Polymer Matrix Composites

L. B. Klett

Engineering Technology Division
Oak Ridge National Laboratory*

***Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U. S. Dept. of Energy under contract DE-AC05-00OR22725.**

What is a Composite Material?

- A new material formed from two or more materials combined on a macroscopic scale
- Composites can exhibit the best qualities of the constituents as well as new characteristics
- Composites have the advantages of flexibility and tailorability

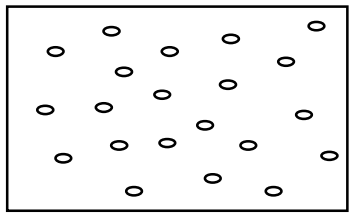
History of Composites

- First Man-Made Composites
  - Israelites - straw in mud bricks
  - Egyptians - plywood
  - Medieval knights - swords and armor
- Natural Composites
  - Wood
  - Bone
  - Celery

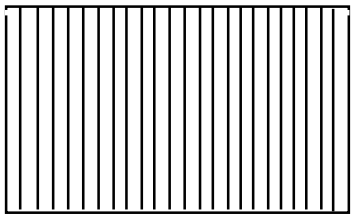
Types of Composites

- Laminated
  - Bimetals, safety glass, clad metals, plywood, Formica
- Particulate
  - Concrete, aluminum flakes in paint, short fiber/whisker reinforced materials, SiC
- Fibrous
  - Fiberglass, advanced composites

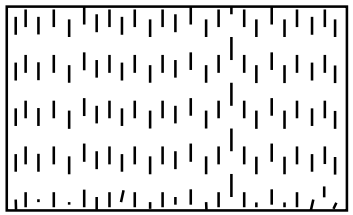
Composites with Different Reinforcements



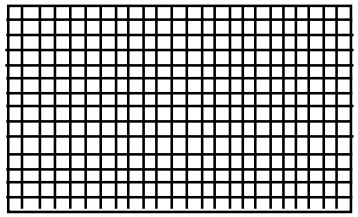
Particulate Composite



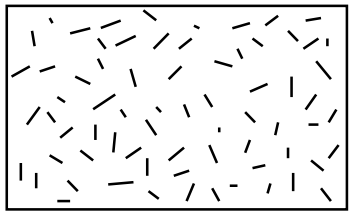
Unidirectional Continuous Fiber Composite



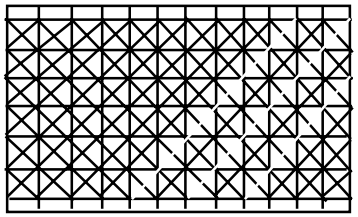
Short-Fiber Unidirectional Composite



Crossply Composite



Short-Fiber Random Orientation Composite

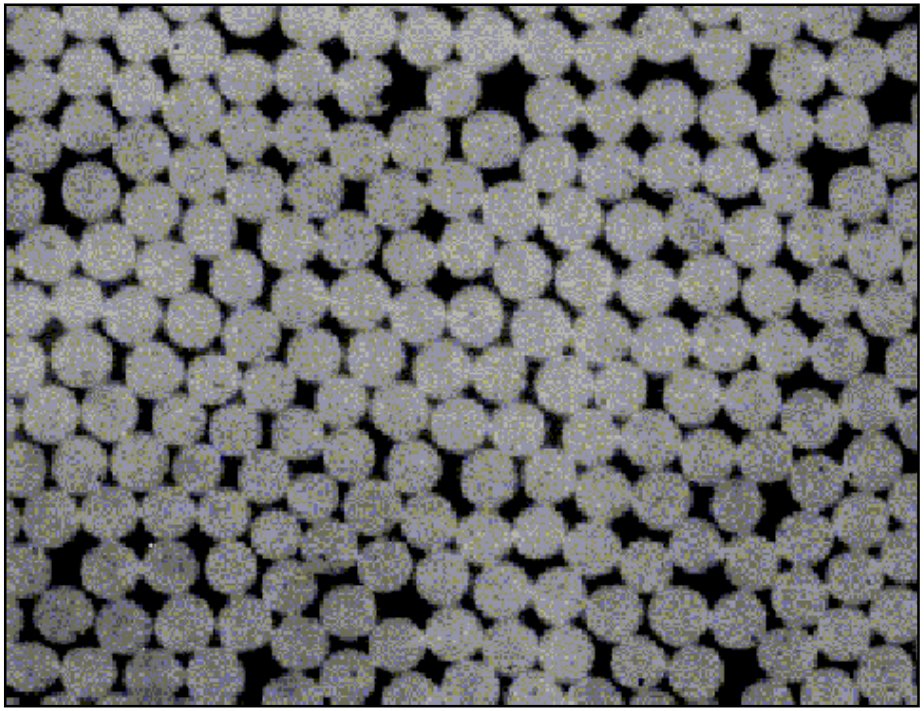


Multidirectional Composite

Two Basic Classes of Fiber Reinforced Composites

- Advanced (Aerospace) Composites
  - Primarily used when performance is the driving issue
  - Used primarily for weight advantage
  - Usually long (continuous) filaments
  - High specific strength and stiffness
  - Anisotropic, or directional, bulk properties
- Commercial Composites
  - Low to medium performance
  - Usually short fiber or particle reinforcements
  - Fiberglass is the most common composite used in manufacturing

Advanced Composites



- Fibers

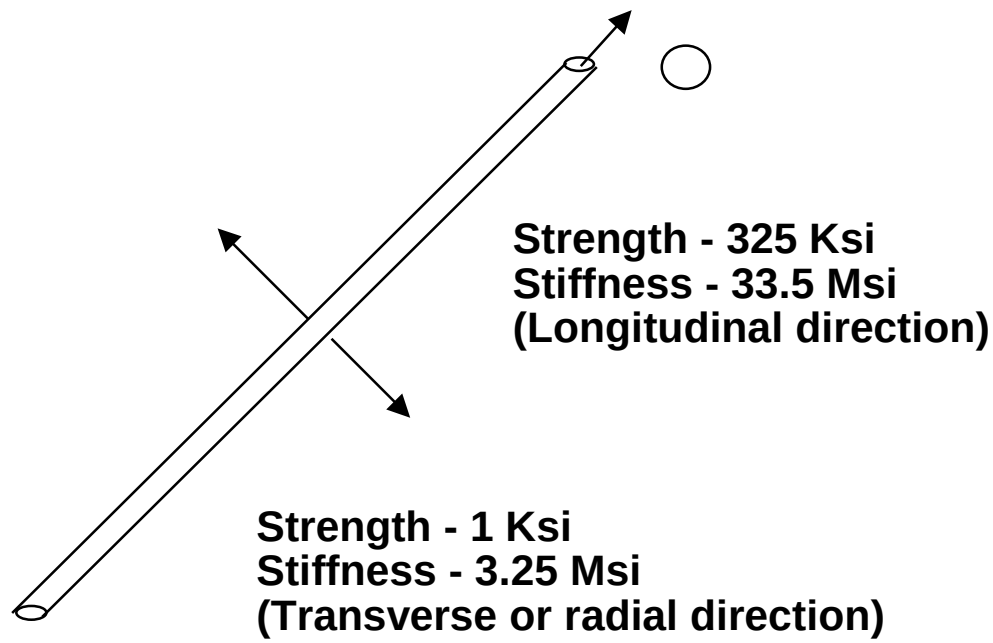
  Provide the mechanical properties (load bearing component)

- Matrix

  Maintains alignment, protects the fibers, and transfers load between the fibers

Fiber Reinforcements

- Glass
- Carbon
- Aramid (Kevlar)
- Polyethylene (Spectra)
- Silicon Carbide
- Boron



Fiber Reinforcements

- Long fibers are inherently much stronger and stiffer than the same bulk material
  - More perfect structurally
  - Crystal alignment (near crystal sized diameter)
  - Fewer internal defects

- Whiskers are generally short and stubby compared to fibers, but have even fewer imperfections in crystalline structure

Carbon (Graphite) Fibers

- Used primarily in aerospace and sporting goods applications

- Trade-off between high strength and high stiffness (modulus)

Tensile Strength	270 - 1000 ksi
Tensile Modulus	30 - 100 Msi
Failure Strain	<2 % (typical)

Low negative coefficient of thermal expansion (CTE)

- Higher performance correlates with higher cost

Glass Fibers

- Used primarily in high-volume commercial applications
- Moisture and corrosion resistant

  Tensile Strength 300 - 500 ksi

  Tensile Modulus 10 - 12 Msi

  Failure Strain 5 %

  Low coefficient of thermal expansion (CTE)
- E-Glass: lowest cost and most widely used
- S-Glass: aerospace version (higher modulus and strength)

Aramid Fibers

- Used in aerospace and armor (bullet-proof vests)

  Tensile Strength 525 ksi

  Tensile Modulus 18 Msi

- Damage tolerant

- Hygroscopic

- Difficult to machine

Boron Fibers

- Deposited on tungsten or graphite filament substrate

  Tensile Strength 500 ksi

  Tensile Modulus 60 Msi

- Large diameter (140 μm)

- Difficult to machine

Matrix Materials

- In fibrous composites, the matrix supports and protects the fibers, provides load transfer between fibers, and governs the composite shear and compressive properties

- The load from a broken fiber or whisker is transferred to adjacent fibers or whiskers by shearing stresses in the matrix
  - Generally isotropic
  - Must flow and bond to fiber
  - Low moisture uptake

Types of Matrix Materials

- Metallic
  - Aluminum
  - Titanium
  - Copper
- Organic
  - Thermosetting polymer
  - Thermoplastic polymer
- Ceramic
  - Glass
  - Silicon carbide
- Carbon
  - High modulus (pitch-derived)
  - High strength (acrylonitrile-derived)

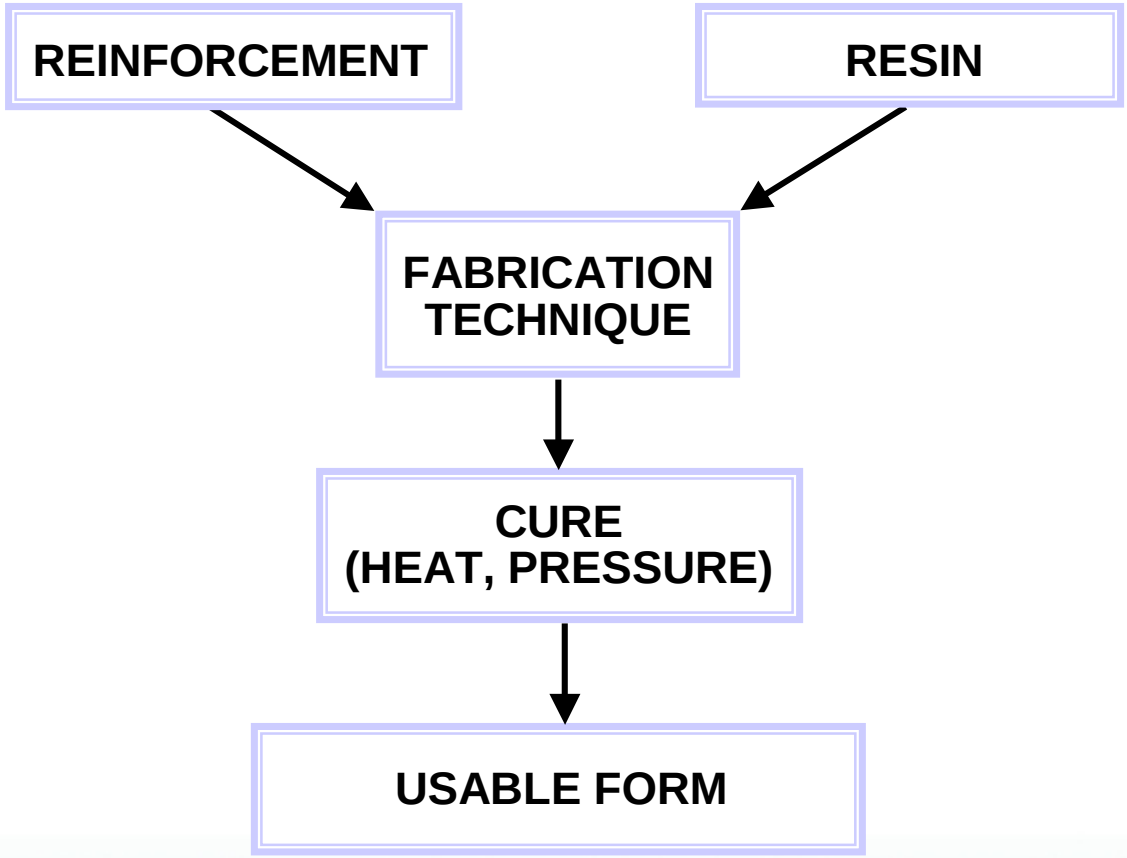
Polymer Matrix Materials

- Thermoset Resins
  - Supplied in “liquid” form
  - Viscosity is a function of polymerization chemistry
  - Chemical triggers (hardeners) cause solidification
  - Heating used to accelerate solidification and crosslinking
  - Cannot be reprocessed by additional heating
- Epoxy, phenolic, polyester, vinyl ester, polyimide

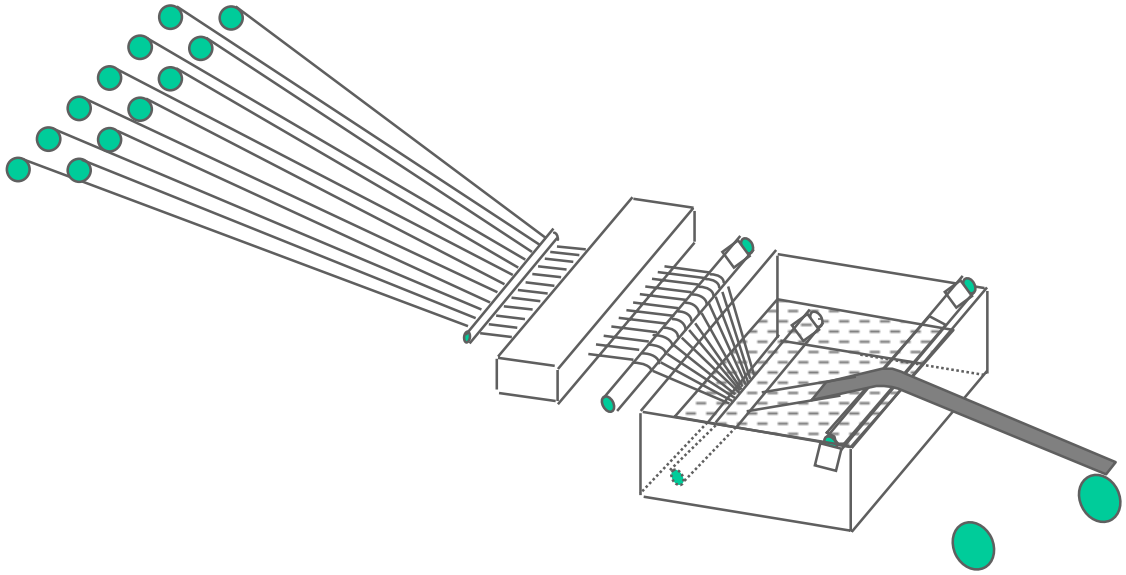
Polymer Matrix Materials

- Thermoplastic Resins
  - Supplied in “solid” form
  - Viscosity is a function of temperature
  - Liquified by heating in fabrication processes
  - Solidified and hardened by cooling
  - May be softened and re-processed by additional heating

Fabrication of Polymer Matrix Composites



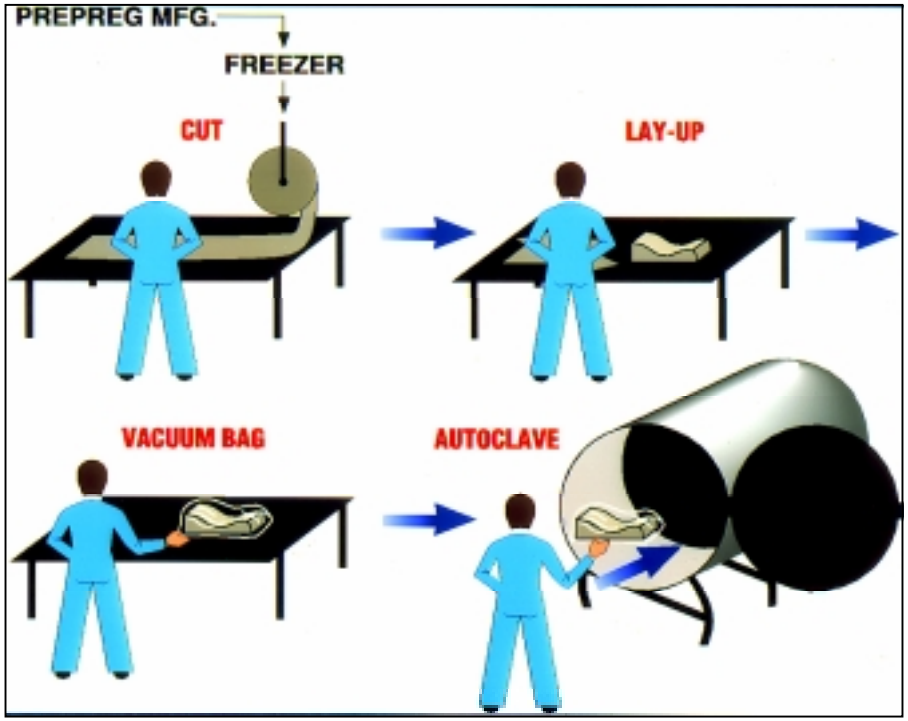
Fabrication Techniques - Prepreg



- Unidirectional prepreg is made in the form of tape or tow
- Cloth prepreg can also be made using woven products
- Usually the lay-up of prepreg is done by hand

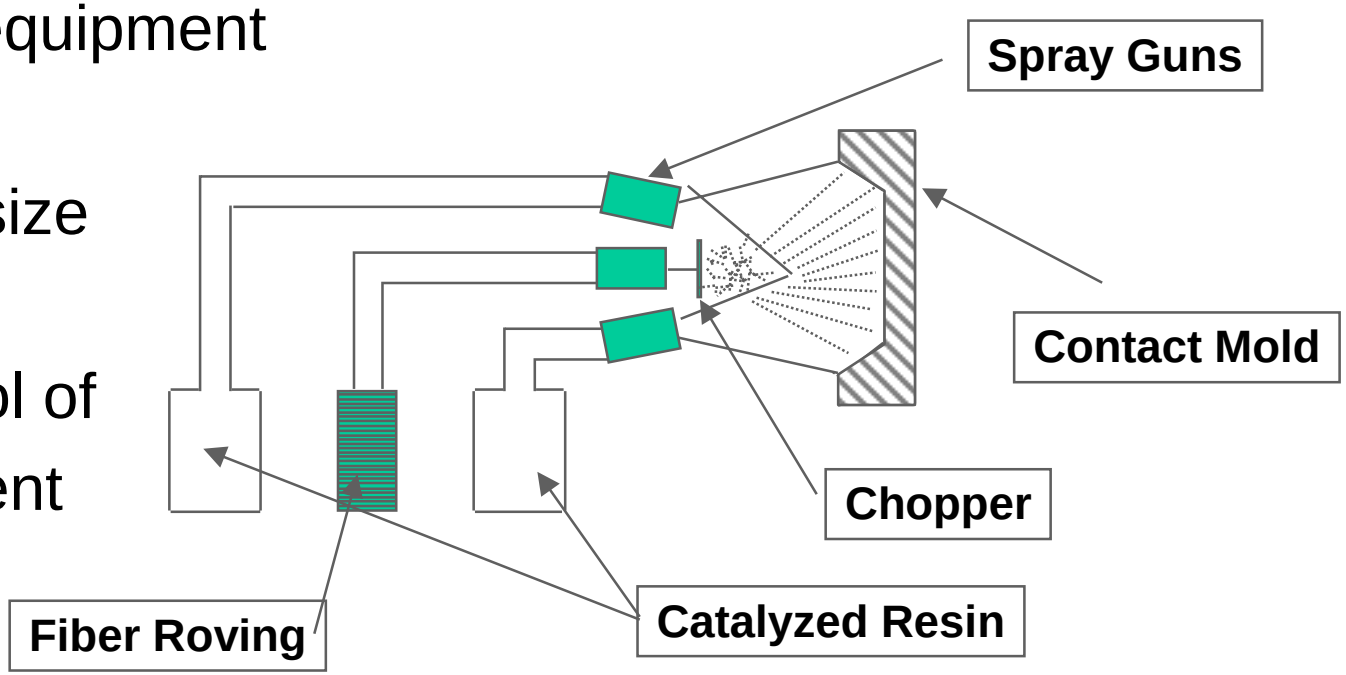
Fabrication Techniques - Hand Lay-Up

- Simplest fabrication method
- Matrix applied by brush, spray, or roller (unless using prepreg)
- Low quality, inexpensive
- Part-to-part variability
- Labor intensive
- Autoclave or press required

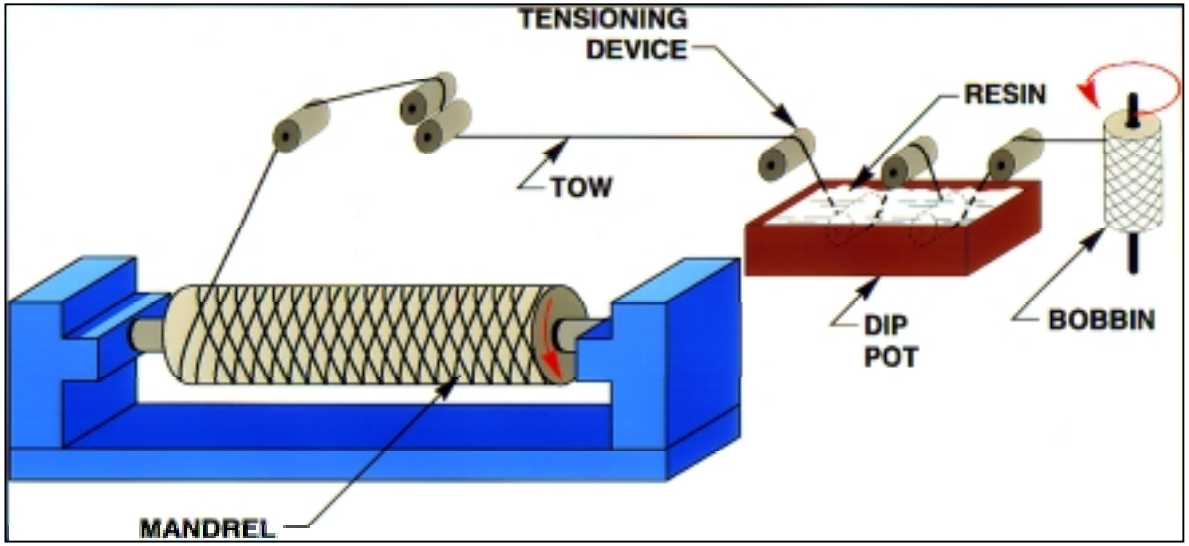


Fabrication Techniques - Spray Lay-Up

- Inexpensive equipment
- Flexible part size
- Limited control of fiber placement



Fabrication Techniques - Filament Winding



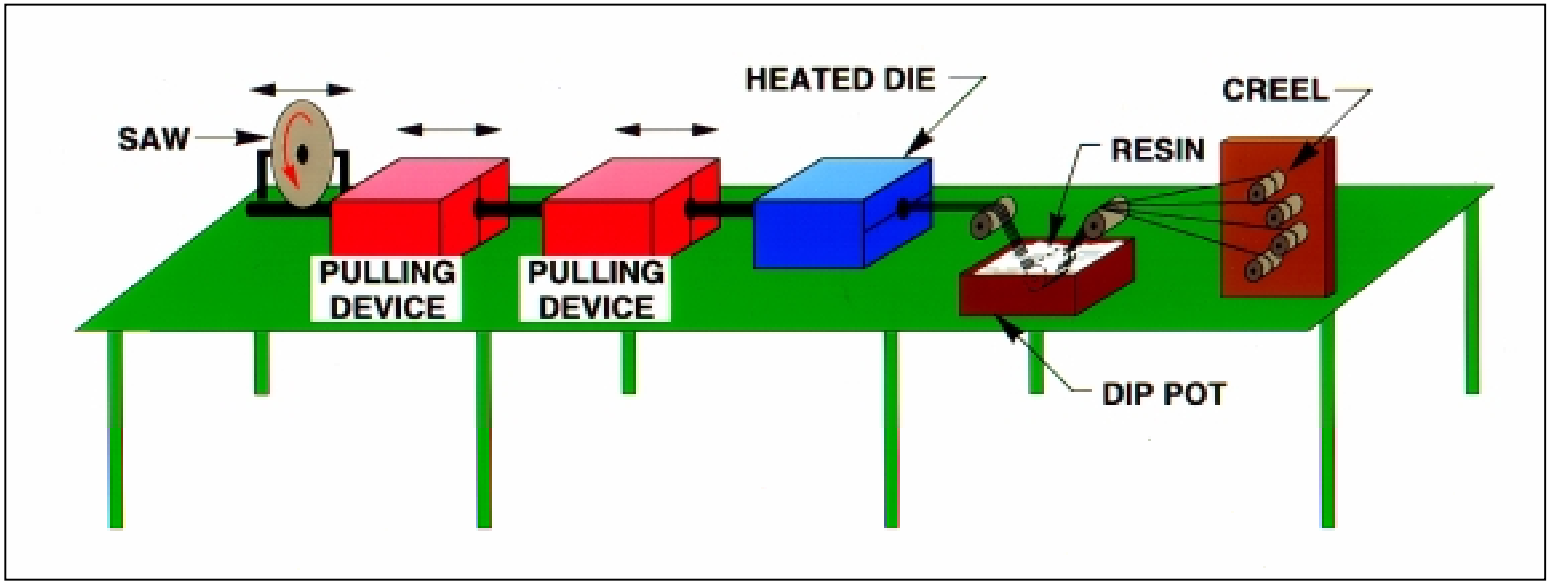
- High-speed, automated process
- Precise and repetitive in fiber placement
- Little waste, no joints, near net-shape parts
- Material costs lower than for prepreg

Fabrication Techniques - Filament Winding

Design Considerations

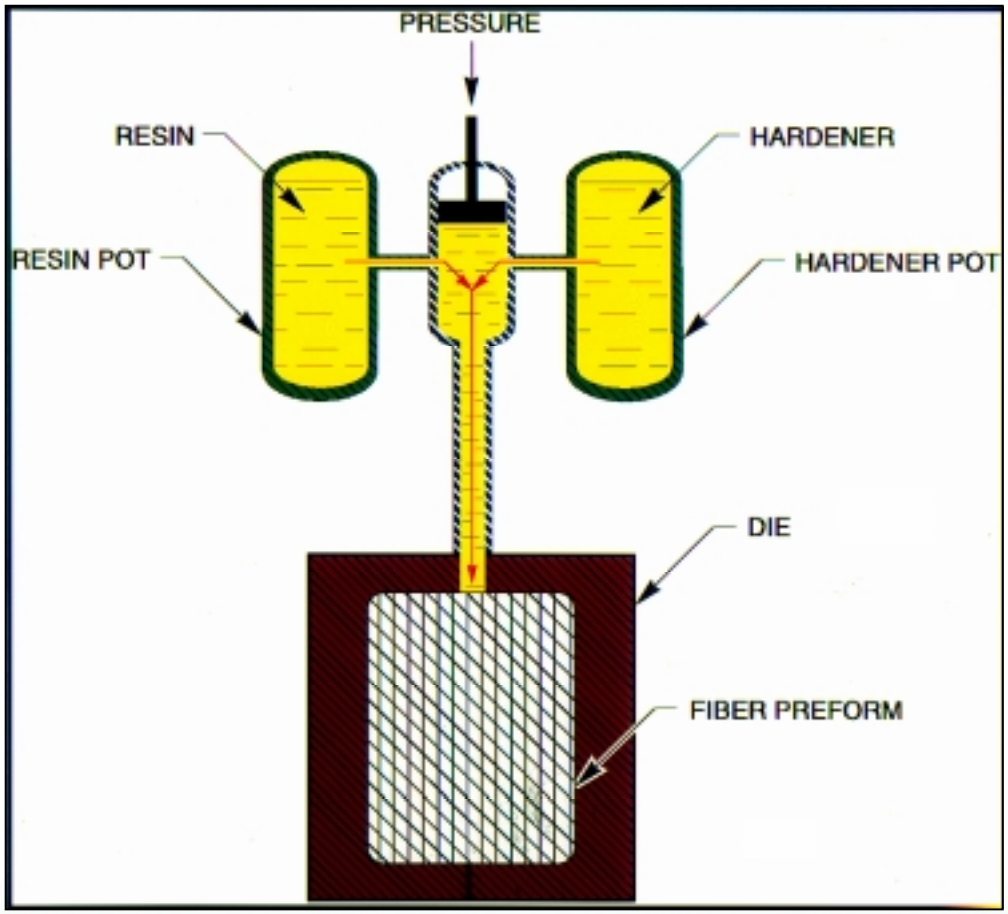
- Shape must permit mandrel removal unless it becomes a part of the structure
- Problems with reverse curvature parts
- Generally poor external surface
- Winding variables: fiber tension, fiber angle
- Usually requires an axis of symmetry

Fabrication Techniques - Pultrusion

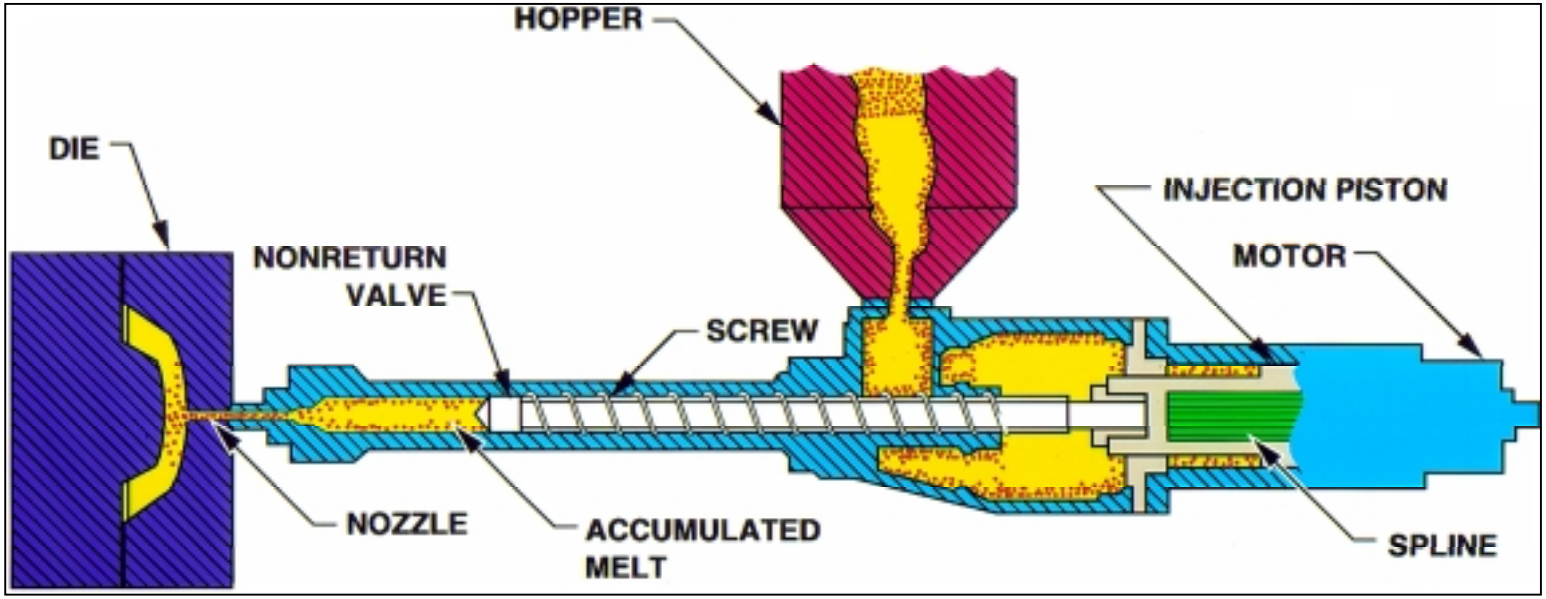


- Constant cross section (poles, boxes, angles)
- Continuous process, continuous reinforcement
- Cure is part of the processing
- Low cost, minimum waste, fast

Fabrication Techniques
Reaction Injection Molding (RIM)



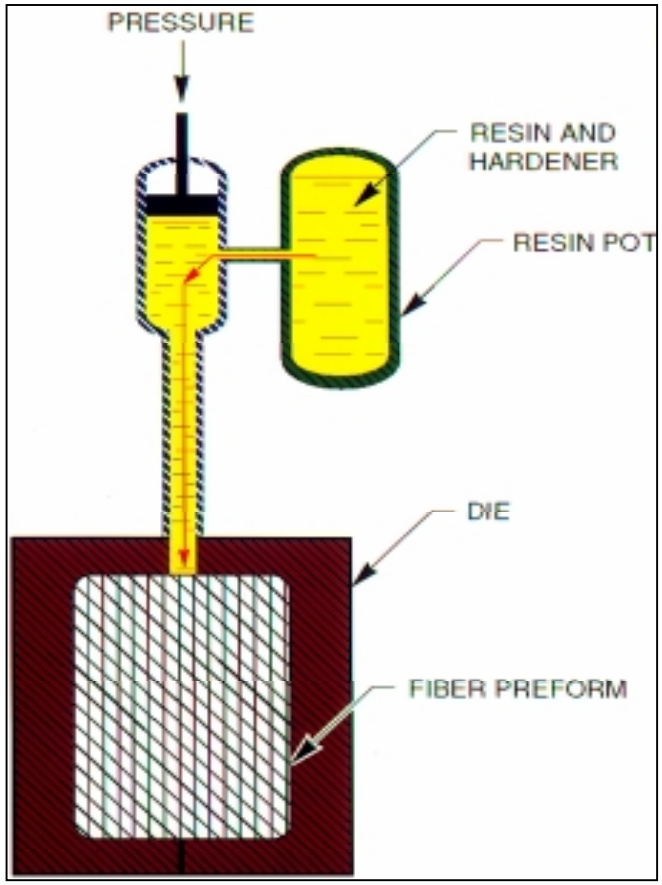
Fabrication Techniques - Injection Molding



- Complex parts
- High speed
- Short fibers
- Expensive equipment

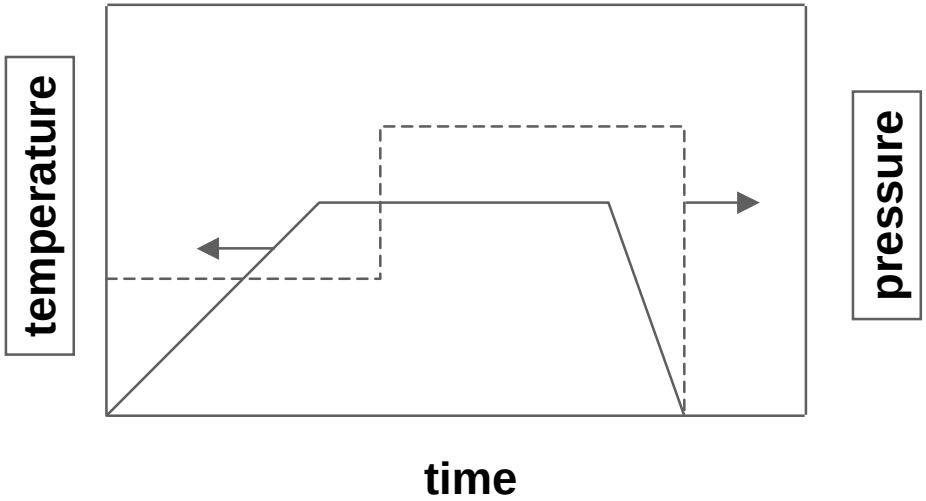
Fabrication Techniques
Resin Transfer Molding (RTM)

- Injection of a resin system into a closed tool containing a fiber preform, foam, and inserts
  - Low capital investment
  - Good surface quality
  - Tight tolerances
  - Low voids
  - Tailored reinforcement
- Early uses were for high-volume, low-cost parts
  - Bathtubs, keyboards



Typical Cure Cycle for Thermoset Resin

- Heating rate and cooling rate are important
- Vacuum may be needed to remove volatiles and trapped air



- Oven curing may use vacuum, but does not use pressure
- Most resins cure at 250ºF to 450ºF

Radiation Curing Of Composites

- Radiation processing is a revolutionary technology for manufacturing high-performance composite parts *efficiently* and *inexpensively*
- Ionizing radiation - in the form of high energy electrons or x-rays - is used at controlled rates to cure polymers
- Result is very fast, non-thermal, non-autoclave curing

Polymer Matrix Composites - Advantages

- Weight savings (high specific strength and specific stiffness).

- Material properties can be tailored by orientation and location of reinforcements
  - Stiffness (modulus)
  - Strength
  - Vibration damping
  - Thermal properties
  - Sound transmision

Polymer Matrix Composites - Advantages

- Mechanical properties
- Dimensional stability
- Fracture resistance
- Fatigue life
- Corrosion and wear resistance
- Ease of fabrication and assembly
- Net shape fabrication
- Reduced number of parts

Polymer Matrix Composites - Concerns

- Complex analysis required due to anisotropy
- Failure modes are often difficult to predict
- Can be environmentally sensitive
  - Moisture absorption
  - Solvents, fuels
  - Radiation
  - Erosion

Polymer Matrix Composites - Concerns

- Mechanical properties can depend on temperature, time and/or loading rate
- Scatter in properties of fibrous composites
- Cost of materials and some manufacturing processes
- Process repeatability
- Inspection difficult
- Reprocess/rework/repair