SHAPING PROCESSES FOR PLASTICS

1. Properties of Polymer Melts
2. Extrusion
3.Sheet and Film
4. Fiber and Filament
5. Coating Processes
6. Injection Molding
7. Compression &Transfer Molding
8. Blow Molding & Rotational Molding
9. Thermoforming
10. Casting
11. Polymer Form
12. Design Consideration

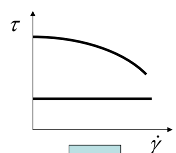
Introduction

- Unlimited variety of part geometries
- Net Shape
- Less energy
- Lower temperature
- No finishing

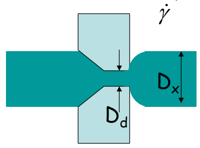
1 Properties of Polymer Melts

- Viscosity
  - Newtonian fluid: $\eta = \frac{\tau}{\dot{\gamma}}$

    η=coefficient of shear viscosity
  - Pseudoplastic fluid: $k = \frac{\tau}{(\dot{\gamma})^n}$



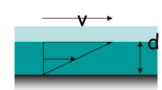
- Viscoelasticity
  - Causes die swell
  - Swell ratio, $r_s = \frac{D_x}{D_d}$



- Mold Flow Index (MFI): A measure of flow and viscosity depending on temp. and shear rate

2. Extrusion

- Shaping process for polymers metals & ceramics.
- A compression process – A material flows through a die orifice to provide long, continuous shaped material.
- Extrudate (extruded product) cut into desirable lengths.
- Equipment
  - Internal Diameter (25-150mm)
  - L/D ratio ranges from 10 to 30.
  - The extruder screw rotates at about 60 rev/min.
    - feed section
    - compression section – transform to liquid
    - metering section – the melt is homogenized and pressurized.

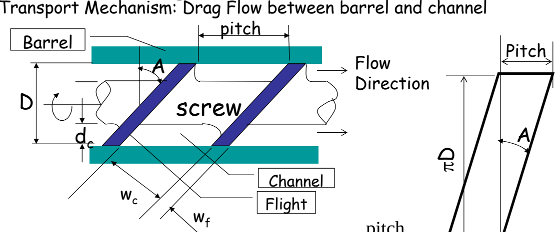


A simple plate model

Volume drag flow rate (m³/s): $Q_d = 0.5 v\, d\, w$

An single-screw Extruder

Transport Mechanism: Drag Flow between barrel and channel



A: the helix angle of the screw $\tan A = \frac{\text{pitch}}{\pi D}$

In relation to the extrusion screw

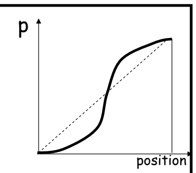
$$w = w_c = (\pi D \tan A - w_f)\cos A \approx \pi D \sin A$$

Assuming $w_c \gg w_f$

$$v = r\varpi = \pi DN \cos A$$

$$d = d_c$$

Analysis of Extrusion



Into the eq. from a plate model

$$Q_d = 0.5\pi^2 D^2 N d_c \sin A \cos A$$

Back pressure flow

$$Q_b = \frac{\pi D d_c^3 \sin^2 A}{12\eta}\left(\frac{dp}{dl}\right) \approx \frac{p\pi D d_c^3 \sin^2 A}{12\eta L}$$

The resulting flow rate, assuming no leak flow

$$Q_x = Q_d - Q_b = 0.5\pi^2 D^2 N d_c \sin A \cos A - \frac{p\pi D d_c^3 \sin^2 A}{12\eta L}$$

Design Parameters: D, d_c and A

Operating Parameters: N, p and η

Analysis of Extrusion

Zero flow condition due to high back pressure

$$Q_x = Q_d - Q_b = 0$$

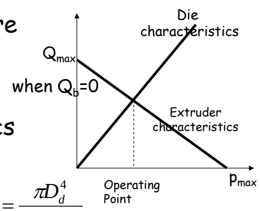
To find the back pressure

$$p_{\max} = \frac{6\pi DNL\eta \cot A}{d_c^2}$$

Extruder Characteristics

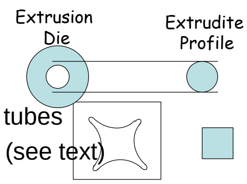
Die Characteristics

$$Q_x = K_s p \qquad \text{where } K_s = \frac{\pi D_d^4}{128\eta L_d}$$

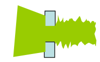


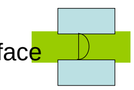
Die Configuration & Defects

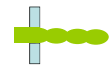
- Extruded shape
  - Solid Profiles
  - Hollow Profiles such as tubes
  - Wire and Cable coating (see text)



- Defects
  - Melt fracture
  - Sharkskin – residual stress on surface
  - Bambooing

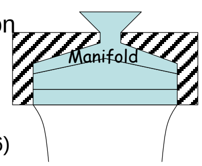


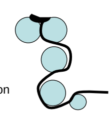




3. Production of Sheet & Film

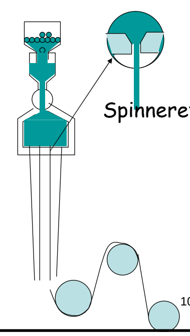
- 0.5mm < Sheet thickness < 12.5mm
- Film thickness < 0.5mm
- Continuous & High Production
- Slit-die Extrusion
  - Water Quenching bath
  - Chill roll extrusion
- Blown-film Extrusion(Fig. 13.16)
- Calendering(2.5m/s)
  - A series of rolls





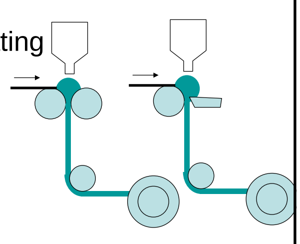
4. Fiber & Filament Production

- Melt Spinning
- Dry Spinning – polymer in solution and the solvent evaporates



5. Coating Processes

- Wire and Cable coating
- Planar coating
  - Roll
  - Doctor blade
- Contour Coating
  - Dipping or spraying



6. Injection Molding

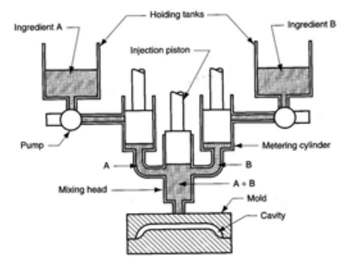
- Video in class
- Three Mold Types
- The Mold, Injection and Clamping Units
- Shrinkage: $D_c = D_p + D_p S + D_p S^2$
- Defects
  - Short Shot
  - Flashing
  - Sink mark and void
  - Weld line
- Other Types (e.g.: Reaction Injection Molding)

D_c = Dimension Cavity

D_p = Mold Part Dimension

S = Shrinkage (Table 13.1)

Reaction Injection Molding



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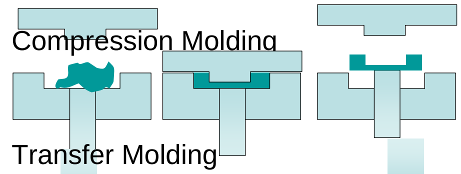
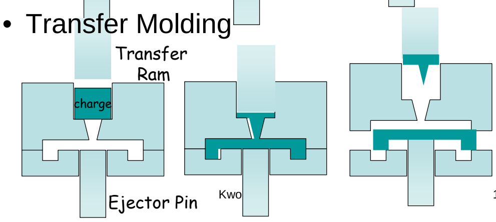
7. Compression & Transfer Molding

- Compression Molding



- Transfer Molding



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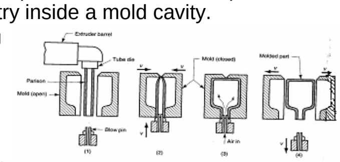
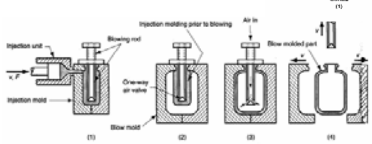
8. Blow Molding

- Blow Molding – uses air pressure to inflate soft plastic to make a hollow geometry inside a mold cavity.
  - Extrusion Blow Molding
  - Injection Blow Molding





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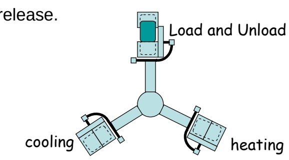
8. Rotational Blow Molding

- Gravity is used to achieve the hollow form inside a rotating mold.
  - A predetermine amount is loaded
  - Heating and rotating
  - Cooling while rotating
  - The mold open and the part release.



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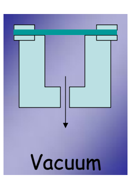
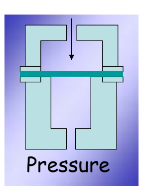
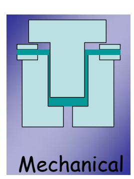
9. Thermoforming

- A flat thermoplastic is heated and deformed into the desirable shape
  - Forming – Vacuum, Pressure and Mechanical







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10. Casting

- Steps
  - Pouring a liquid resin into a mold
  - Filling the cavity
  - Hardening
- Materials: acrylics, polystyrene, polyamides, PVC.
- Slush or shell casting

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11. Polymer Foam Processing

- Polymer Foam – a composite of polymer and gas (air, nitrogen and carbon dioxide)
  - Introduction of gas
    - mechanical agitation
    - physical blowing agents
    - chemical blowing agents
  - Depending on the amount of gas and processing, open or closed cells

12. Design Consideration

- General consideration
  - Strength and Stiffness
  - Impact Resistance
  - Service temperature
  - Thermal expansion
  - Degradation
- Extruded Plastics
  - Wall thickness
  - Hollow sections
  - Corners
- Molded Part
  - Economic production quantities
  - Part Complexity
  - Wall thickness: reinforcing ribs
  - Corner radii ad Fillet
  - Holes but careful
  - Draft
  - Tolerance

See Table 13.2

RUBBER PROCESSING TECHNOLOGY

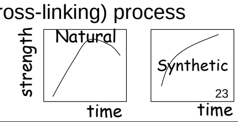
1. Rubber Processing and Shaping
2. Manufacture of Tire and other Rubber Products
3. Design Consideration

Introduction

- Similar to many production methods for plastics
- But different from the plastics industry
- Dominated by one product: *tires*
- Technological breakthrough
  - Vulcanization (cross-linking) to transform weak natural rubber into a stronger material.
  - The introduction of synthetic rubbers such as Styrene-butadiene rubber (SBR), Butadiene Rubber (BR) and Ethylene-Propylene-diene rubber (EPDM) (around WWII)

Rubber Processing and Shaping

- Two basic steps
  - Production - Agricultural crop or Petroleum
  - Shaping of rubber into finished goods
    - Compounding – Addition of Sulfur for Vulcanization
    - Mixing - Additives such as carbon black or calcium carbonate, china clay, silica and other polymers
    - Shaping – extrusion, calendering, coating, molding and casting
    - Vulcanization – A curing (cross-linking) process developed by Goodyear



Production of Natural Rubber

- Natural Rubber
  - Rubber trees (*Hevea brasiliensis*) grown on plantations in Southeast Asia and other part of the world -> Latex (a colloidal dispersion (30%) of solid particles called polymer polyisoprene in water)
- The latex is collected in large tanks - Diluted to 50% with additional water and coagulated by adding formic or acetic acids.
- Coagulum , now soft solid slabs, is then squeezed through a series of rollers to loose water.

Production of Natural Rubber

- ***Ribbed smoked sheet*** in dark brown color - The sheets draped over wooden frames is dried in smokehouses for several days, which are folded into large bales.
- ***Air-dried sheet*** - A better grade of rubber can be attained by drying in hot air rather than smokehouses.
- ***Pale crepe*** rubber in light tan - A even better grade involves two coagulation steps and warm air drying.

Production of Synthetic Rubber

- Most synthetic rubbers are produced from petroleum by the same polymerization techniques.
- Unlike shaping polymers in the form of pellets or liquid resins, synthetic rubbers start in the form of large bales.

Shaping of rubber: Compounding

- The specific rubber is designed by vulcanization, (adding sulfur) or fillers.
- Fillers to enhance the rubber's mechanical properties (reinforcing fillers) or to extend the rubber to reduce cost (non-reinforcing fillers)
- *Carbon black*, a colloidal form of carbon, obtained by thermally decomposing hydrocarbons (soot)
  - to increase tensile strength and resistance to abrasion and tearing
  - To protect from ultraviolet radiation
  - Appear black in color

Shaping of rubber: Compounding

- China clays - hydrous aluminum silicates ($Al_2Si_2O_5(OH)_4$) for other colors but less reinforcing than carbon black.
- Calcium carbonate (non-reinforcing) and Silica
- Other polymers (styrene, PVC, and phenolics)
- Recycled rubber (usually 10% or less)
- Antioxidants (anti-aging by oxidation); fatigue- and ozone-protective chemicals; coloring pigments; plasticizers and softening oils; blowing agents in the production of foamed rubber; and mold release compounds

Shaping of rubber: Mixing

- The additives must be thoroughly mixed to achieve uniform dispersion of ingredients
- Mechanical working of the rubber can increase its temperature up to 150°C (300°F)
- An early introduction of vulcanizing agents would result in the "rubber processor's nightmare"
- To avoid this, a two-stage mixing process

  Stage 1 - carbon black and other non-vulcanizing additives (*masterbatch)*

  Stage 2 - After some time for cooling, vulcanizing agents are added.

Shaping of rubber: Mixing

- Many products require filament reinforcement to reduce extensibility but retain the other desirable properties of rubber.
  - Examples: tires, conveyor belts
  - Filaments include cellulose, nylon, and polyester.
  - Fiber-glass and steel (e.g., steel-belted radial tires)
  - Continuous fiber materials must be added during shaping; not mixed like the other additives.

Shaping and Related Processes

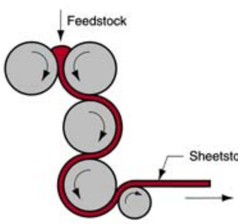
- Four basic categories of shaping processes :
  1. Extrusion
  2. Calendering
  3. Coating
  4. Molding and casting

Extrusion

- Screw extruders are generally used
- The L/D ratio of the extruder barrel is less than for thermoplastics, typically in the range 10 to 15, to reduce the risk of premature cross-linking
- Die swell occurs in rubber extrudates due to its highly plastic condition and the "memory" property
- It is done before vulcanization.

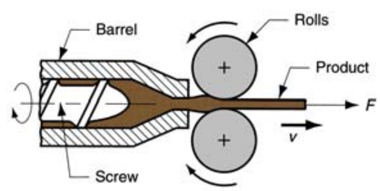
Calendering

- Stock is passed through a series of gaps of decreasing size made by a stand of rotating rolls where final roll gap determines sheet thicknes



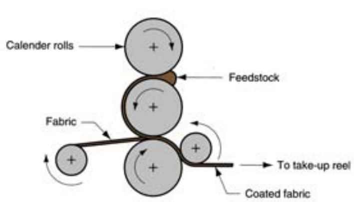
Roller Die Process

Combination of extrusion and calendering for better quality product.



Coating or Impregnating Fabrics with Rubber

- Used in producing automobile tires, conveyor belts, inflatable rafts, and waterproof cloth tents and rain coats

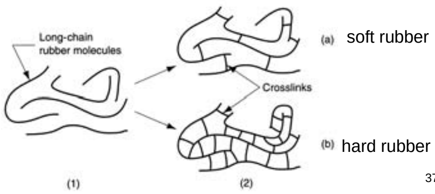


Molding

- Products include shoe soles and heals, gaskets and seals, suction cups, bottle stops, tires and foamed rubber parts.
- (1) compression molding (tire manufacture) (Fig. 13.28), (2) transfer molding (Fig. 13.19), and (3) injection molding (Fig. 13.21)
- Curing (vulcanizing) is accomplished in the mold in all three processes, this representing a departure from the previous shaping methods, all of which use a separate vulcanizing step

Vulcanization

- Cross-linking of elastomer molecules to make stiffer and stronger while retaining extensibility.
- On a submicroscopic scale, the long-chain molecules of rubber become joined at certain tie points (1 or 2 cross-links per 1000 mers).



Vulcanization Chemicals and Times

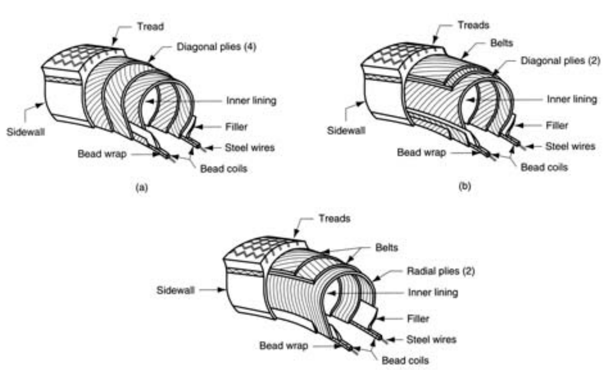
- First invented by Goodyear in 1839, vulcanization used sulfur at 140°C (280°F) for about 5 hours.
- Now various other chemicals are combined with smaller doses of sulfur to accelerate and strengthen the treatment resulting in the cure time of 15-20 minutes.
- A variety of non-sulfur vulcanizing treatments have also been developed.

Tires

- Functions of vehicle tires:
  - Support the weight of the vehicle, passengers, and cargo
  - Transmit the motor torque
  - Absorb road vibrations and shock
- Automobiles, trucks, buses, farm tractors, earth moving equipment, military vehicles, bicycles, motorcycles, and aircraft
- A tire is an assembly of many parts about 50 to as many as 175 components
  - The internal structure, known as the *carcass*, consists of multiple layers of rubber coated cords, called *plies*
  - The cords are strands of nylon, polyester, fiber glass, or steel, which provide inextensibility to reinforce the rubber in the carcass

Manufacture of Tire and Others

- Footwear, Seals, Shock-absorbing parts, Conveyor belts, Hose, Foamed rubber products, Sports equipment
- ¾ of rubber product: Tire
- Three basic constructions (see Fig. 16.6)
  - Diagonal ply
  - Belted Bias
  - Radial ply



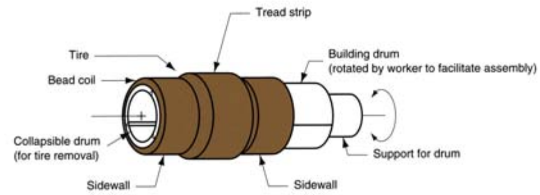
Tire Production Sequence

- Three steps:
  1. Preforming of components
  2. Building the carcass and adding rubber strips to form the sidewalls and treads
  3. Molding and curing the components into one integral piece
- Variations in processing depending on construction, tire size, and type of vehicle

Preforming of Components

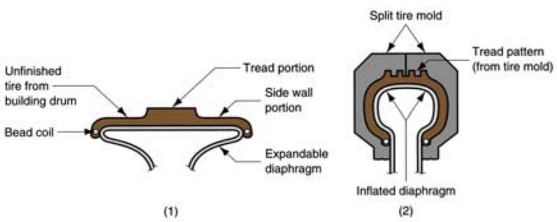
- The carcass consists of a number of components, most of which are rubber or reinforced rubber
- These, as well as the sidewall and tread rubber, are produced by continuous processes and then pre-cut to size and shape for subsequent assembly
- The components include: bead coil, plies, inner lining, belts, tread, and sidewall

Building the Carcass



The carcass is traditionally assembled using a machine known as a *building drum*, whose main element is a cylindrical arbor that rotates. Tire just before removal from building drum, but prior to molding and curing

Molding and Curing



Tire molding: (1) uncured tire is placed over expandable diaphragm; (2) mold is closed and diaphragm is expanded to force uncured rubber against mold cavity, impressing tread pattern into rubber; mold & diaphragm are heated to cure rubber

Other Rubber Products - Rubber Belts

- Widely used in conveyors and mechanical power transmission systems
- Rubber is an ideal material for these products but the belt must have little or no extensibility
  - Reinforced with polyester or nylon fibers
- Fabrics of these polymers are usually coated by calendering, assembled together to obtain required number of plies and thickness, and subsequently vulcanized by continuous or batch heating processes

Other Rubber Products – Hose

- Two basic types of Hose:
  1. Plain hose is extruded tubing
  2. Reinforced tube consists of:
     - *Inner tube - extruded of a rubber compounded for particular liquid that will flow through it*
     - *Reinforcement layer - applied to the inner tube as a fabric, or by spiraling, knitting, braiding*
     - *Outer layer – compounded for environmental conditions and applied by extrusion*

Other Rubber Products – Footwear

- Rubber components in footwear include soles, heels, rubber overshoes, and certain upper parts
- Molded parts are produced by injection molding, compression molding, and certain special molding techniques developed by the shoe industry
- The rubbers include both solid and foamed
- For low volume production, manual methods are sometimes used to cut rubber from flat stock

Processing of Thermoplastic Elastomers

A *thermoplastic elastomer* (TPE)

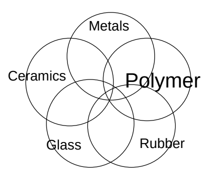
- Processed like thermoplastics, but used like elastomer
- Shaping processes: injection molding and extrusion. More economical and faster than the traditional processes
- Molded products: shoe soles, athletic footwear, and automotive components such as fender extensions and corner panels
- Extruded items: insulation coating for electrical wire, tubing for medical applications, conveyor belts, sheet and film stock

Product Design Considerations

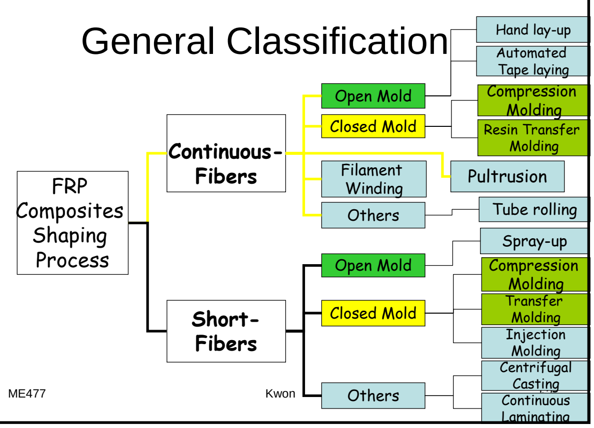
- Rubber parts can be produced by compression molding in quantities of 1000 or less
  - The mold cost is relatively low
- Injection molding requires higher production quantities due to more expensive mold
- Draft is usually unnecessary due to its flexibility to deform for removal from the mold
- Shallow undercuts, although undesirable, are possible

Shaping Processes for Polymer Matrix Composites (PMC)

1. Starting Materials for PMC
2. Open Mold Processes
3. Closed Mold Processes
4. Filament Winding
5. Pultrusion Processes
6. Other PMC Shaping Proceess



General Classification

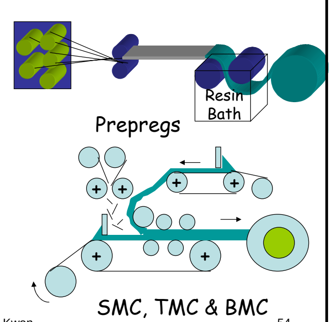


Polymer and Reinforcement

- In a PMC, polymer and reinforcing phase (fibers, particles and flakes) are processed separately
  - Polymers – Thermoplastics, Thermosets on most molding compounds & Elastomers with carbon black
  - Reinforcing fibers
    - Roving(Untwisted strands)-> Woven roving
    - Yarn (Twisted strands)-> Cloth
    - Mat – a felt made of randomly oriented short fibers cuts to shape called preforms which are impregnate with resin.
- They are subsequently combined into composites.
  - Combining Matrix and Reinforcement in a intermediated form called **prepregs** or **sheet-, thick- or bulk-molding** compounds occurs before shaping.
  - Combining occurs during shaping.

Combining

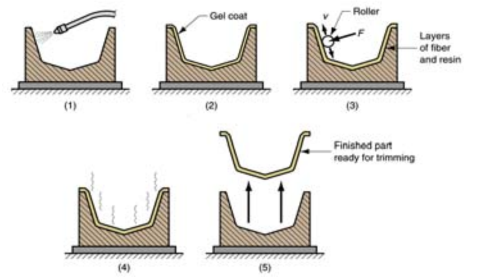
- Prepreg
- Sheet Molding Compounds (SMC) – polymer sheet
- Thick Molding Compounds (TMC) – thicker polymer sheet
- Bulk Molding Compounds (BMC) – polymer billets



Open Mold Process

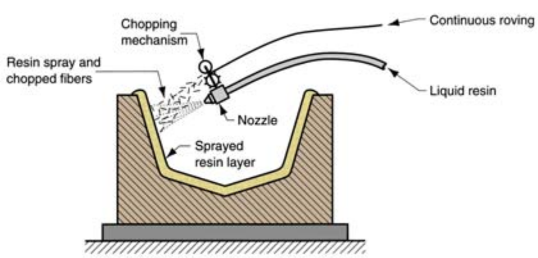
- Mold – Negative or positive mold
- Lay-up – wet lay-up or Prepregs
  - Hand lay-up – high labor cost but strong
  - Spray lay-up - randomly oriented short fibers, not as strong
    - Boat hulls, bathtubs, automobile body parts, furniture, large structural panels, containers, Movie and stage props
  - Automated Tape-laying - dispensing a prepreg tape onto a mold following a programmed path
- Curing for thermosetting resins (Crosslinking)
  - Room temp, Oven, Microwave, Autoclave
  - *Autoclave* - an enclosed chamber equipped to apply heat and/or pressure at controlled levels

Hand Lay-up



(1) mold is treated with mold release agent;
(2) thin gel coat (resin, colored) is applied, to be the outside surface of molding;
(3) layers of resin and fiber, the fiber in the form of mat or cloth; each layer is rolled to impregnate the fiber with resin and remove air;
(4) part is cured;
(5) fully hardened part is removed from mold

Spray-up



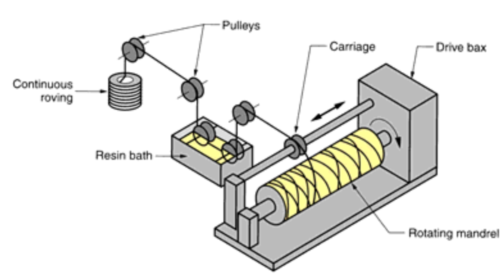
Automated tape-laying machine

(courtesy Cincinnati Milacron)

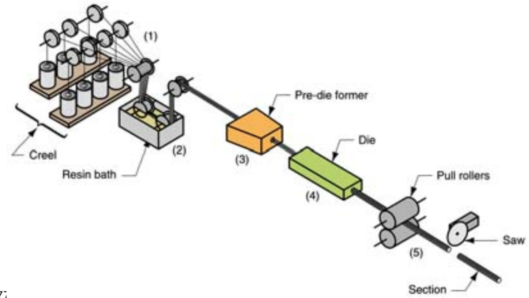
Closed Mold Processes

- Match Die (negative and positive) Molding
  - Compression molding
  - Transfer molding
  - Injection molding
- More Tooling cost due to the more complex equipment
- Advantages:
  - good finish on all part surfaces
  - higher production rates
  - closer control over tolerances, and
  - more complex three-dimensional shapes

Filament Winding



Pultrusion

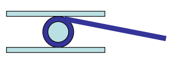


Pultrusion

- Common resins: unsaturated polyesters, epoxies, and silicones, all thermosetting polymers
- Reinforcing phase: E-glass is most widely, in proportions from 30% to 70%
- Products: solid rods, tubing, long flat sheets, structural sections (such as channels, angled and flanged beams), tool handles for high voltage work, and third rail covers for subways.

Other PMC Shaping

- Centrifugal casting
- Tube rolling
- Continuous laminating
  - Gathering either impregnated or woven fabric with resin
  - Compacting with roller and curing
- Many of the traditional thermoplastic shaping processes are applicable to FRPs (with short fibers)
  - Blow molding
  - Thermoforming
  - Extrusion
- Cutting of FRPs



Cutting methods

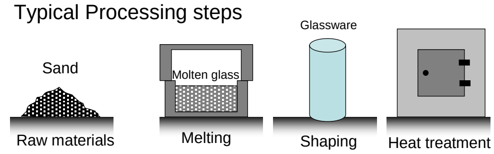
- Uncured (prepregs, preforms, SMCs, and etc.):
  - Cut to size for lay-up, molding, etc.
  - Typical cutting tools: knives, scissors, power shears, and steel-rule blanking dies
  - Nontraditional methods (laser beam cutting and water jet cutting)
- Cured FRPs are hard, tough, abrasive, and difficult-to-cut
  - To trim excess material, cut holes and outlines, etc.
  - For glass FRPs, cemented carbide cutting tools and high speed steel saw blades
  - For other advanced composites, diamond cutting tools
  - Water jet cutting reduces dust and noise problems

GLASSWORKING

1. Raw Materials
2. Shaping
3. Heat Treatment & Finishing
4. Production Design Consideration

Introduction

- Glass is one of three types of ceramic materials. The other two are traditional and new ceramics.
- A type of ceramics which is Non-crystalline [SiO_2(sand) +other oxides]
- Shaping: melting, casting, pressing and blowing or rolling.
- Glass remain in the glass state even after cooling.
- Typical Processing steps

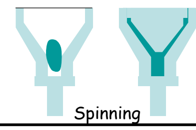


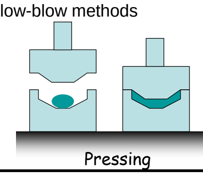
1. Raw Materials

- The sand is washed and classified according to size (ideal size: 0.1 to 0.6mm).
  - Other ingredients such as soda ash (Na_2O), limestone (CaO), aluminum oxide, potash (K_2O) and other minerals.
  - Recycled glass is added (up to 100%).
- A starting material before melting is called 'charge'
- Glass-melting furnace: 1500-1600°C typically for 24 to 48 hours.
- Temperature(up) dictates viscosity(down) for shaping.

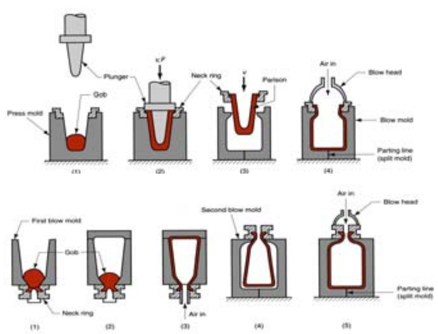
2. Shaping Processes

- Three Categories
  - Discrete(bottles, jars, plates, light bulbs)
  - Continuous (sheet, plate and tubing)
  - Fiber-making (insulation and fiber optics)
- Shaping Piece ware
  - Casting – melting, solidifying, lapping & polishing
  - Spinning – centrifugal casting
  - Pressing – gob
  - Blowing – press-blow and blow-blow methods



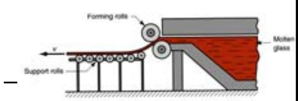


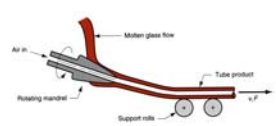
Press-and-blow and Blow-and-blow

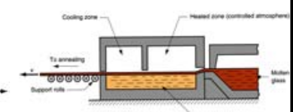


Shaping Flat and Tubular Glass

- Rolling of Flat Plate
- Float Process
- Drawing of Glass Tubes – Danner process

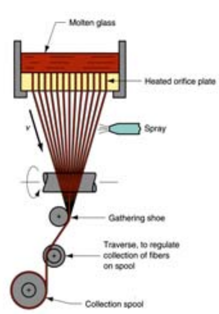






Glass Fibers

- Fibrous glass – insulation
  - Centrifugal Spraying – molten glass in a rotating bowl flows out though small orifices.
- Long continuous filament – for composites and fiber optics



Long continuous filament

3. Heat Treatment & Finishing

- Annealing – get rid of undesirable internal stresses by heating at 500°C.
- Tempered glass – heated above tempering temperature and the surfaces cooled to induce **compress stress** on the surface. Shatters into numerous small fragments to take more energy.
- Finishing – grinding, polishing and cutting