equations, or few more sophisticated models with parameters that are determined from experiments. The fibrous reinforcements have been found to have visco-elastic, plastic and visco-plastic behavior under compaction.

These efforts are mainly focused on developing models that account for inelastic reinforcement behavior.

1.4.1.2 Experimental Compaction Characterization

The compaction response of fiber reinforcements can be obtained via performing compaction experiments on a universal testing machine equipped with a load cell and displacement measuring sensors. Generic experimental procedures involve; compressing test sample between two flat and rigid platens installed in a universal testing machine. A typical setup of a reniforcement compaction test is shown in Fig. 1.4. The rate of compression, as well as the target load or thickness is controlled via integrated software. The applied load and the displacement of the platens are also recoded. The data is converted into stress versus time or fiber volume fraction curve. The cavity thickness and V_f are related by the following equation,

$$V_f = \frac{A_w N}{\rho_s h}$$

(1.3)

where A_w is the areal weight of the reinforcement, N is the number of layers, ρ_s is the density of fiber and h is the cavity thickness.

In order to investigate the internal deformations, composite parts are manufactured using the separate test sample, to which the compaction levels of interest are applied. The part is then cut such that its cross-section may be viewed using an optical microscope or a Scanning Electron Microscope [SEM]. However, this step is independent of the compaction test and requires fresh test samples, as well as a very different set of equipment.
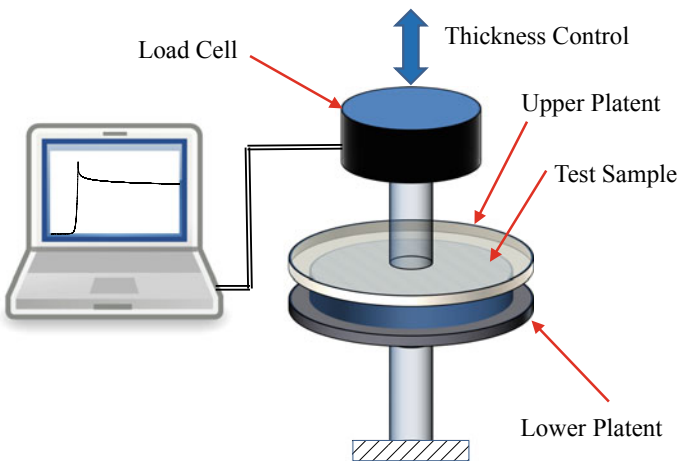
Fig. 1.4 Illustration of experimental setup of reinforcement compaction characterization

1.4.1.3 Numerical Simulations

Numerical simulation using finite element method (FEM), is a powerful tool to predict the compaction behavior of fiber reinforcements. Compaction simulations are carried out by mimicking the loading conditions on a geometrical configuration. The main challenge is to obtain accurate models for the geometry of woven reinforcements while simultaneously being able to describe their mechanical and physical behavior. The prediction quality of an FEM analysis of a fibrous structure strongly depends on the model, i.e. its geometry, the material model, and the associated boundary, as well as contact conditions. The inhomogeneous structure of woven reinforcements and locally varying material properties associated with the fiber architecture make their modeling a complex and challenging task. It is necessary to consider realistic textile geometries in order to accurately predict the performance of 3D woven reinforcements and their composites. Importantly, 3D woven reinforcements feature a more complex architecture than 2D woven fabrics.

1.4.1.4 Micro CT Assisted Compaction

Micro CT has been used by a number of researchers to investigate the internal geometry changes due to compaction and other loading conditions typical of those encountered in LCM processes. Through special experimental procedures, Hemmer et al. [10] quantified the evolution of a given dual-scale fibrous microstructure under controlled infusion. Emerson et al. [11] quantified the fiber re-orientation during axial compression of a composite through time-lapse micro CT imaging and individual fiber tracking. Vanaerschot et al. [12] quantified geometrical variability of laminated composite textiles in terms of geometrical parameters of the tows such as, centroid location, aspect ratio, area, orientation, etc. using the micro CT images of a composite part produced by resin transfer molding. In a similar study by the same authors, a dry 3D reinforcement sample was used for acquiring the micro CT images [13]. Mahadik et al. [14] used five different potted samples at each fiber volume fraction to study the yarn waviness caused by compaction of two 3D angle interlock woven reinforcements. However, all of these studies presented geometrical data for a single V_f and the effects of compaction were not included. An in-house designed compression rig was used by Yousaf et al. [15, 16] to obtain micro CT images of an E-glass plain woven reinforcement under different compressive loadings to validate compaction simulation using digital element methods. The micro CT images were used to measure the geometrical features of the meso-structure.

1.4.2 Permeability Characterization

Similar to the compaction characterization, there are various approaches to permeability characterization as well. These are described below.