2

FABRICATION PROCESSES

The mixture of reinforcement/resin does not really become a composite material until the last phase of the fabrication, that is, when the matrix is hardened. After this phase, it would be impossible to modify the material, as in the way one would like to modify the structure of a metal alloy using heat treatment, for example.

In the case of polymer matrix composites, this has to be polymerized, for example, polyester resin. During the solidification process, it passes from the liquid state to the solid state by copolymerization with a monomer that is mixed with the resin. The phenomenon leads to hardening. This can be done using either a chemical (accelerator) or heat. The following pages will describe the principal processes for the formation of composite parts.

2.1 MOLDING PROCESSES

The flow chart in Figure 2.1 shows the steps found in all molding processes. Forming by molding processes varies depending on the nature of the part, the number of parts, and the cost. The mold material can be made of metal, polymer, wood, or plaster.

2.1.1 Contact Molding

Contact molding (see Figure 2.2) is open molding (there is only one mold, either male or female). The layers of fibers impregnated with resin (and accelerator) are placed on the mold. Compaction is done using a roller to squeeze out the air pockets. The duration for resin setting varies, depending on the amount of accelerator, from a few minutes to a few hours. One can also obtain parts of large dimensions at the rate of about 2 to 4 parts per day per mold.

2.1.2 Compression Molding

With compression molding (see Figure 2.3), the countermold will close the mold after the impregnated reinforcements have been placed on the mold. The whole assembly is placed in a press that can apply a pressure of 1 to 2 bars. The polymerization takes place either at ambient temperature or higher.

The process is good for average volume production: one can obtain several dozen parts a day (up to 200 with heating). This has application for automotive and aerospace parts.

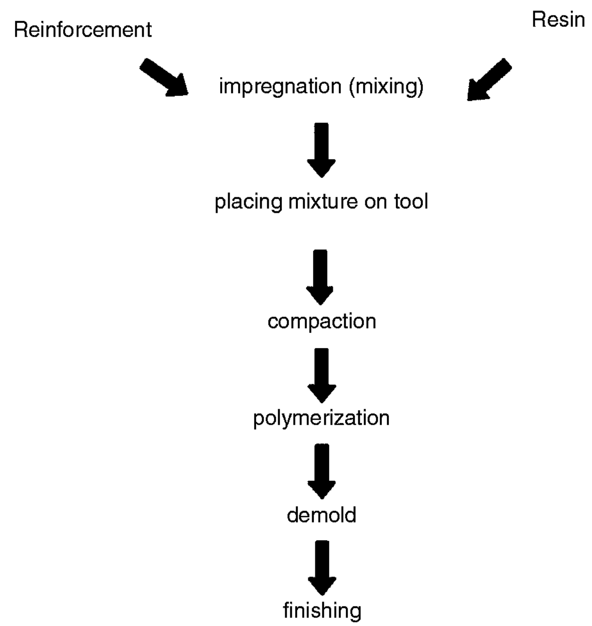

Figure 2.1 Steps in Molding Process

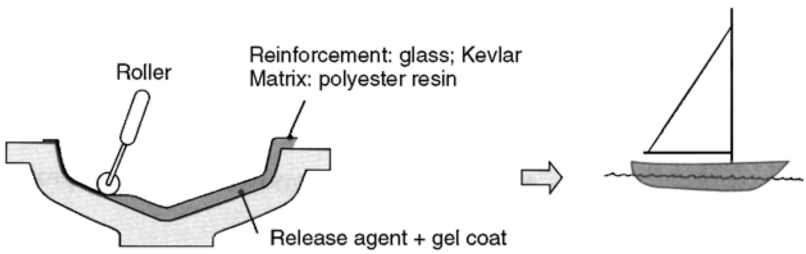

Figure 2.2 Contact Molding

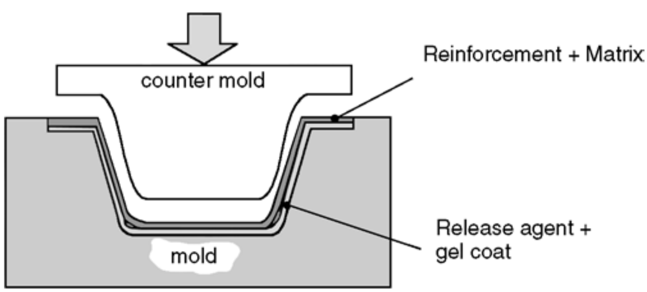

Figure 2.3 Compression Molding

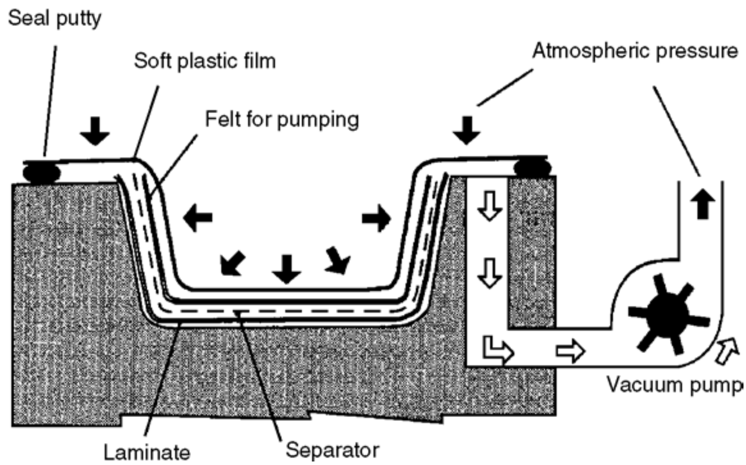

Figure 2.4 Vacuum Molding

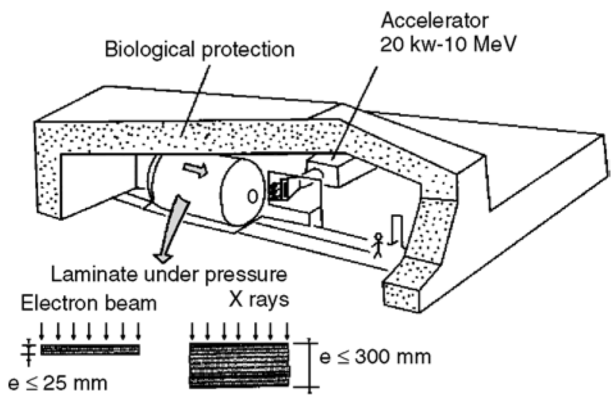

Figure 2.5 Electron Beam or X-ray Molding

2.1.3 Molding with Vacuum

This process of molding with vacuum is still called **depression molding** or **bag molding**. As in the case of contact molding described previously, one uses an open mold on top of which the impregnated reinforcements are placed. In the case of sandwich materials, the cores are also used (see Chapter 4). One sheet of soft plastic is used for sealing (this is adhesively bonded to the perimeter of the mold). Vacuum is applied under the piece of plastic (see Figure 2.4). The piece is then compacted due to the action of atmospheric pressure, and the air bubbles are eliminated. Porous fabrics absorb excess resin. The whole material is polymerized by an oven or by an autoclave under pressure (7 bars in the case of carbon/epoxy to obtain better mechanical properties), or with heat, or with electron beam, or x-rays; see Figure 2.5). This process has applications for aircraft structures, with the rate of a few parts per day (2 to 4).

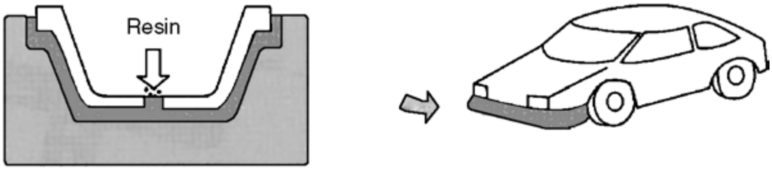

Figure 2.6 Resin Injection Molding

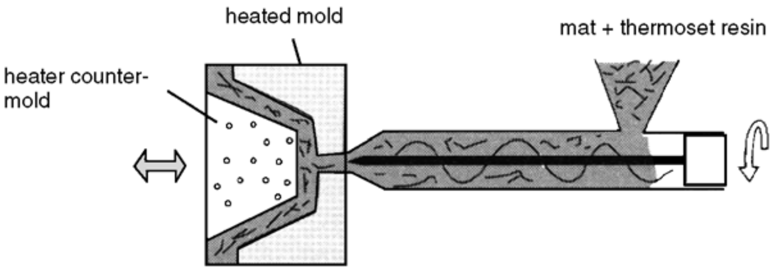

Figure 2.7 Injection of Premixed

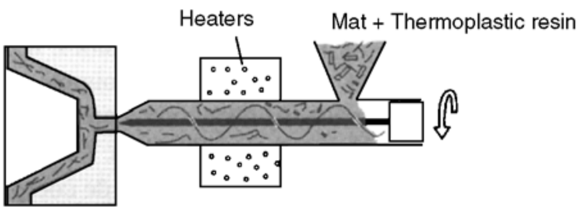

Figure 2.8 Injection of Thermoplastic Premixed

2.1.4 Resin Injection Molding

With resin injection molding (see Figure 2.6), the reinforcements (mats, fabrics) are put in place between the mold and countermold. The resin (polyester or phenolic) is injected. The mold pressure is low. This process can produce up to 30 pieces per day. The investment is less costly and has application in automobile bodies.

2.1.5 Molding by Injection of Premixed

The process of molding by injection of premixed allows automation of the fabrication cycle (rate of production up to 300 pieces per day).

- **Thermoset resins:** Can be used to make components of auto body. The schematic of the process is shown in Figure 2.7.
- **Thermoplastic resins:** Can be used to make mechanical components with high temperature resistance, as shown in Figure 2.8.

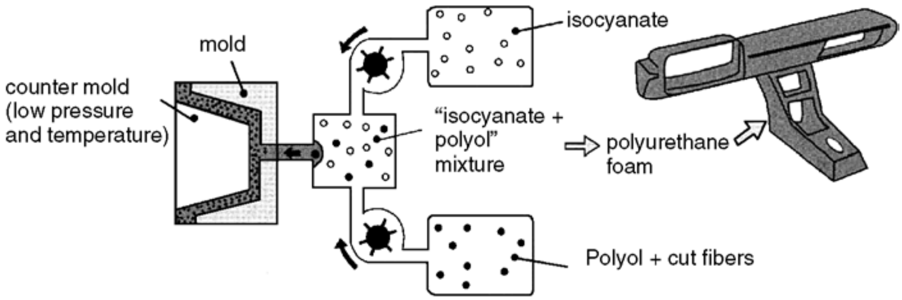

Figure 2.9 Foam Injection

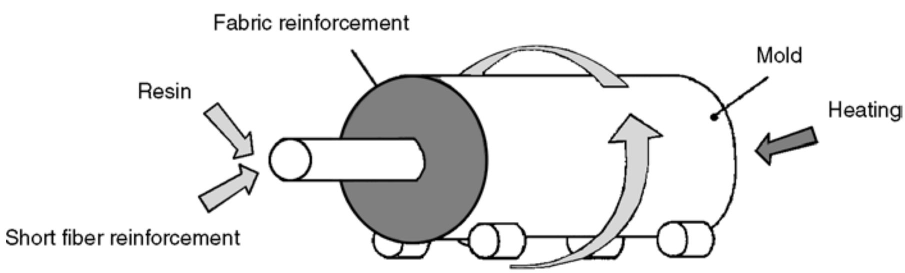

Figure 2.10 Centrifugal Molding

2.1.6 Molding by Foam Injection

Molding by foam injection (see Figure 2.9) allows the processing of pieces of fairly large dimensions made of polyurethane foam reinforced with glass fibers. These pieces remain stable over time, with good surface conditions, and have satisfactory mechanical and thermal properties.

2.1.7 Molding of Components of Revolution

The process of **centrifugal molding** (see Figure 2.10) is used for the fabrication of tubes. It allows homogeneous distribution of resin with good surface conditions, including the internal surface of the tube. The length of the tube depends on the length of the mold. Rate of production varies with the diameter and length of the tubes (up to 500 kg of composite per day).

The process of **filament winding** (see Figure 2.11) can be integrated into a continuous chain of production and can fabricate tubes of long length. The rate of production can be up to 500 kg of composite per day. These can be used to make missile tubes, torpillas, containers, or tubes for transporting petroleum.

For pieces which must revolve around their midpoint, winding can be done on a mandrel. This can then be removed and cured in an autoclave (see Figure 2.12). The fiber volume fraction is high (up to 85%). This process is used to fabricate components of high internal pressure, such as reservoirs and propulsion nozzles.

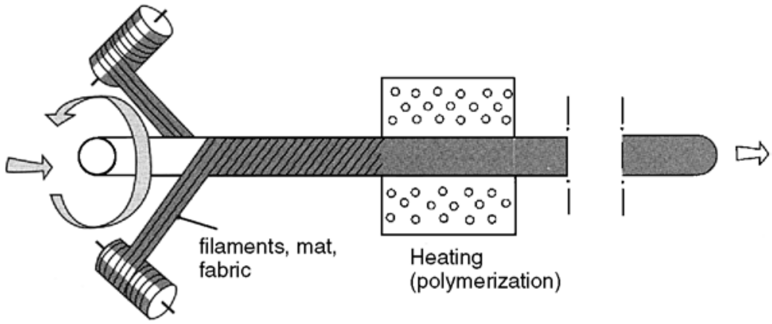

Figure 2.11 Filament Winding

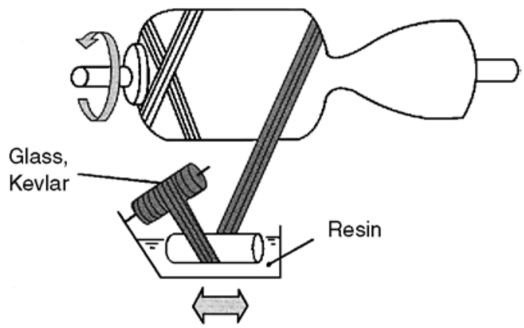

Figure 2.12 Filament Winding on Complex Mandrel

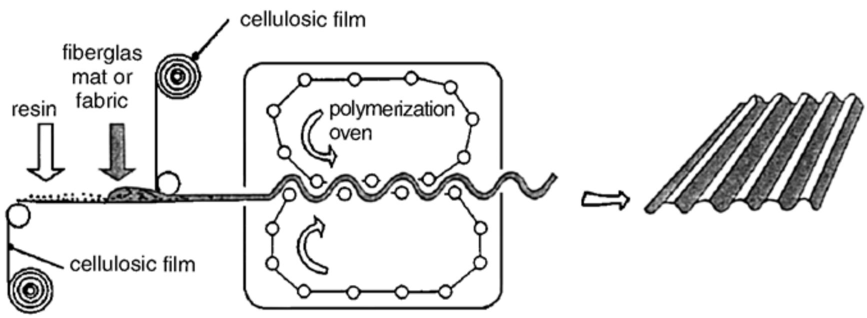

Figure 2.13 Sheet Forming

2.2 OTHER FORMING PROCESSES

2.2.1 Sheet Forming

This procedure of sheet forming (see Figure 2.13) allows the production of plane or corrugated sheets by corrugation or ribs.

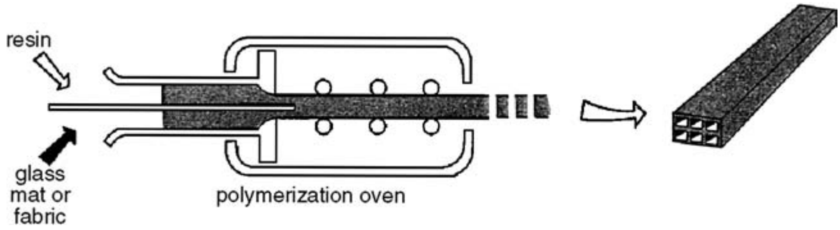

Figure 2.14 Profile Forming

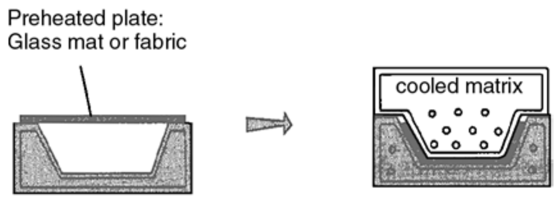

Figure 2.15 Stamp Forming

2.2.2. Profile Forming

The piece shown in Figure 2.14 is made by pultrusion. This process makes possible the fabrication of continuous open or closed profiles. The fiber content is important for high mechanical properties. The rate of production varies between 0.5 and 3 m/minute, depending on the nature of the profile.

2.2.3 Stamp Forming

Stamp forming (see Figure 2.15) is only applicable to thermoplastic composites. One uses preformed plates, which are heated, stamped, and then cooled down.

2.2.4 Preforming by Three-Dimensional Assembly

Example: Carbon/carbon: The carbon reinforcement is assembled by depositing the woven tows along several directions in space. Subsequently the empty space between the tows is filled by "impregnation." The following two techniques are used:

- **Impregnation using liquid:** Pitch is used under a pressure of 1000 bars, followed by carbonization.
- **Impregnation using gas:** This involves chemical vapor deposition using a hot gaseous hydrocarbon atmosphere.

Example: Silicon/silicon. The reinforcement is composed of filaments of silicon ceramics. The silicon matrix is deposited in the form of liquid solution of colloidal silicon, followed by drying under high pressure and high temperature (2000 bars, 2000°C). The preforms are then machined. The phases of development of these composites, such as the densification (formation of the matrix) are long and delicate. These make the products very onerous. Applications include missile and launcher nozzles, brake disks, ablative tiles for reentry body of spacecraft into the atmosphere.

2.2.5 Cutting of Fabric and Trimming of Laminates

Some components need a large number of fabric layers (many dozens, can be hundreds). For the small and medium series, it can be quite expensive to operate manually for

- following the form of a cut.
- respect the orientation specified by the design (see Chapter 5).
- minimizing waste.

There is a tendency to produce a cut or a drape automatically with the following characteristics:

- a programmed movement of the cutting machine
- a rapid cutting machine, such as an orientable vibrating cutting knife or a laser beam with the diameter of about 0.2 mm and a cutting speed varying from 15 to 40 meters/minute, depending on the power of the laser and the thickness of the part.

Example: With a draping machine MAD Forest-Line (FRA), the draping is done in two steps by means of two distinct installations:

- A cutting machine that produces a roller to which the cut pieces are attached (cassettes)
- A depositing machine which uses the cassette of cut pieces to perform the draping.

The two operations are shown schematically in Figure 2.16.

2.3 PRACTICAL HINTS ON MANUFACTURING PROCESSES

2.3.1 Acronyms

To describe the modes of fabricating the composite pieces, the professionals use many abbreviations. Each is detailed below, with reference to the paragraph number where the process is explained.

> **B.M.C.:** "Bulk Molding Compound." Matrix: resins. Reinforcement: cut fibers; additional fillers (powder). Pressure: 5–10 *MPa*. Temperature: 120–150°C.
> **Centrifugation:** Matrix: resins. Reinforcement: cut fibers, mat, fabrics; see Section 2.1.7.

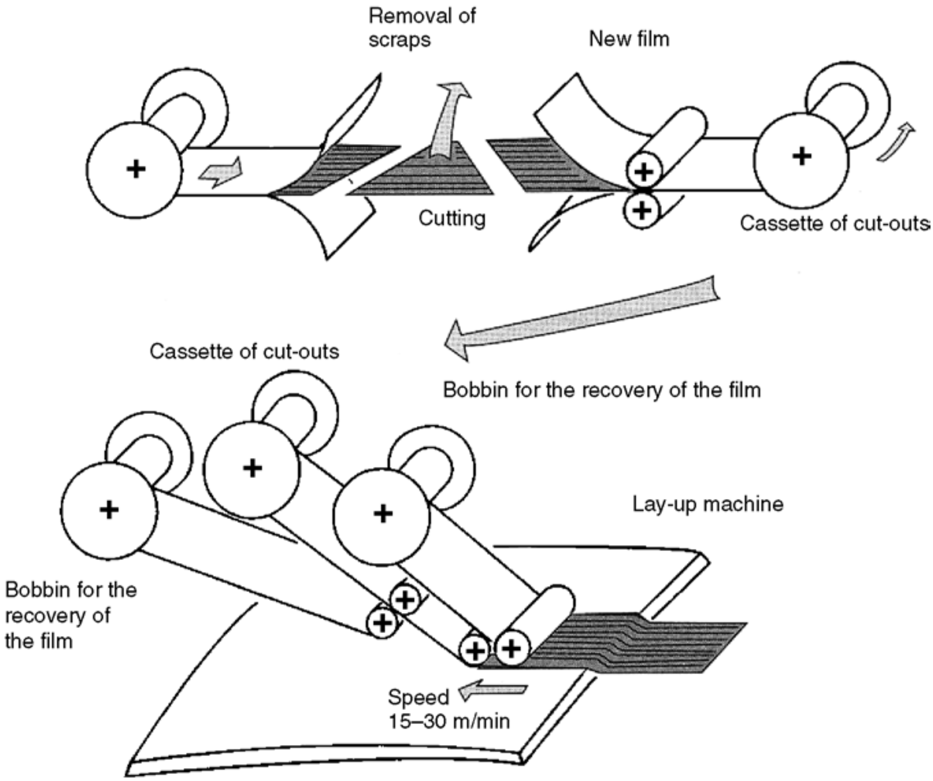

Figure 2.16 Draping Process

Contact molding: Matrix: resins. Reinforcement: mat, fabrics; see Section 2.1.1.

Filament winding: Matrix: resins. Reinforcement: continuous fibers; see Section 2.1.7.

Compression molding: Matrix: resins. Reinforcement: fabrics or unidirectionals; see Section 2.1.2.

Autoclave molding: Matrix: resins. Reinforcement: fabrics or unidirectionals; under pressure in an autoclave; see Section 2.1.3.

Pultrusion: Matrix: resins. Reinforcement: mat, fabrics, continuous fibers; see Section 2.2.2.

R-RIM: "Reinforced–Reaction Injection Molding" (there is expansion in the mold). Pressure: 0.5 MPa. Temperature: 50–60° C; see Section 2.1.6.

S-RIM: "Structural Reaction Injection Molding" (components for structure, particularly in automobiles). Similar to R-RIM, injection of liquid thermoset resins consists of two highly reactive constituents.

RTM: "Resin Transfer Molding." Matrix: resins.. Reinforcement: Preforms of cut fibers or fabrics. Pressure: low (in vacuum or 0.1–0.3 *MPa*). Temperature: 80°C.

SMC: "Sheet Molding Compound." Matrix: liquid resin with addition of magnesia. Reinforcement: mat, unidirectionals. Pressure: 5–10 *MPa*. Temperature: 120–150°C.

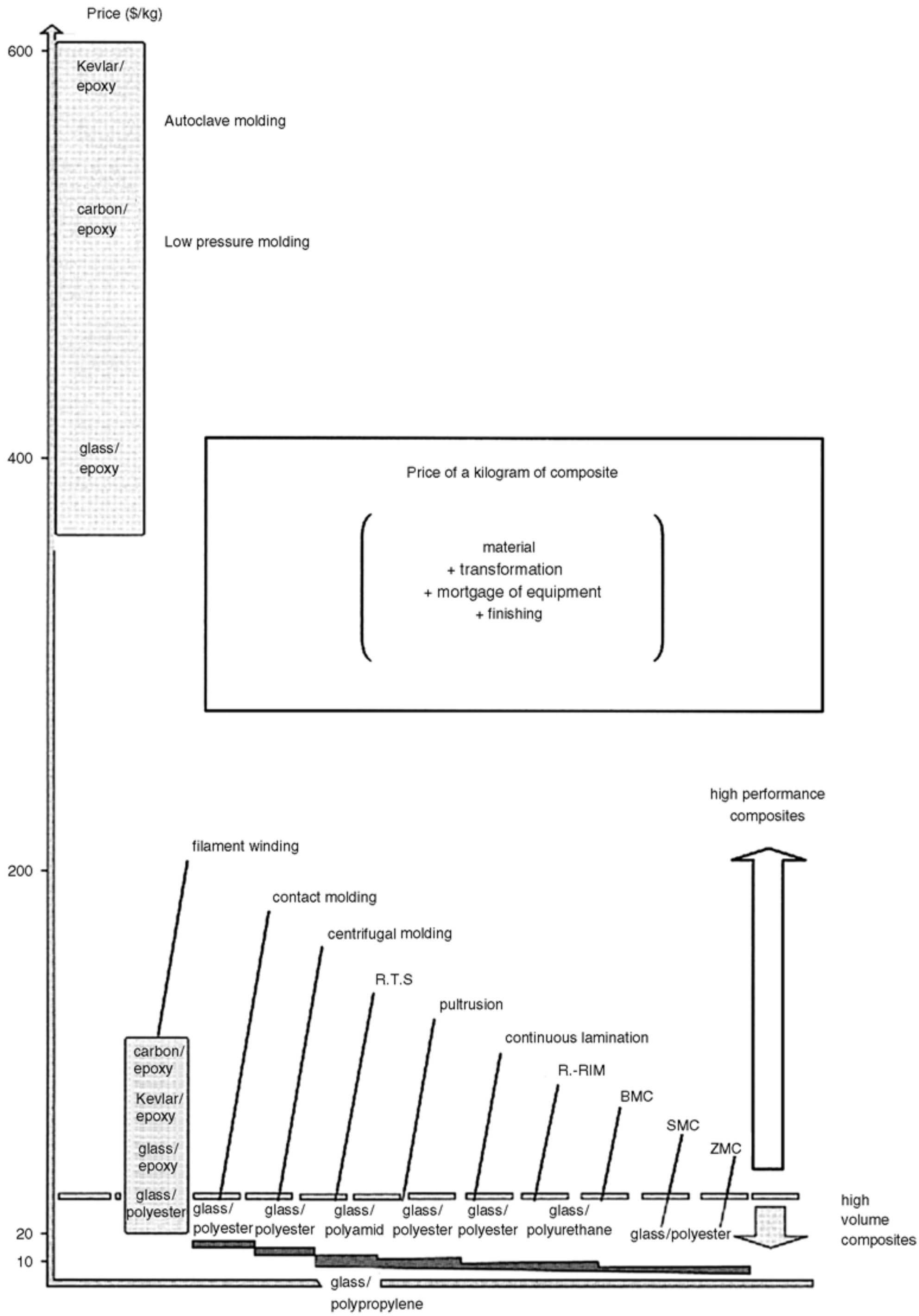

Figure 2.17 Cost Comparison for Different Processes

RTP: "Reinforced Thermoplastics." Matrix: thermoplastic resins. Reinforcement: cut fibers. Pressure: 50 to 150 *MPa*. Temperature: 120–150°C.

RST: "Reinforced Stamped Thermoplastics." Pressure: 15–20 *MPa*. Initial temperature: ≈200°C; see Section 2.2.3.

ZMC: Matrix: resin. Reinforcement: cut fibers. Pressure: 30–50 *MPa*. Temperature: 120–150°C.

TMC: Similar to "SMC" but with higher amount of glass fibers (a few millimeters in thickness).

XMC: Similar to "SMC" but with specific orientation of the fibers.

2.3.2 Cost Comparison

The diagram in Figure 2.17 allows the comparison of the cost to fabricate composite products. One needs to note the important difference between the cost of composites produced in large volume and the cost of high performance composites.