Chapter 4: Manufacturing Processes of Composite Materials

Contents

Introduction

The manufacturing process determines not only the shape of a composite component but also its internal quality fibre volume fraction, void content, fibre alignment, and interfacial bonding all of which directly govern mechanical performance. Selecting an appropriate process requires matching the matrix and reinforcement type, component geometry, production volume, and required quality level to the capabilities and constraints of available techniques [10], [11].

This chapter presents the principal manufacturing methods organised by increasing process complexity and automation, followed by common manufacturing defects and quality control methods.

4.1 Open-Mould Processes

Open-mould processes are the simplest composite manufacturing methods, in which the reinforcement and matrix are combined on an open mould surface without external pressure from a matched mould. They offer low tooling cost and geometric flexibility but provide limited control over fibre content and part consistency [11], [9].

A. Hand Lay-Up

Hand lay-up is the most basic composite fabrication technique. Reinforcement layers are placed onto a mould surface and manually impregnated with liquid resin using rollers or brushes. The laminate cures at ambient temperature or under controlled thermal conditions [11].

The simplicity of this process low equipment cost, no size limitation, and suitability for complex geometries makes it widely used for prototypes, low-volume production, and large structures such as boat hulls. Its principal limitations are low production rate, dependence on operator skill, and variability in fibre volume fraction and void content between parts [11].

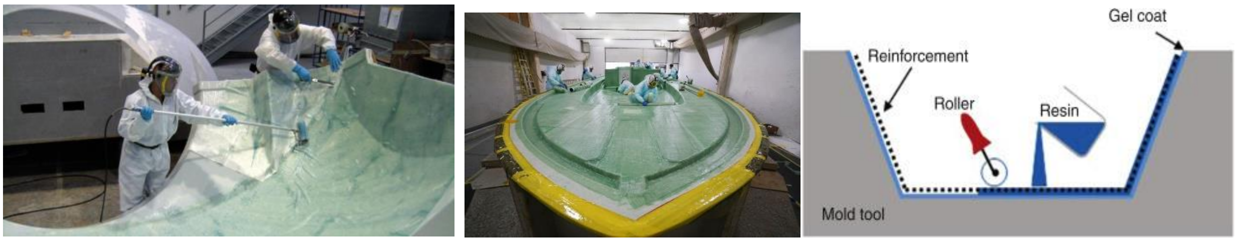

Figure 4.1 Schematic illustration of the hand lay-up process.

B. Vacuum Bagging

Vacuum bagging improves upon hand lay-up by sealing a flexible membrane over the laminate and applying vacuum pressure. The vacuum extracts entrapped air, compacts the laminate, and improves fibre wet-out, producing lower void content and more consistent mechanical properties than hand lay-up alone [9].

This technique is widely employed in aerospace and high-performance applications where the quality improvement over basic hand lay-up justifies the additional processing step, but full autoclave consolidation is not required [9].

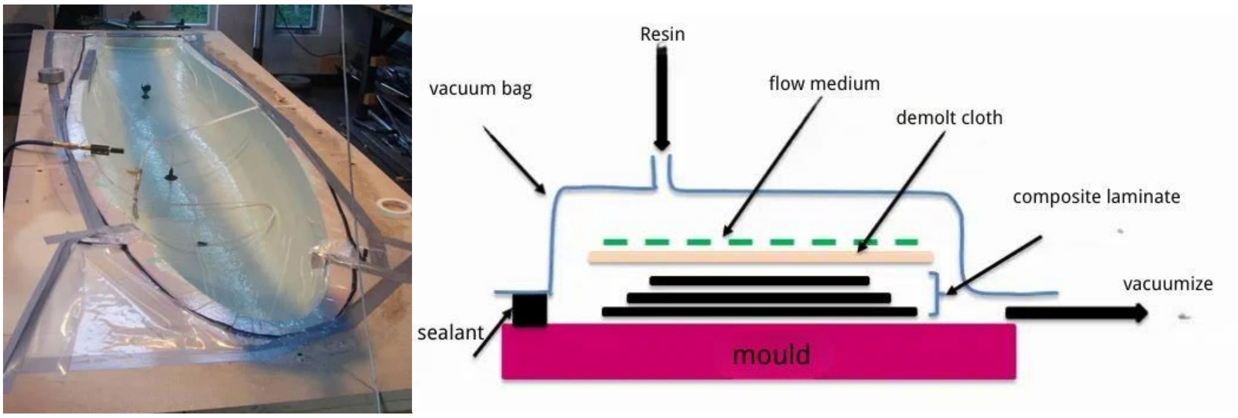

Figure 4.2 Schematic illustration of the vacuum bagging process.

4.2 Closed Mould Processes

Closed mould processes use matched moulds or sealed systems to apply controlled pressure during manufacturing, providing improved dimensional accuracy, surface finish, and fibre content control compared with open mould methods [10], [11].

A. Resin Transfer Moulding (RTM)

In RTM, dry fibre preforms are placed into a rigid mould cavity, the mould is closed, and liquid resin is injected under controlled pressure to impregnate the reinforcement. This approach provides good control over fibre volume fraction, consistent part quality, and reduced void content compared with open mould processes. RTM is suited to moderate complexity structural parts in automotive, aerospace, and marine applications, though tooling costs are higher than for open mould methods [10].

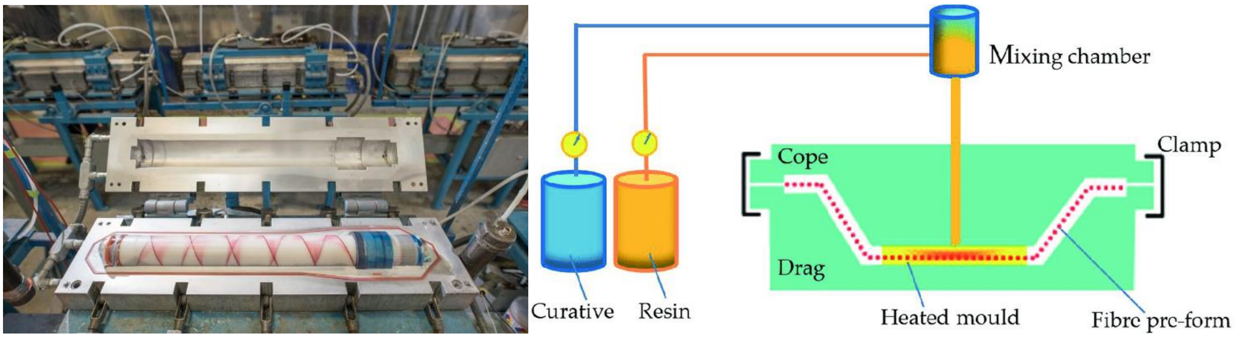

Figure 4.3 Schematic illustration of the RTM process.

B. Vacuum Assisted Resin Infusion (VARI)

VARI uses vacuum pressure rather than positive injection pressure to draw resin through dry reinforcement placed on an open mould sealed with a flexible membrane. This reduces tooling cost relative to RTM and is particularly suited to large components such as wind turbine blades, marine hulls, and infrastructure elements. The trade off is longer cycle time and less precise control over fibre volume fraction [11].

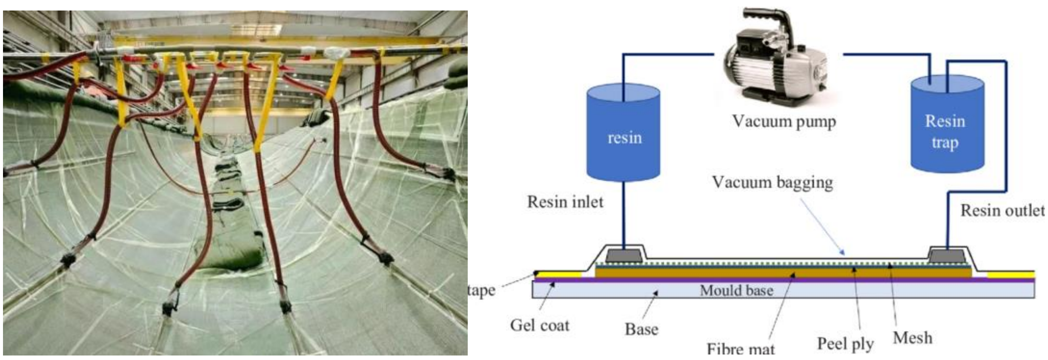

Figure 4.4 Schematic illustration of the VARI process.

C. Injection Moulding (SMC/BMC)

Injection moulding processes manufacture composite parts reinforced with short fibres or particulate fillers at high production rates. Two material forms are processed by this route: **Sheet Moulding Compound (SMC)**, pre impregnated sheets of chopped fibres compression moulded under heat and pressure, and **Bulk Moulding Compound (BMC)**, a dough like mixture of short fibres and resin injected or compression moulded into a heated cavity [10], [11].

These processes offer high dimensional accuracy, good surface finish, and cost effectiveness for mass production. The principal limitation is restriction to short fibre reinforcement, which produces lower mechanical performance than continuous fibre composites. SMC/BMC moulding is widely used in automotive and electrical industries for structural and semi structural components [10].

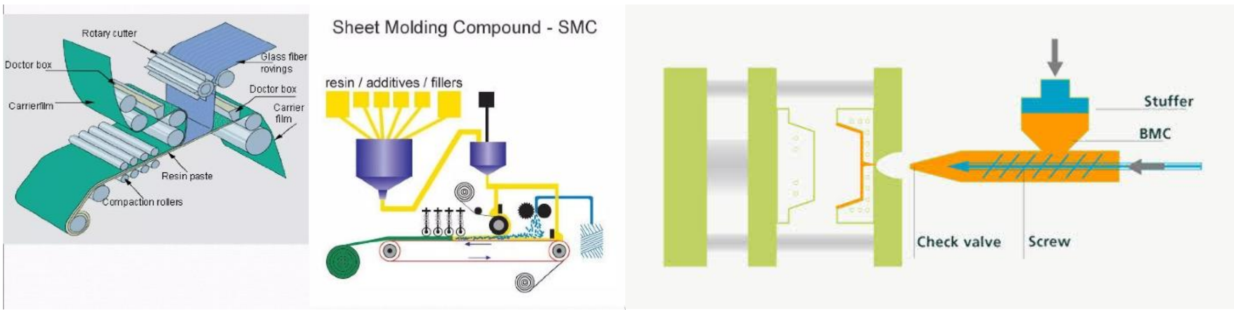

Figure 4.5 Schematic illustration of SMC/BMC injection moulding.

4.3 Continuous and Semi Automated Processes

Continuous processes produce composite components with constant cross sections or controlled fibre placement at high efficiency, combining automated fibre handling with continuous curing [5], [9].

A. Pultrusion

Pultrusion produces composite profiles with constant cross section by pulling continuous fibres through a resin bath, then through a heated die that shapes and cures the composite in a single continuous operation. The cured profile is cut to length as it exits the die [5].

This process achieves consistent fibre alignment, high volume fraction, and good longitudinal mechanical properties at high production rates. It is restricted, however, to components with uniform cross section — beams, rods, channels, and structural profiles for civil engineering and industrial applications [5].

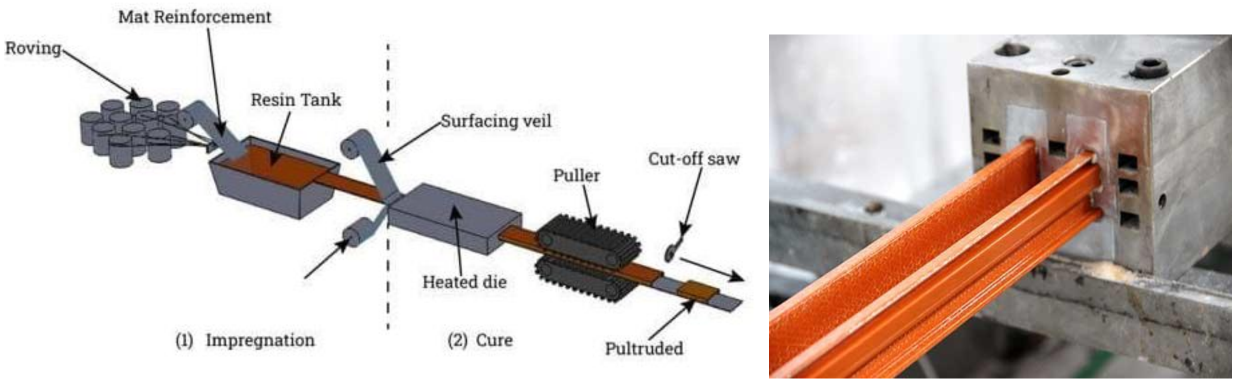

Figure 4.6 Schematic illustration of the pultrusion process.

B. Filament Winding

Filament winding is a semi automated process in which continuous resin impregnated fibre tows are wound onto a rotating mandrel at controlled angles following a predetermined pattern. The wound structure is then cured and the mandrel removed [9].

The process provides precise control over fibre orientation and achieves high fibre volume fractions, making it the standard method for manufacturing pressure vessels, pipes, rocket motor casings, and cylindrical storage tanks. Its principal limitation is restriction to primarily convex and axially symmetric geometries [9].

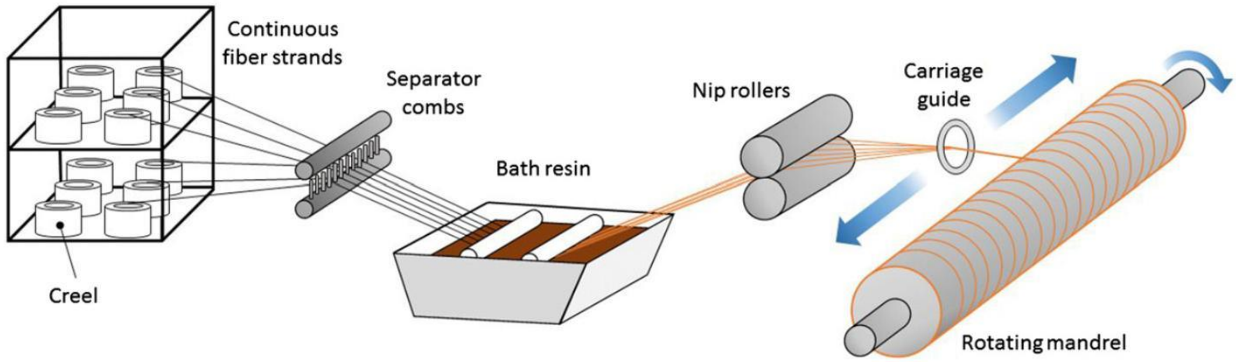

Figure 4.7 Schematic illustration of the filament winding process.

4.4 Modern Industrial Techniques

Modern manufacturing techniques improve production efficiency, reproducibility, and the capability to produce complex geometries beyond the reach of conventional methods [10], [11].

A. Automated Fibre Placement (AFP)

AFP is a computer-controlled process in which a robotic head places narrow strips of pre impregnated fibre (prepreg tapes or tows) onto a mould surface with high positional precision. The process offers precise fibre orientation control, reduced material waste, and the ability to manufacture large complex curved structures such as fuselage sections and wing skins. The principal barrier is high capital investment and the need for advanced programming and process control [10].

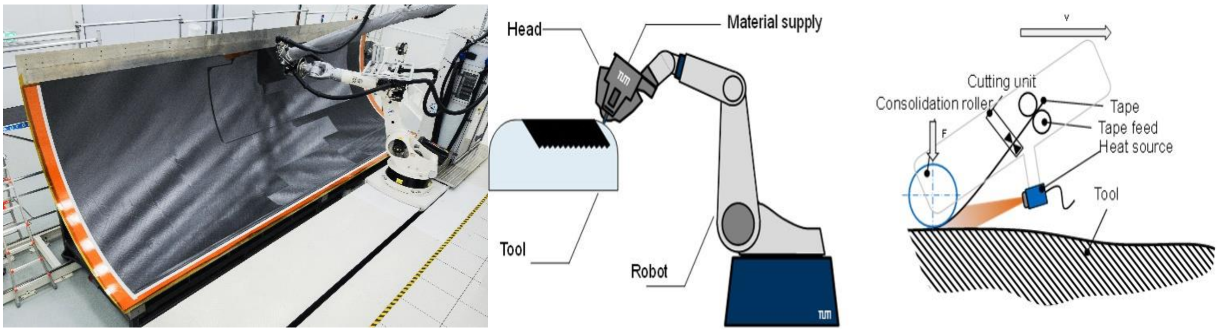

Figure 4.8 Automated Fibre Placement (AFP) robotic system.

B. Prepreg Processing

Prepreg processing uses pre impregnated reinforcement layers — fibres already combined with a controlled amount of partially cured resin — which are laid onto a mould in the required orientation and stacking sequence, then consolidated under heat and pressure, typically in an autoclave [11].

This method provides the most precise control over resin content and fibre volume fraction among all composite manufacturing techniques, producing high quality laminates with minimal void content and consistent mechanical properties. It is the standard method for high performance aerospace and motorsport structures. The trade offs are high material and processing cost, and the requirement for refrigerated storage to prevent premature curing of the prepreg material [11].

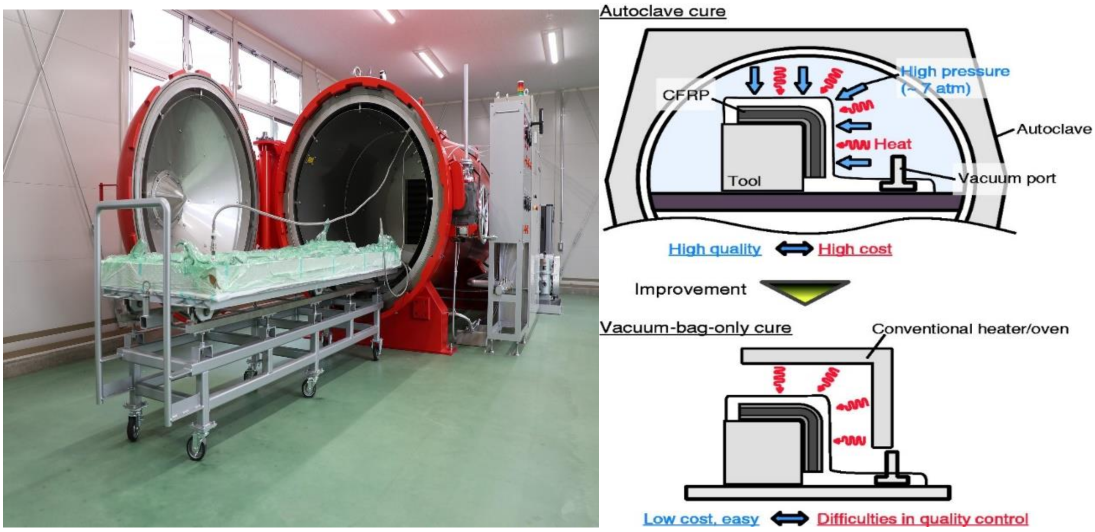

Figure 4.9 Prepreg lay up and autoclave curing process.

C. Additive Manufacturing of Composites (3D Printing)

Additive manufacturing enables composite part fabrication by depositing material layer by layer from a digital model. The two principal approaches are **Fused Deposition Modelling (FDM)**, which extrudes thermoplastic filaments reinforced with short fibres, and **Continuous Fibre Printing**, which deposits continuous fibres within a thermoplastic matrix during the printing process [10].

The technology offers high design freedom, rapid prototyping capability, and reduced material waste. Current limitations include lower mechanical performance compared with conventional methods, restricted build volume, and a limited range of compatible materials. Additive manufacturing is an active area of development with growing applications in aerospace, biomedical, and custom engineering components [10].

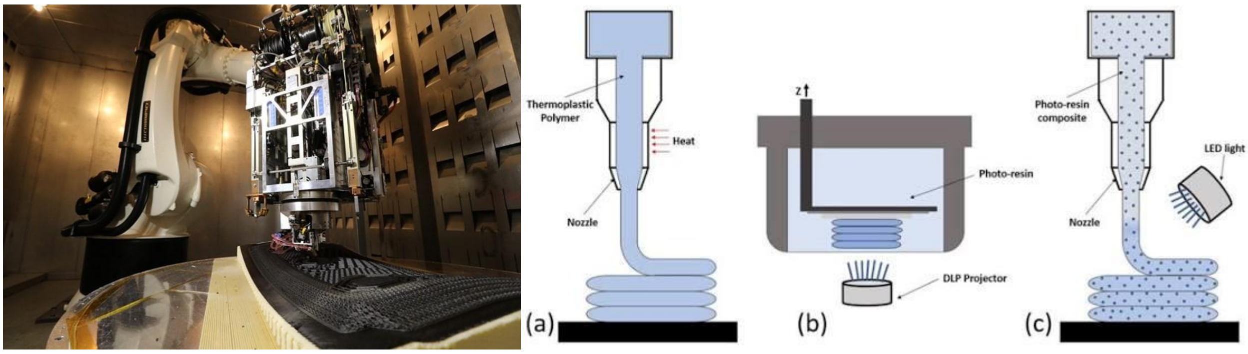

Figure 4.10 Additive manufacturing of composite materials.

4.5 Manufacturing Defects and Quality Control

The manufacturing process significantly affects the structural reliability of composite components. Defects introduced during processing can degrade mechanical performance and compromise service life [4], [10].

A. Common Manufacturing Defects

The principal defects encountered in composite manufacturing are:

- **Voids** entrapped air or gas pockets within the laminate that reduce mechanical strength and interfacial stress transfer efficiency. Void content is influenced directly by the consolidation pressure and degassing effectiveness of the manufacturing process.
- **Fibre misalignment** deviation from the intended fibre orientation, which reduces strength and stiffness in the designed loading direction. This defect is particularly critical in processes relying on manual fibre placement.
- **Incomplete curing** insufficient or non-uniform resin cross linking, leading to reduced mechanical properties and dimensional instability. It results from inadequate temperature control or premature interruption of the cure cycle.
- **Weak interfacial bonding** insufficient adhesion between reinforcement and matrix, reducing stress transfer efficiency and promoting premature failure under loading [4], [10].

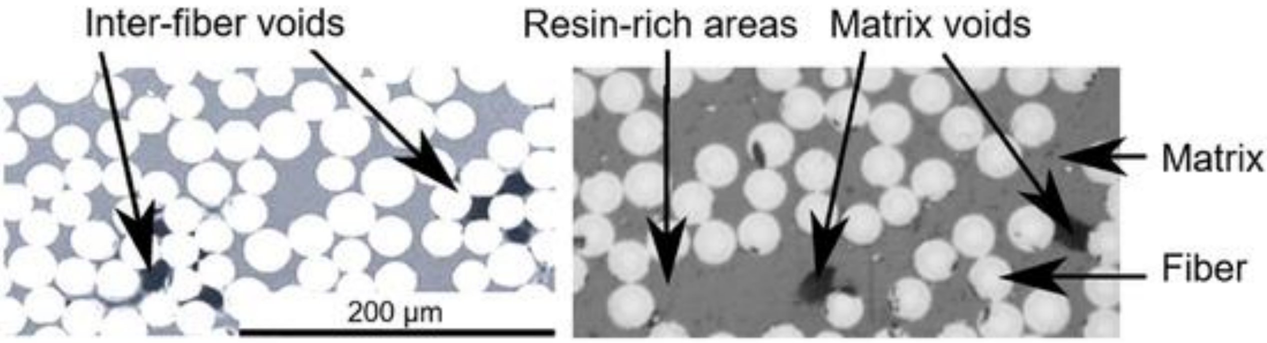

Figure 4.11 Common manufacturing defects in composite laminates: voids, fibre misalignment, incomplete curing, and interfacial debonding.

B. Quality Control and Inspection

Quality control methods verify that composite components conform to specified performance and reliability standards. Process monitoring tracks key parameters — temperature, pressure, and cure cycle duration — during manufacturing. Visual inspection identifies surface defects in finished components [11].

For internal defects that are not visible on the surface, Non-Destructive Testing (NDT) techniques are employed:

- **Ultrasonic inspection** detects delamination's, voids, and variations in laminate thickness by analyzing the propagation of sound waves through the material.
- **X ray inspection** reveals internal voids, fibre misalignment, and foreign inclusions.
- **Infrared thermography** identifies subsurface defects by detecting thermal anomalies on the component surface during controlled heating [11].

Quality control is essential in aerospace and high-performance applications where undetected defects can lead to catastrophic structural failure during service [11].

Figure 4.12 Non-destructive testing methods for composite inspection

References

[4] D. Hull and T. W. Clyne, An Introduction to Composite Materials, 2nd ed., Cambridge, UK: Cambridge University Press, 1996.

[5] R. M. Jones, Mechanics of Composite Materials, 2nd ed., Boca Raton, FL, USA: CRC Press, 2018.

[9] A. B. Strong, Fundamentals of Composites Manufacturing, 2nd ed., Dearborn, MI, USA: SME, 2008.

[10] P. K. Mallick, Fiber Reinforced Composites, 3rd ed., Boca Raton, FL, USA: CRC Press, 2007.

[11] S. K. Mazumdar, Composites Manufacturing, Boca Raton, FL, USA: CRC Press, 2002.