MATERIAIS COMPÓSITOS 3ª Parte

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Processos de Fabricação de Compósitos

Aspectos importantes a serem considerados na escolha do processo:

- **Custo**: envolve o custo do equipamento, se houver, do treinamento, da mão-de-obra, da matéria-prima, etc.
- **Escala de produção**: alta produção em série, como na indústria automobilística, ou baixa escala, como na indústria aeronáutica e naval, ou ainda, peças únicas como protótipos e modelos.
- **Dimensão física do componente**: peças grandes como cascos de barcos, carrocerias de ônibus e caminhões, piscinas, tanques e reservatórios necessitam processos de produção distintos de peças diminutas.
- **Volume relativo de fibra**: certos métodos serão mais adequados à produção de peças com baixa porcentagem de fibras, como nos processos manuais com mantas, enquanto outros conseguirão naturalmente altas proporções, como no bobinamento.
- **Repetibilidade de características do item**: processos manuais tenderão à baixa repetibilidade e alta variação das dimensões e qualidade geral dos itens produzidos, em oposição aos métodos automatizados.

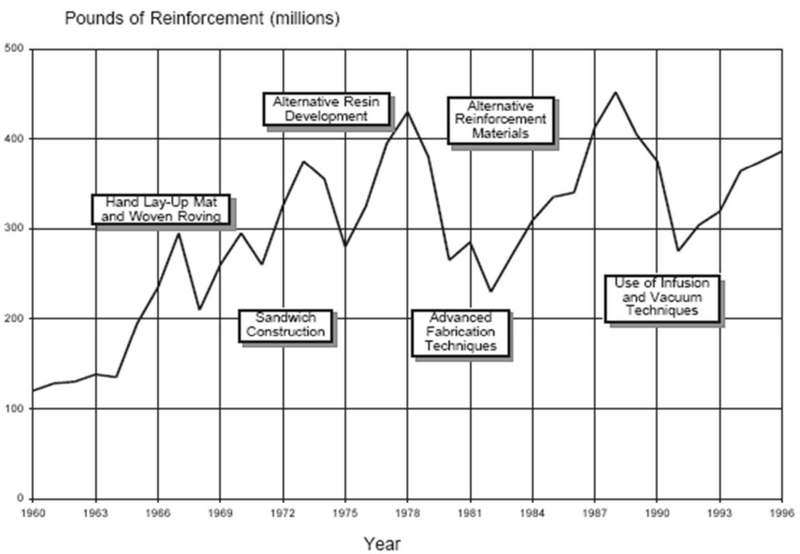


Figure Annual Shipment of Reinforced Thermoset and Thermoplastic Resin Composites for the Marine Industry with Associated Construction Developments. [Data Source: SPI Composites Institute (1960-1973 Extrapolated from Overall Data)]

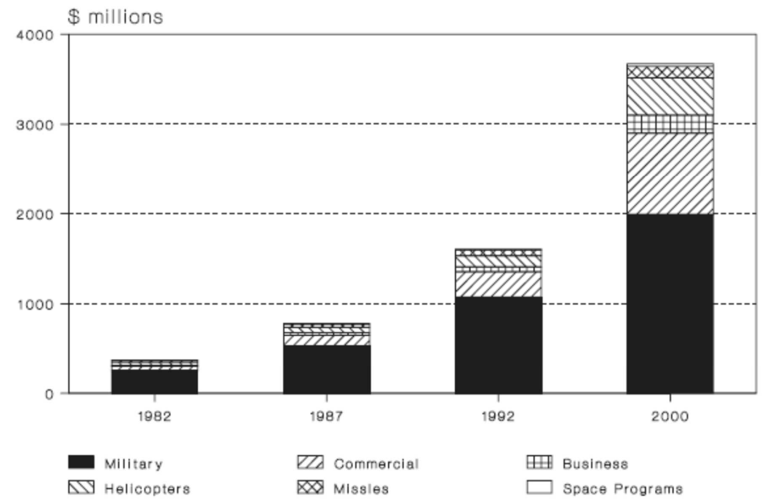


Figure Advanced Composite Sales for the Aerospace Industry. [Source: *P-023N Advanced Polymer Matrix Composites*, Business Communication Company, Inc.]

Classificação dos Processos

Processos de Conformação Molhada

- Processo manual (*hand lay-up*)
- Bobinamento (*filament winding*)
- Trefilação (*pultrusion*)
- Moldagem por membrana (*bug molding*)

Processos com Pré-Formados

- Premix em bloco (*bulk molding compounding = BMC*)
- Premix em folha (*sheet molding compounding = SMC*)
- Prepregs)

Processo Manual (Vantagens)

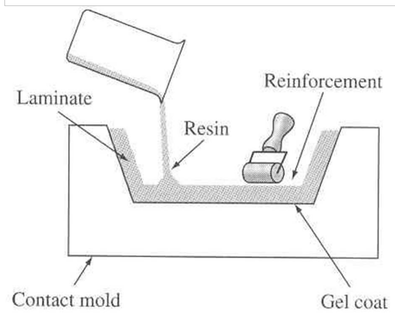
- Adequada a baixos volumes de produção (e.g. partes de avião)
- Permite a produção de peças grandes de forma contínua, sem emendas ou uniões (redução de custos e melhoria da resistência)
- Baixo investimento inicial (não requer equipamento, exceto para construção do molde).
- Processo artesanal (flexibilidade do projeto e facilidade de alterações na estrutura.
- Facilidade de construção de painéis sanduíche.

Processo Manual (Desvantagens)

- Requer muita mão-de-obra.
- Limitada a baixos volumes de produção
- Tempos de cura altos (em geral produzidos à temperatura ambiente).
- A qualidade do item depende da habilidade do operário.
- A porcentagem de refugo e desperdício pode ser alta.

Processo Manual (Hand Layup)

- Gel coat is applied to open mold.
- Fiberglass reinforcement is placed in the mold.
- Base resin mixed with catalysts is applied by pouring and brushing.
- Layup is made by building layer upon layer to obtain the desired thickness.
- Disadvantage: low concentration of reinforcing phase (up to 30%) and low densification of the composites (entrapped air bubbles).



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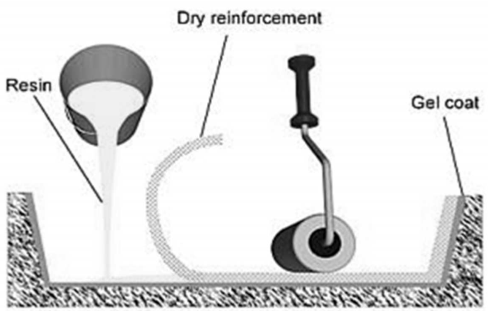


Hand Layup

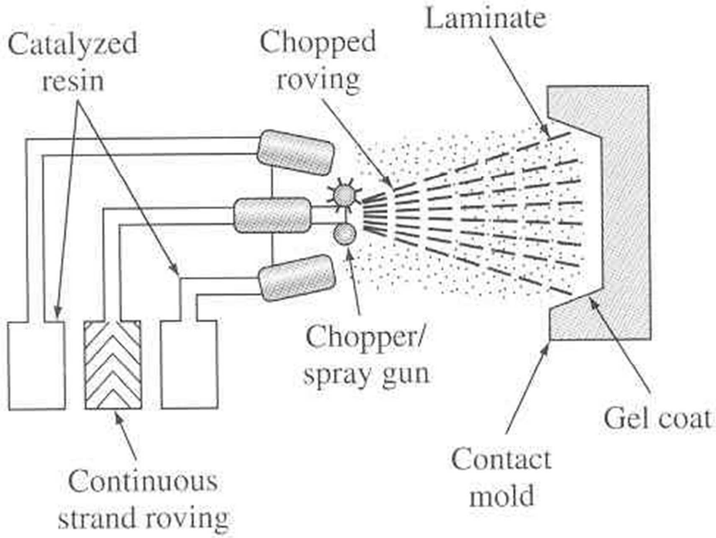
Advantages:

- Widely used.
- Low tooling cost.
- Custom shape.
- Larger and complex items can be produced.

Potential Problems:

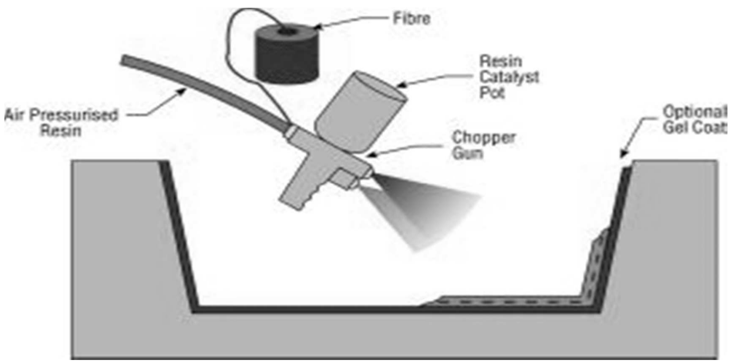
- Labour intensive.
- Low-volume process.
- Quality control is entirely dependent on the skill of labourers.

Spray up Process



In spray up process, chopped fibers and resins are sprayed simultaneously into or onto the mold.

Applications are lightly loaded structural panels, e.g. caravan bodies, truck fairings, bathtubs, small boats, etc



Bobinamento (Filament Winding)

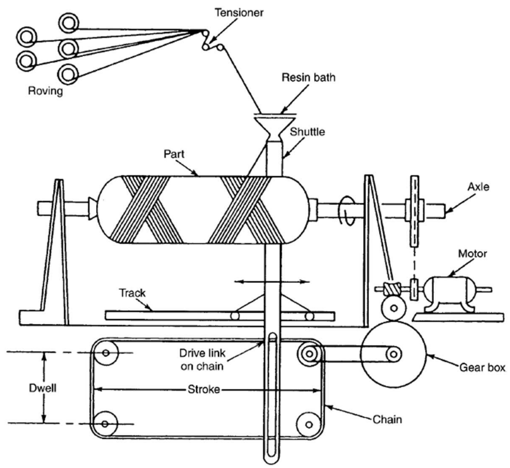


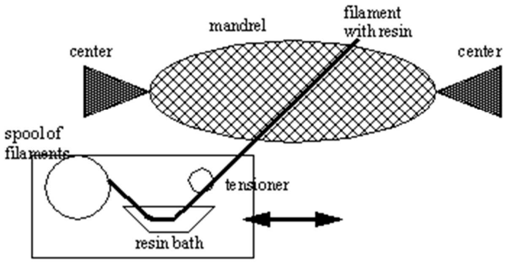
Figure F.2 Filament winding process using a liquid thermosetting resin system. (Ref: Hull, J.L., "Processing of Thermosets", *Modern Plastics Handbook*, McGraw-Hill, New York, 2000)

Involves a continuous filament of reinforcing material wound onto a rotating mandrel in layers at different layers.

If a liquid thermosetting resin is applied on the filament prior to winding the, process is called Wet Filament Winding.

If the resin is sprayed onto the mandrel with wound filament, the process is called Dry Filament Winding.

Besides conventional curing of molded parts at room temperature, autoclave curing may be used.



Advantages

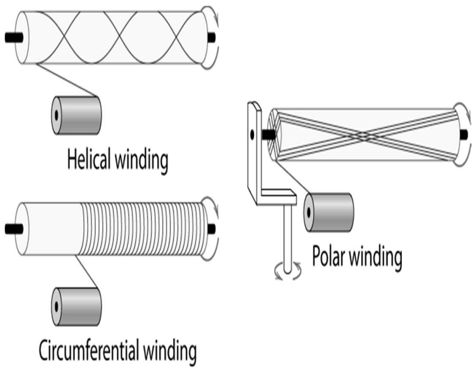
- Good for wide variety of part sizes
- Parts can be made with strength in several different directions
- Very low scrap rate
- Non-cyclindrical parts can be formed after winding
- Flexible mandrels can be left in as tank liners
- Reinforcement panels, and fittings can be inserted during winding
- Due to high hoop stress, parts with high pressure ratings can be made

Disadvantages

- Viscosity and pot life of resin must be carefully chosen
- NC programming can be difficult
- Some shapes can't be made with filament winding
- Factors such as filament tension must be controlled

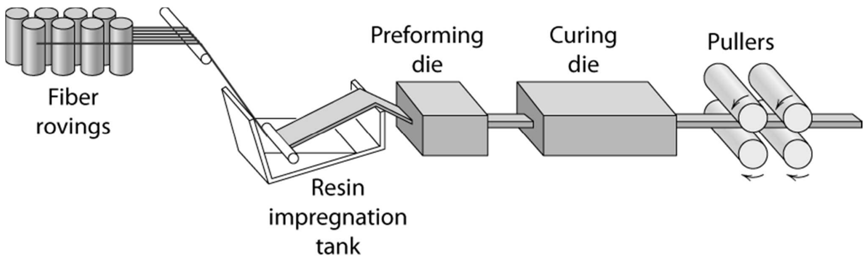
Winding Patterns

- **hoop** (90º) - girth or circumferential winding
  - angle is normally just below 90° degrees
  - each complete rotation of the mandrel shifts the fibre band to lie alongside the previous band.
- **helical**
  - complete fibre coverage without the band having to lie adjacent to that previously laid.
- **polar**
  - domed ends or spherical components
  - fibres constrained by bosses on each pole of the component.
- **axial** (0º)
  - **beware:** difficult to maintain fibre tension

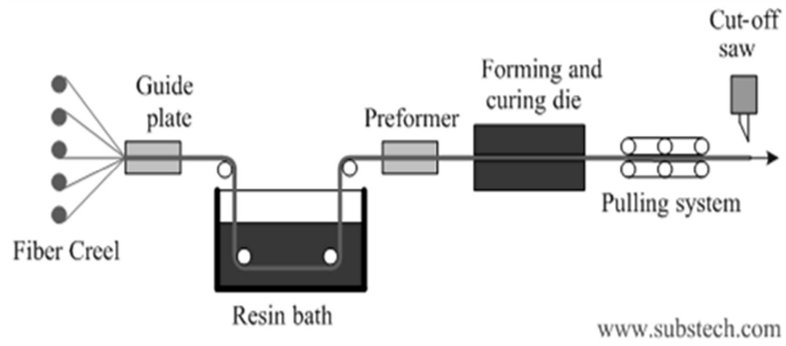


Pultrusão

Process where composite parts are manufactured by pulling layers of fibres/fabrics, impregnated with resin, through a heated die, thus forming the desired cross-sectional shape with no part length limitation.



- *Pultrusion process involves the following operations:*
- Reinforcing fibers are pulled from the creels. Fiber (roving) creels may be followed by rolled mat or fabric creels. Pulling action is controlled by the pulling system.
- Guide plates collect the fibers into a bundle and direct it to the resin bath.
- Fibers enter the resin bath where they are wetted and impregnated with liquid resin. Liquid resin contains thermosetting polymer, pigment, fillers, catalyst and other additives.
- The wet fibers exit the bath and enter preformer where the excessive resin is squeezed out from fibers and the material is shaped.
- The preformed fibers pass through the heated die where the final cross-section dimensions are determined and the resin curing occurs.
- The cured product is cut on the desired length by the cut-off saw.



Advantages:

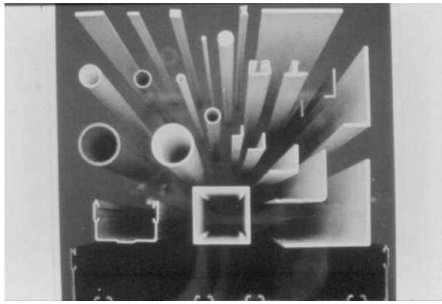
- ➢ Minimal kinking of fibres/fabrics
- ➢ Rapid processing
- ➢ Low material scrap rate
- ➢ Good quality control

Potential Problems:

- ➢ Improper fibre wet-out
- ➢ Fibre breakage
- ➢ Inadequate cure
- ➢ Die jamming
- ➢ Complex die design

Pultrusion -applications

- panels – beams – gratings – ladders
- tool handles - ski poles – kites
- electrical insulators and enclosures
- light poles - hand rails – roll-up doors
- 450 km of cable trays in the Channel Tunnel



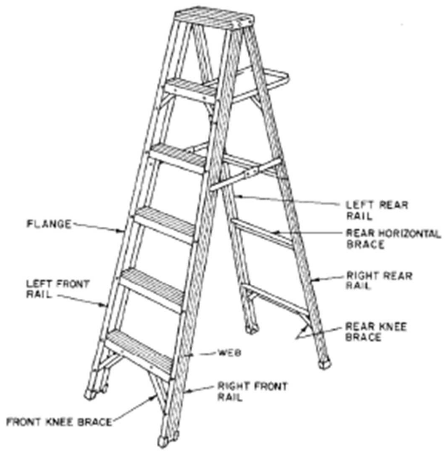
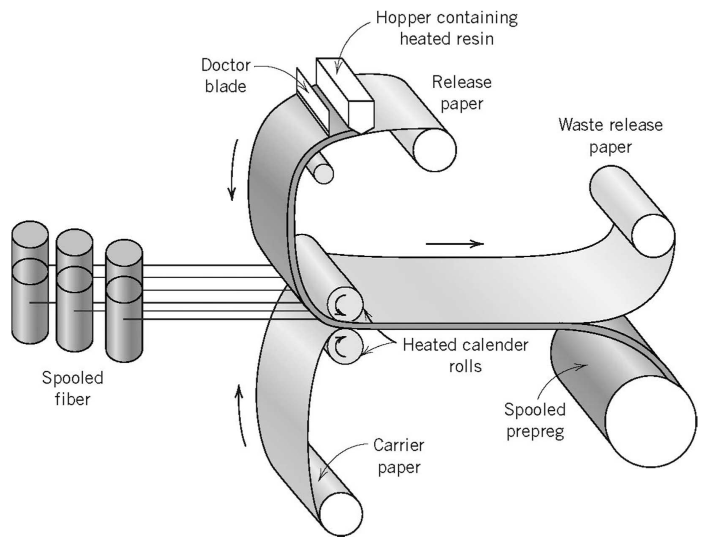
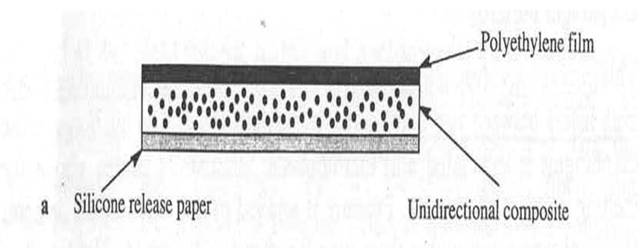


Figure Stepladder with Composite Rails [ANSI standard A14.5-1982]

Produção de Prepregs



- Manufacturing begins by collimating a series of spool-wound continuous fiber tows.
- Tows are then sandwiched and pressed between sheets of release and carrier paper using heated rollers (calendering).
- The release paper sheet has been coated with a thin film of heated resin solution to provide for its thorough impregnation of the fibers.
- The final prepreg product is a thin tape consisting of continuous and aligned fibers embedded in a partially cured resin.



- The prepreg is stored at 0°C (32 °F) or lower because matrix undergoes curing reactions at room temperature. Also the time in use at room temperature must be minimized. Life time is about 6 months if properly handled.
- Both thermoplastic and thermosetting resins are utilized: carbon, glass, and aramid fibers are the common reinforcements.
- Actual fabrication begins with the lay-up. Normally a number of plies are laid up to provide the desired thickness.
- The layup can be by hand or automated.
- Easily obtained with epoxies.

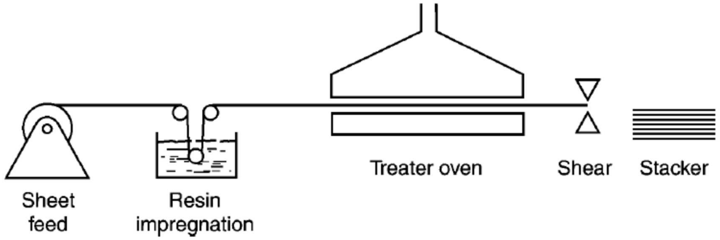


Figure L.1 Horizontal treater for preparing prepreg for laminates. (Ref: Harper, C.A., "Laminate Reinforced Plastic Materials and Processes", *Handbook of Plastics, Elastomers, and Composites*, 3r C.A. Harper, ed., McGraw-Hill, New York, 1996)

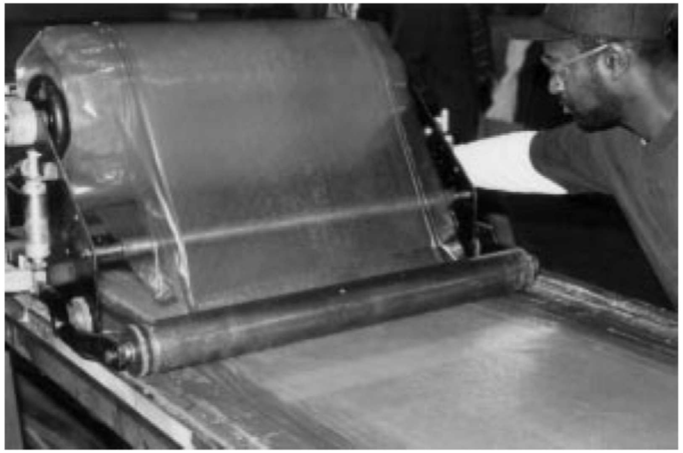


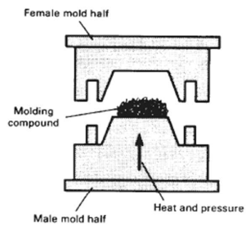
Figure Prepreg Ply of E-Glass is Rolled Out on Consolidation Table by Composite Ships

Outros Tipos de Processos

Premix em Bloco (BMC)

COMPRESSION MOLDING

A high-volume, high-pressure method suitable for molding complex, high-strength fiberglass-reinforced plastic parts. Fairly large parts can be molded with excellent surface finish. Thermosetting resins are normally used.



Process Description

Matched molds are mounted in a hydraulic or mechanical molding press. A weighed charge of sheet or bulk molding compound, or a "preform" or fiberglass mat with resin added at the press, is placed in the open mold. In the case of preform or mat molding, the resin may be added either before or after the reinforcement is positioned in the mold, depending on part configuration. The two halves of the mold are closed, and heat (225 to 320°F) and pressure (150 to 2000 psi) are applied. Depending on thickness, size, and shape of the part, curing cycles range from less than a minute to about five minutes. The mold is opened and the finished part is removed. Typical parts include: automobile front ends, appliance housings and structural components, furniture, electrical components, business machine housings and parts.

Resin Systems

Polyesters (combined with fiberglass reinforcement as bulk or sheet molding compound, preform or mat), general purpose flexible or semi-rigid, chemical resistant, flame retardant, high heat distortion; also phenolics, melamines, silicones, dallyl phtalate, and some epoxies.

Molds

Single- or multiple-cavity hardened and chrome plated molds, usually cored for steam or hot oil heating: sometimes electric heat is used. Side cores, provisions for inserts, and other refinements are often employed. Mold materials include cast of forged steel, cast iron, and cast aluminum.

Major Advantages

Highest volume and highest part uniformity of any thermoset molding method. The process can be automated. Great part design flexibility, good mechanical and chemical properties obtainable. Inserts and attachments can be molded in. Superior color and finish are obtainable, contributing to lower part finishing cost. Subsequent trimming and machining operations are minimized.

Premix em Folha (SMC)

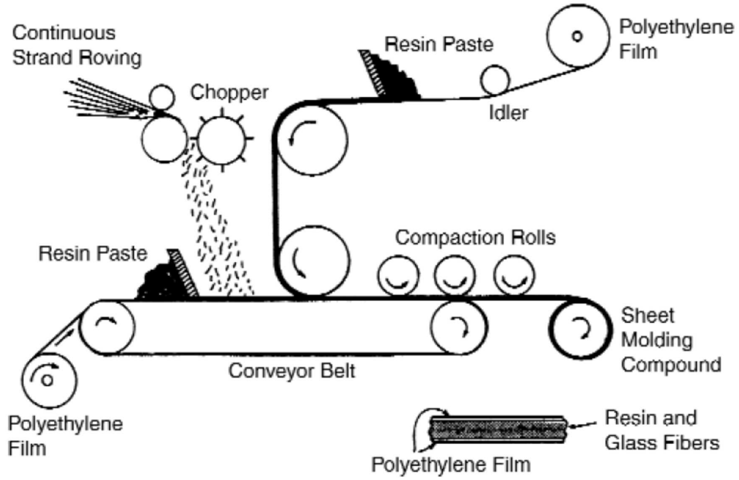
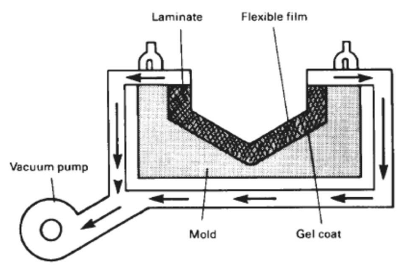


Figure Sheet molding compound process. (Ref: Harper, C.A., "Thermosets, Reinforced Plastics, and Composites", *Modern Plastics Handbook*, C.A. Harper, ed., McGraw-Hill, New York, 2000)

VACUUM BAG MOLDING

Mechanical properties of open-mold laminates can be improved with a vacuum-assist technique. Entrapped air and excess resin are removed to produce a product with a higher percentage of fiber reinforcement.



Process Description

A flexible film (PVA or cellophane) is placed over the completed lay-up, its joint sealed, and a vacuum drawn. A bleeder ply of fiberglass cloth, non-woven nylon, polyester cloth or other absorbent material is first placed over the laminate. Atmospheric pressure eliminates voids in the laminate, and forces excel resin and air from the mold. The addition of pressure further results in high fiber concentration and provides better adhesion between layers of sandwich construction. When laying non-contoured sheets of PVC foam or balsa into a female mold, vacuum bagging is the technique of choice to ensure proper secondary bonding of the core to the outer laminate.

Resin Systems

Polyesters, vinyl esters and epoxies.

Molds

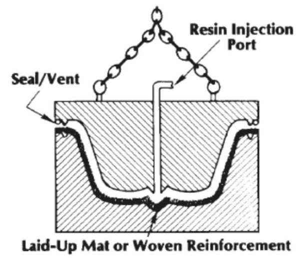
Molds are similar to those used for conventional open-mold processes.

Major Advantages

Vacuum bag processing can produce laminates with a uniform degree of consolidation, while at the same time removing entrapped air, thus reducing the finished void content. Structures fabricated with traditional hand lay-up techniques can become resin rich, especially in areas where puddles can collect. Vacuum bagging can eliminate the problem of resin rich laminates. Additionally, complete fiber wet-out can be accomplished when the process is done correctly. Improved core-bonding is also possible with vacuum bag processing.

RESIN TRANSFER MOLDING

Resin transfer molding is an intermediate-volume molding process for producing reinforced plastic parts and a viable alternative to hand lay-up, spray-up and compression molding.



Process Description

Most successful production resin transfer molding (RTM) operations are now based on the use of resin/catalyst mixing machinery using positive displacement piston-type pumping equipment to ensure accurate control of resin to catalyst ratio. A constantly changing back pressure condition exists as resin is forced into a closed tool already occupied by reinforcement fiber.

The basic RTM molding process involves the connection of a meter, mix and dispense machine to the inlet of the mold. Closing of the mold will give the predetermined shape with the inlet injection port typically at the lowest point and the vent ports at the highest.

Resin System

Polyesters, vinyl esters, polyurethanes, epoxies and nylons.

Molds

RTM can utilize either "hard" or "soft" tooling, depending upon the expected duration of the run. Hard tooling is usually machined from aluminum while soft tooling is made up of a laminated structure, usually epoxy.

Major Advantages

The close-mold process produces parts with two finished surfaces. By laying up reinforcement material dry inside the mold, any combination of materials and orientation can be used, including 3-D reinforcements. Part thickness is also not a problem as exotherm can be controlled. Carbon/epoxy structures up to four inches thick have been fabricated using this technique.

Table 2-12 Qualitative Assessment of Constituent Material Properties

	Fiber			Resin					Core					
	E-Glass	Kevlar	Carbon	Polyester	Vinyl Ester	Epoxy	Phenolic	Thermoplastic	Balsa	Cross Link PVC	Linear PVC	Nomex/Alum Honeycomb	Thermoplastic Honeycomb	Syntactic Foam
Static Tensile Strength	■	■	■	□	□	■	□	□	■	■	■	□	□	□
Static Tensile Stiffness	□	■	■	□	□	□	□	□	■	□	□	■	□	□
Static Compressive Strength	■	□	□	□	□	□	□	□	■	□	■	■	□	□
Static Compressive Stiffness	□	□	■	□	□	□	□	□	■	□	□	■	□	□
Fatigue Performance	□	■	■	□	■	■	□	■	■	□	■	□	■	□
Impact Performance	■	■	□	□	■	■	□	■	□	■	■	□	□	□
Water Resistance	■	□	□	□	■	■	□	■	□	■	■	□	□	□
Fire Resistance	■	□	□	□	□	□	■	□	■	□	□	■	□	□
Workability	■	□	□	■	□	□	□	□	■	□	□	□	□	■
Cost	■	□	□	■	□	□	□	■	■	□	□	□	■	■
	■ Good Performance □ Fair Performance													

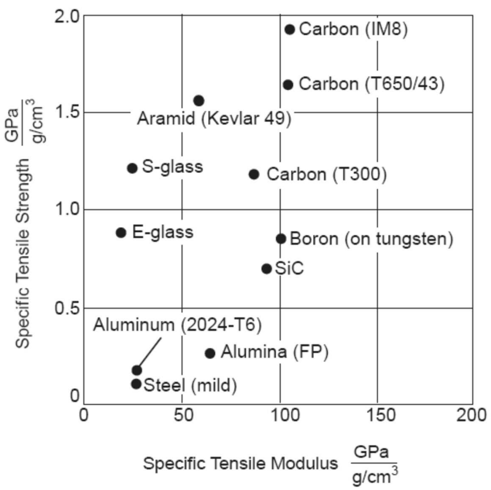


Figure Specific Strength and Stiffness of Various Construction Materials [DuPont]