sophisticated technologies. Starting from a few selected materials and fiber composites, which were produced in very labor intensive, manual processes, today a variety of industries, including the aerospace and automotive industries, rely on low-weight, stiff, high-performance composites that could not be produced if it were not for prepreg materials and fully automated processes.

■ 3.2 Introduction: Manufacturing Methods

Prepregs, as semi-finished products containing pre-impregnated fibers (Figure 3.1), are a prerequisite for high quality and load-optimized lightweight fiber composites. The current manufacturing techniques and processes guarantee consistent quality of the prepregs, e.g., in terms of FAW and resin content, at a very high level. On the one hand, this simplifies processing for the manufacturer, and on the other it allows the reproducible production of high-quality components.

Prepregs always consist of a combination of a typically highly viscous matrix and a fiber reinforcement. Once the reinforcing material has been pre-impregnated with a matrix, it is considered a prepreg material. Both thermoplastic and thermosetting materials (reactive resin systems) can be used as matrices (see also Chapter 2) [2]. In the following, we will discuss the production of thermoset prepregs.

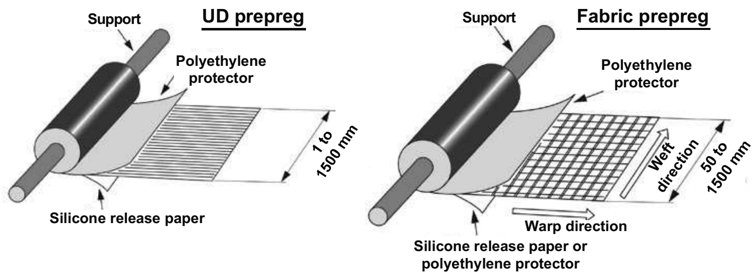

Figure 3.1 Delivery form of UD prepreg (left) and fabric prepreg (right) on supports [Courtesy: © Hexcel Corporation]

Fiber reinforcements are supplied in a number of different forms:

- uni-, bi-, and multidirectional fabrics
- fabrics
- non-wovens and random fiber mats

Depending on the reinforcing structure, processing techniques include creel sets (for rovings) and roll unwinders for fabrics.

Today, a number of different methods and machine concepts are available for the production of coating lines. They are able to use different fiber materials and combine them with a wide selection of matrix resins. State-of-the-art technologies include:

- solution coating processes (also called dipping (solvent) processes) (Figure 3.2)
- hot melt processes (Figure 3.2)
- knife systems
- powder scattering
- slot die systems

Some processes, such as powder scattering, were initially developed for thermoplastic matrices, but later adapted to thermoset processing. However, these processes have not found widespread industrial-scale use. Today, there are two major impregnating methods in industrial practice: the dipping (solvent) process and the hot melt process [2].

Not only do the base materials require cautious handling, but many parameters, including winding, control, impregnating, and drying, have to be considered and adapted individually depending on the type of reinforcement, the impregnating matrix, and the properties of the final product [1].

Thermoset prepregs are available in four typical variations: UD prepreg, fabric prepreg, slit tape, and tow prepregs.

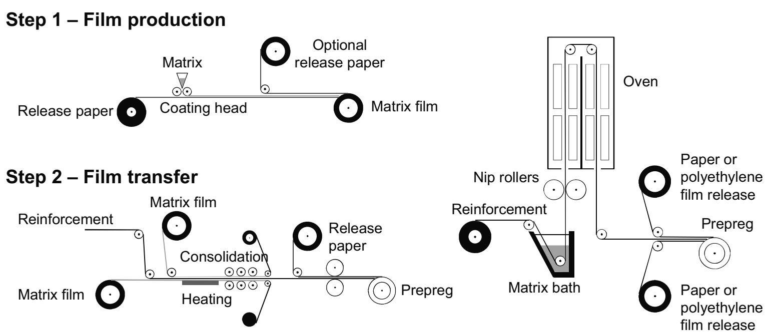

Figure 3.2 Manufacturing methods, left: hot melt process; right: solvent process

4 Prepregs: Processing Technology

Hauke Lengsfeld and Javier Lacalle

4.1 Introduction

In this chapter, we will describe the different technologies used to process prepregs and to transform them into prepreg components. We will introduce both manual and automated deposition methods as well as methods to cut and form prepreg materials.

One of the advantages of fiber reinforced materials is the fact that the fiber reinforcement can be strategically placed in the component to optimize the relationship between mechanical properties and weight.

Manufacturing methods using prepreg are particularly efficient because they achieve highest quality and most accurate fiber placement in the component. This also ensures optimum fiber volume content in the component, because the ratio of resin to fiber has already been coordinated in the prepreg. The layer structure may be deposited by hand or by automated processes.

In general, the processes used to manufacture composites are laminating and deposition processes that use flat, semi-finished products (e. g., prepregs) and deposit them in a specific sequence and in a defined orientation and shape on a mold or tool.

Today, there is a wide variety of processes available. There are two different approaches to classify these processes. First, considering the pressure applied during forming and curing leads to the classification of the most common processes as shown in Figure 4.1:

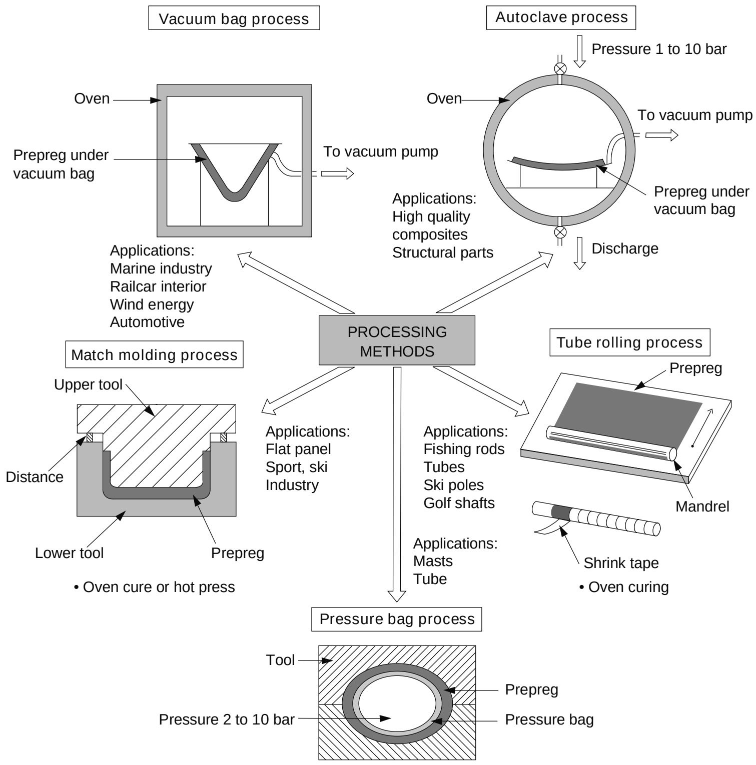

Figure 4.1 Curing and forming processes for prepregs [Courtesy: © Hexcel Corporation]

An alternative perspective considers the deposition and processing technologies that are used to process prepregs (Figure 4.2). This approach also includes the subsequent process of manufacturing a fiber reinforced composite part and provides a differentiated classification in the various technologies. While the pressure-oriented approach (see Figure 4.1) often includes the curing process, it is deliberately separated from the deposition and processing technologies. Curing is considered a separate step and thus includes the pressure processes shown in Figure 4.1.

Direct labeling of the finished cuts during cutting (whether manual or by cutter) prevents the interchange of cuttings during lamination. In addition, nowadays laser positioning systems are used that project the exact position and form of individual cuts on the lay-up area. These systems also prevent turning of cuttings and lay-up in the wrong orientation. The disadvantage of using templates becomes apparent when many different-sized cuts require the same high number of templates. With larger cuts, templates tend to become rather unwieldy. Another problem with hand lay-up of prepreg cuts is the sheer number of prepreg cuts necessary for the manufacture of complex components, which can reach several hundreds. This results in an additional logistics problem, especially when the cuts cannot be stored at room temperature but have to be kitted and frozen for storage.

Several parameters, including size, production rate, and the required accuracy and repeatability of the prepreg lay-up (form and positional tolerances) determine whether a component will be manufactured by hand lay-up or by an automated process. On the one hand, hand lay-up processes are time and personnel intensive; on the other hand, the high capital and operating costs of automated processes have to be considered.

In the past (until approx. 2004), large components, such as the vertical tail plane of the Airbus A320 and A330 series, were manufactured by hand lay-up of unidirectional tapes. For large components, the handling, exact positioning, and laying of long prepreg cuts without entrapping air is extremely difficult, and defects in the composite part are therefore hard to avoid. Therefore, the prepreg structure of such large components is typically manufactured using automated systems.

■ 4.4 Automated Laying Systems: Automated Tape Laying (ATL) and Automated Fiber Placement (AFP)

4.4.1 Introduction

Today, the automated laying of pre-impregnated fiber materials is a key technology for the manufacture of large composite components in the aerospace industry. For a number of years, automated tape laying has been used in conjunction with other technologies, such as hot-forming, to manufacture vertical tail panels, wing structures, stringers, spars, etc. The fast growing use of composite components both in aerospace and automotive applications, together with the increasing complexity of these components, has triggered the continuous growth in use and research of automated and highly efficient laying technologies. Figure 4.16 and Figure 4.17 show the geometric complexity as well as the size of composite parts.

Figure 4.16 Carbon fiber reinforced composite fuselage structures
[Courtesy: Airbus Operations GmbH]

The use of automated tape laying (ATL) and fiber placement (AFP) systems for the processing of UD tapes offers significant quality and productivity advantages compared to hand lay-up processes:

- Ply positioning and repeatability
- Deposition rate
- Uniform and void-free pre-compaction, etc.

Automatic lay-up by ATL und AFP is a widely-used standard process for the production of large parts in the aviation industry, one of the principal customers of prepregs. Both lay-up technologies deposit resin impregnated continuous fibers on the surface of a tool or mold. However, both processes have specific characteristics that make them ideally suited for various applications. Criteria for selecting a specific process include component geometry and manufacturing requirements such as the following:

- Component curvature
- Height and slope of the ramps
- Material drape
- Positive or negative (male or female) tool, etc.

ATL technology is typically used for geometrically simple contours, such as wing skins and flaps, panels for vertical and horizontal tail planes, flat laminates for hot-formed components, etc. AFP technologies are preferred over ATL for geometries with sections of double curvature and variable laminate thickness, such as spars and fuselage panels, etc., owing to their superior flexibility.

Additional important requirements for a tooling are favorable mechanical handling characteristics, such as good demolding and cleaning behavior, the possibility to make surface repairs, and low net weight; some of these are interrelated. The simpler it is to demold a component and to clean the tooling surface, the less wear the tooling is subjected to, and thus the less likely is the need for repairs. Low tooling net weight facilitates not only fast curing, but it also reduces handling costs, such as moving it by crane, rail system, or on a simple roll car. Implementation of a crane system is typically more cost intensive than utilization of a rail system.

Additional economic aspects are tooling manufacturing costs and service life, which depend on the tooling material, its availability, and its durability. The durability of the selected tooling material is of particular importance for autoclave toolings that have to withstand high cyclical temperature and pressure loads in order to avoid premature high wear.

■ 6.2 Tooling Materials

A variety of different materials is available for the manufacture of tools for the forming and curing operations of prepregs materials; these materials can also be combined, depending on the area of application.

Table 6.2 provides an overview of common tooling materials that will be described in more detail in the following.

Table 6.2 Examples of Tooling Materials

Material	Description	Type (examples)
Metals	▪ Steel ▪ Aluminum ▪ Nickel-steel alloy (Ni-[illegible])	▪ S[illegible]JR, S[illegible]JR ▪ ALMG [illegible]/ [illegible].[illegible] ▪ INVAR [illegible], Pernifer [illegible].[illegible]
CFRP (epoxy resin)	▪ Fabric prepreg ▪ Quasi-isotropic prepreg mat	▪ Cycom® [illegible], ▪ HexTOOL® M[illegible]
CFRP (BMI or BOX resin)	▪ Fabric prepreg ▪ Quasi-isotropic prepreg mat	▪ Duratool® [illegible] ▪ HexTOOL® M[illegible] ▪ Toolmaster BetaPreg
CFRP foam	▪ Carbon foam	▪ Touchstone CFoam® [illegible]
GFRP	▪ Dry fabric + resin, processed by resin infusion or hand lay-up	
Other materials	▪ Wood ▪ Epoxy tooling boards ▪ Cellular concrete	▪ OBO-Plywood, RETIstab ▪ Necuron, Rampf WB[illegible], ▪ OBO-Modulan, TB[illegible] Series ▪ Ytong

6.2.1 Metals

Metals are the easiest and most commonly used class of materials for the construction of tools for prepreg processing. This is due to their easy availability as well as their high load capacity. In addition, metal curing tools stand out for their robustness and thus high structural durability so that they can be utilized without difficulty for more than 1000 cycles. The surface of these tools is resistant to organic solvents and release agents, and even damage, such as scratches and dents, can typically be repaired easily.

Steel, aluminum, and ferronickel alloys are generally utilized, with steel and aluminum being the materials of choice because of their price and durability. Both materials exhibit a high coefficient of thermal expansion (Table 6.4) that needs to be taken into consideration during design of the tooling, in particular for high curing temperatures, in order to ensure its dimensional accuracy. Depending on tooling and application, thermal expansion may be desired, e. g., in order to facilitate for the finished component to shrink off the tooling during cooling (Chapter 8). Contour accuracy of 0.3 to 0.4 mm, even with large toolings (e. g., 20 × 5 m), can be achieved with metal tools at room temperature.

Figure 6.3 Steel tooling for the manufacture of rotor blades
[Courtesy: Premium Aerotec GmbH]

A disadvantage of steel is its high weight, which complicates handling and impedes heat transfer. Metal curing tools are generally manufactured by contour milling, but also by preforming of sheet metal. In order to ensure the created geometry, in particular for a large tooling (e. g., thick profiled sheet), even at high temperatures and/or during handling (e. g., by crane), the geometry is often stabilized by a stiff sub-structure ("egg carton" structure). This sub-structure also facilitates safe handling and installation, e. g., of vacuum lines and hoisting points to lift the tooling via crane.

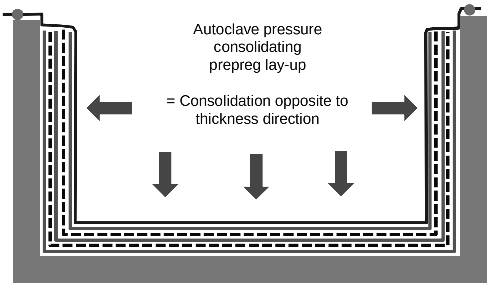

Figure 8.29 Consolidation and compaction inside tooling

Thus the inner plies are forced to expand or to perform a relative movement in order to balance the change in length caused by the consolidation. However, they may not always be able to make these adjustments. The applied autoclave pressure (typically 7 to 10 bar) and the bonding between the plies by the prepreg resin render relative movement of individual plies impossible. Because the autoclave pressure is more effective on the plane than on the radii, the inner prepreg plies will bridge the radius to a certain degree, thus changing force progression and load capacity of the component (Figure 8.30). The continuous, inner line marks the actual, the dotted line the required fiber orientation.

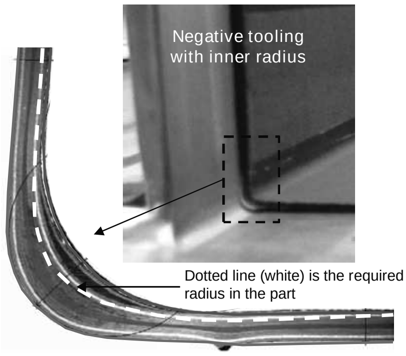

Figure 8.30 Micrograph of radius area showing the bridging effect of inner plies

This problem can be mitigated by one of several measures. For one, using a prepreg with a higher level of impregnation may minimize the consolidation. Another approach is the manufacture of a flat prepreg stack via ATL (rather than hand lay-up) and subsequent hot forming that would facilitate a pre-compaction of the stack prior to the curing process. Yet another, although somehow controversial, method is the use of pressure strips (rubber or silicone corner profiles) in the radii. It is possible to effectively increase the autoclave pressure in this area using pressure intensifiers in the form of round cords. However, they often cause deep undesired indentations in the laminate or the formation of beads in the border area of the pressure strips.

Interrelations: Example of a Sandwich Structure

The interrelations between component design, material, and curing process and their implications will be described using a sandwich structure as an example.

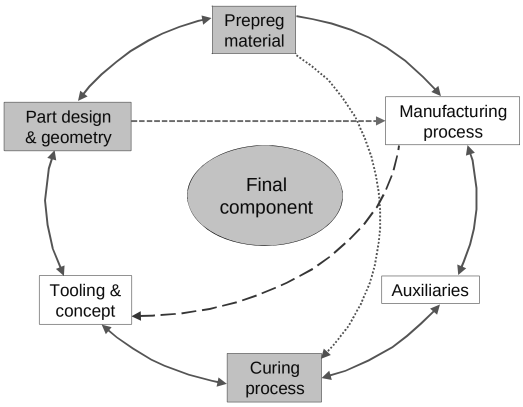

Figure 8.31 Effects of design, material, and curing process on component

PMI rigid foams (Evonik) can be used for the manufacture of Omega stringers (Figure 8.32). Typically, the formed foam remains in the component after curing of the prepreg, allowing for one-step curing of stringer and skin segment to be reinforced.

The cell walls of certain rigid foams do not exhibit sufficient dimensional stability under the temperatures (typically 180 °C) and pressures (7–10 bar) required for prepreg curing. Therefore, the pressure on the component is reduced to, e. g., 3 bar absolute.

Figure 8.32 Example of sandwich design: Omega-stringer with foam core

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