

Introduction to Composite Materials

LECTURE : 2: CHAPTER ONE

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1.1 Introduction to Composite Materials

1.2 Classification

How are composites classified?

Composites are classified by the geometry of the reinforcement, such as particulate, flake, and fibers (Figure 1.8) — or by the type of matrix, such as polymer, metal, ceramic, and carbon.

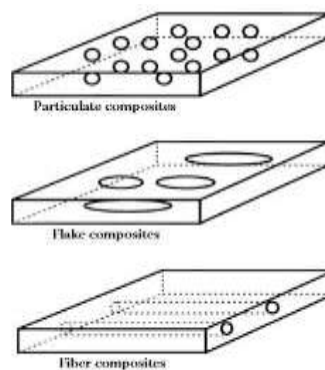


FIGURE 1.8
Types of composites based on reinforcement shape.

- **Particulate composites** consist of particles immersed in matrices such as alloys and ceramics. They are usually isotropic because the particles are added randomly. Particulate composites have advantages such as improved strength, increased operating temperature, oxidation resistance, etc. Typical examples include use of aluminum particles in rubber; silicon carbide particles in aluminum; and gravel, sand, and cement to make concrete.
- **Flake composites** consist of flat reinforcements of matrices. Typical flake materials are glass, mica, aluminum, and silver. Flake composites provide advantages such as high out-of-plane flexural modulus,* higher strength, and low cost. However, flakes cannot be oriented easily and only a limited number of materials are available for use.

- **Fiber composites** consist of matrices reinforced by short (discontinuous) or long (continuous) fibers. Fibers are generally anisotropic† and examples include carbon and aramids. Examples of matrices are resins such as epoxy, metals such as aluminum, and ceramics such as calcium–alumino silicate. Continuous fiber composites are emphasized in this lecture and are further discussed in this chapter by the types of matrices: polymer, metal, ceramic, and carbon. The fundamental units of continuous fiber matrix composite are unidirectional or woven fiber laminas. Laminas are stacked on top of each other at various angles to form a multidirectional laminate.
- **Nanocomposites** consist of materials that are of the scale of nanometers (10^{-9} m). The accepted range to be classified as a nanocomposite is that one of the constituents is less than 100 nm. At this scale, the properties of materials are different from those of the bulk material. Generally, advanced composite materials have constituents on the microscale (10^{-6} m). By having materials at the nanometer scale, most of the properties of the resulting composite material are better than the ones at the microscale. Not all properties of nanocomposites are better; in some cases, toughness and impact strength can decrease. **Applications of nanocomposites** include packaging applications for the military in which nanocomposite films show improvement in properties such as elastic modulus, and transmission rates for water vapor, heat distortion, and oxygen.

Body side molding of the 2004 Chevrolet Impala is made of olefinbased nanocomposites.⁹ This reduced the weight of the molding by 7% and improved its surface quality. General Motors™ currently uses 540,000 lb of nanocomposite materials per year.

Rubber containing just a few parts per million of metal conducts electricity in harsh conditions just like solid metal. Called Metal Rubber®, it is fabricated molecule by molecule by a process called electrostatic self-assembly. **Awaited applications of the Metal Rubber** include artificial muscles, smart clothes, flexible wires, and circuits for portable electronics.

1.2.1 Polymer Matrix Composites

What are the most common advanced composites?

The most common advanced composites are polymer matrix composites (PMCs) consisting of a polymer (e.g., epoxy, polyester, urethane) reinforced by thin diameter fibers (e.g., graphite, aramids, boron). For example, graphite/ epoxy composites are approximately five times stronger than steel on a weight-for-weight basis. The reasons why they are the most common composites include their low cost, high strength, and simple manufacturing principles.

What are the drawbacks of polymer matrix composites?

The main drawbacks of PMCs include low operating temperatures, high coefficients of thermal and moisture expansion,* and low elastic properties in certain directions.

What are the typical mechanical properties of some polymer matrix composites? Compare these properties with metals.

Table 1.4 gives typical mechanical properties of common polymer matrix composites.

TABLE 1.4

Typical Mechanical Properties of Polymer Matrix Composites and Monolithic Materials

Property	Units	Graphite/ epoxy	Glass/ epoxy	Steel	Aluminum
<i>System of units: USCS</i>					
Specific gravity	—	1.6	1.8	7.8	2.6
Young's modulus	Msi	26.25	5.598	30.0	10.0
Ultimate tensile strength	ksi	217.6	154.0	94.0	40.0
Coefficient of thermal expansion	μin./in./°F	0.01111	4.778	6.5	12.8
<i>System of units: SI</i>					
Specific gravity	—	1.6	1.8	7.8	2.6
Young's modulus	GPa	181.0	38.6	206.8	68.95
Ultimate tensile strength	MPa	150.0	1062	648.1	275.8
Coefficient of thermal expansion	μm/m/°C	0.02	8.6	11.7	23

Give names of various fibers used in advanced polymer composites.

The most common fibers used are glass, graphite, and Kevlar. Typical properties of these fibers compared with bulk steel and aluminum are given in Table 1.5.

TABLE 1.5

Typical Mechanical Properties of Fibers Used in Polymer Matrix Composites

Property	Units	Graphite	Aramid	Glass	Steel	Aluminum
<i>System of units: USCS</i>						
Specific gravity	—	1.8	1.4	2.5	7.8	2.6
Young's modulus	Msi	33.35	17.98	12.33	30	10.0
Ultimate tensile strength	ksi	299.8	200.0	224.8	94	40.0
Axial coefficient of thermal expansion	$\mu\text{in./in./}^\circ\text{F}$	-0.722	-2.778	2.778	6.5	12.8
<i>System of units: SI</i>						
Specific gravity	—	1.8	1.4	2.5	7.8	2.6
Young's modulus	GPa	230	124	85	206.8	68.95
Ultimate tensile strength	MPa	2067	1379	1550	648.1	275.8
Axial coefficient of thermal expansion	$\mu\text{m/m/}^\circ\text{C}$	-1.3	-5	5	11.7	23

Give a description of the glass fiber.

Glass is the most common fiber used in polymer matrix composites. Its advantages include its high strength, low cost, high chemical resistance, and good insulating properties. The drawbacks include low elastic modulus, poor adhesion to polymers, high specific gravity, sensitivity to abrasion (reduces tensile strength), and low fatigue strength.

The glass used for making fibers is classified into five major types, explain each one.

The letter designation is based on the characteristic property of the glass:

- (i) A-glass is a high-alkali glass; it has very good resistance to chemicals, but lower electrical properties.
- (ii) C-glass is a chemical grade, which offers extremely high chemical resistance.
- (iii) E-glass has low alkali content and it is electrical grade. It provides good insulation property and strong resistance to water.
- (iv) S-glass has 33 % higher tensile strength than E-glass.
- (v) D-glass has superior electrical properties with low dielectric constant.

The difference in the properties is due to the compositions of E-glass and S-glass fibers. The main elements in the two types of fibers are given in Table 1.7.

TABLE 1.7
Chemical Composition of E-Glass
and S-Glass Fibers

Material	% Weight	
	E-Glass	S-Glass
Silicon oxide	54	64
Aluminum oxide	15	25
Calcium oxide	17	0.01
Magnesium oxide	4.5	10
Boron oxide	8	0.01
Others	1.5	0.8

Give a description of graphite fibers.

Graphite fibers are very common in high-modulus and high-strength applications such as aircraft components, etc. The advantages of graphite fibers include high specific strength and modulus, low coefficient of thermal expansion, and high fatigue strength. The drawbacks include high cost, low impact resistance, and high electrical conductivity.

Are carbon and graphite the same?

No, they are different. Carbon fibers have 93 to 95% carbon content, but graphite has more than 99% carbon content. Also, carbon fibers are produced at 2400°F (1316°C), and graphite fibers are typically produced in excess of 3400°F (1900°C).

Give a description of the aramid fiber.

An aramid fiber is an aromatic organic compound made of carbon, hydrogen, oxygen, and nitrogen. Its advantages are low density, high tensile strength, low cost, and high impact resistance. Its drawbacks include low compressive properties and degradation in sunlight.

Types: The two main types of aramid fibers are Kevlar 29®* and Kevlar 49®†. Both types of Kevlar fibers have similar specific strengths, but Kevlar 49 has a higher specific stiffness. Kevlar 29 is mainly used in bulletproof vests, ropes, and cables. High performance applications in the aircraft industry use Kevlar 49.

Give names of various polymers used in advanced polymer composites.

These polymers include epoxy, phenolics, acrylic, urethane, and polyamide.

Why are there so many resin systems in advanced polymer composites?

Each polymer has its advantages and drawbacks in its use:

- **Polyesters:** The advantages are low cost and the ability to be made translucent; drawbacks include service temperatures below 170°F (77°C), brittleness, and high shrinkage* of as much as 8% during curing.

- **Phenolics:** The advantages are low cost and high mechanical strength; drawbacks include high void content.
- **Epoxies:** The advantages are high mechanical strength and good adherence to metals and glasses; drawbacks are high cost and difficulty in processing.

As can be seen, each of the resin systems has its advantages and drawbacks. The use of a particular system depends on the application. These considerations include mechanical strength, cost, smoke emission, temperature excursions, etc.

Epoxy is the most common type of matrix material. Why?

Although epoxy is costlier than other polymer matrices, it is the most popular PMC matrix. More than two-thirds of the polymer matrices used in aerospace applications are epoxy based. The main reasons why epoxy is the most used polymer matrix material are

- High strength
- Low viscosity and low flow rates, which allow good wetting of fibers and prevent misalignment of fibers during processing
- Low volatility during cure
- Low shrink rates, which reduce the tendency of gaining large shear stresses of the bond between epoxy and its reinforcement
- Available in more than 20 grades to meet specific property and processing requirements.

Polymers are classified as thermosets and thermoplastics. What is the difference between the two? Give some examples of both.

Thermoset polymers are insoluble and infusible after cure because the chains are rigidly joined with strong covalent bonds; thermoplastics are formable at high temperatures and pressure because the bonds are weak and of the van der Waals type.

Typical examples of thermoset include epoxies, polyesters, phenolics, and polyamide;

Thermosetting Plastic Advantages:

- More resistant to high temperatures

- Highly flexible design
- Thick to thin wall capabilities
- High levels of dimensional stability
- Cost-effective

Thermosetting Plastics Disadvantages:

- Can't be recycled
- More difficult to surface finish
- Can't be remolded or reshaped

Typical examples of thermoplastics include polyethylene, polystyrene, polyether–ether–ketone (PEEK), and polyphenylene sulfide (PPS).

Thermoplastic Advantages:

- Highly recyclable
- High-Impact resistance
- Reshaping capabilities
- Chemical resistant
- Aesthetically superior finishes
- Hard crystalline or rubbery surface options

Thermoplastic Disadvantages:

- Expensive
- Can melt if heated.

What are Current Manufacturing Methods of Polymer Matrix Composites?

1) Hand Lay-up Technique:

Hand layup is an oldest open-mold process used for the composite manufacturing. This process is simple, and it is a low-volume and labor-intensive process. Large components, such as boat hulls, can be prepared by this technique. Reinforcing mat or woven fabric or roving is placed manually in the open mold, and resin is poured, brushed, or sprayed over and into the glass plies. Squeegees or rollers are used to remove the entrapped air manually to complete the laminated structure as shown in Fig.1.3. The most commonly used matrixes are polyesters and epoxies that can be cured at room temperature. The time of curing depends on the type of polymer used for composite processing. For example, for epoxy-based system, normal curing time at room temperature is 24–48 h. A catalyst and accelerator are added to the resin, which enables room-temperature curing of the resin. In order to get high quality part surface, a pigmented gel layer is first applied on the mold surface. Hand layup is the most

commonly preferred process for the manufacture of polymeric composites. Composites were basically manufactured by hand lay-up process, using a fiber-to-resin ratio of 40:60 (w:w).

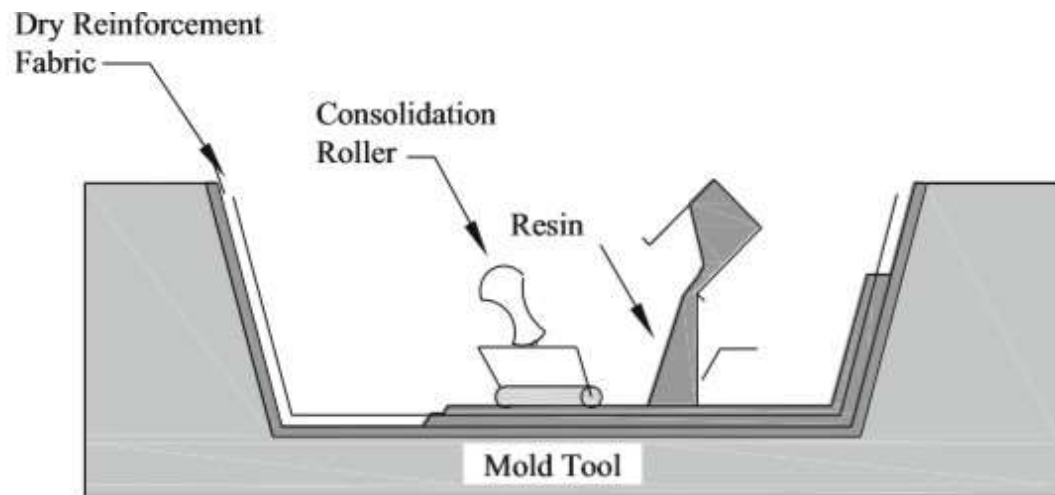


Fig. 1.3 Schematic of hand layup

2) Vacuum Bag Molding

In vacuum bag molding, the entrapped air and excess resin are removed using vacuum. After fabrication of the lay-up, a perforated release film or peel ply is placed over the laminate. The bleeder ply, which is placed above the peel ply, is made of fiber glass cloth, nonwoven nylon, polyester cloth, or other material that absorbs excess resin from the laminate, followed by a breather ply of a nonwoven fabric. The vacuum bag is placed over the entire assembly and sealed at the mold flange as shown in Fig. 1.4.

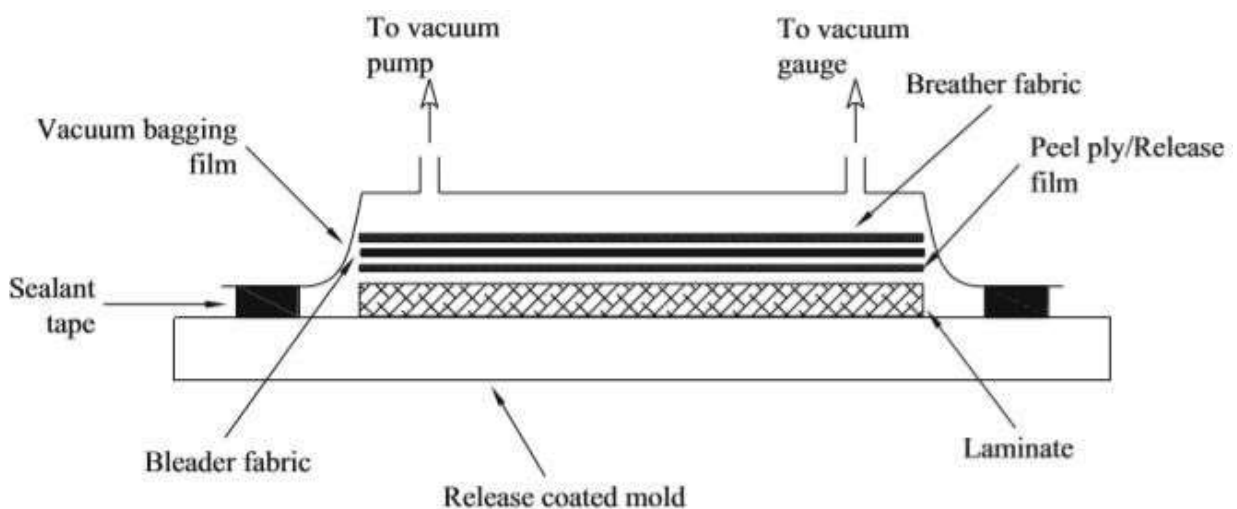


Fig. 1.4 Schematic of vacuum bag molding

A vacuum is created under the bag, and thus the laminate can be merged by applying a pressure up to one atmosphere. [This process provides a high reinforcement, improved adhesion between layers, and great control of fiber volume percent compared to the hand lay-up.](#)

Major advantages of vacuum bag molding are higher fiber content in the laminate, lower void content, better fiber wet-out, and reduced volatile emissions as compared to the hand layup. Large cruising boats and racing car components can be manufactured by vacuum bag molding. Disadvantages of vacuum bag molding include expensive and disposable bagging materials, labor intensive, inconsistent performance, trapped air/volatiles, wrinkles, loss of seal, and requirement of higher level of operator skills.

3) Pressure Bag Molding (or Autoclave)

Pressure bag molding or autoclave is identical to the vacuum bag molding except that the pressure, usually provided by compressed air or water, is applied to the flexible bag that covers the prepreg composite. The application of pressure forces out the entrapped air, vapors, and excess resin. It also facilitates better wetting of fibers.

Autoclaves are basically heated pressure vessels. These are usually provided with the vacuum systems. The bagged lay-up is cured inside the autoclave as shown in Fig.1.5.

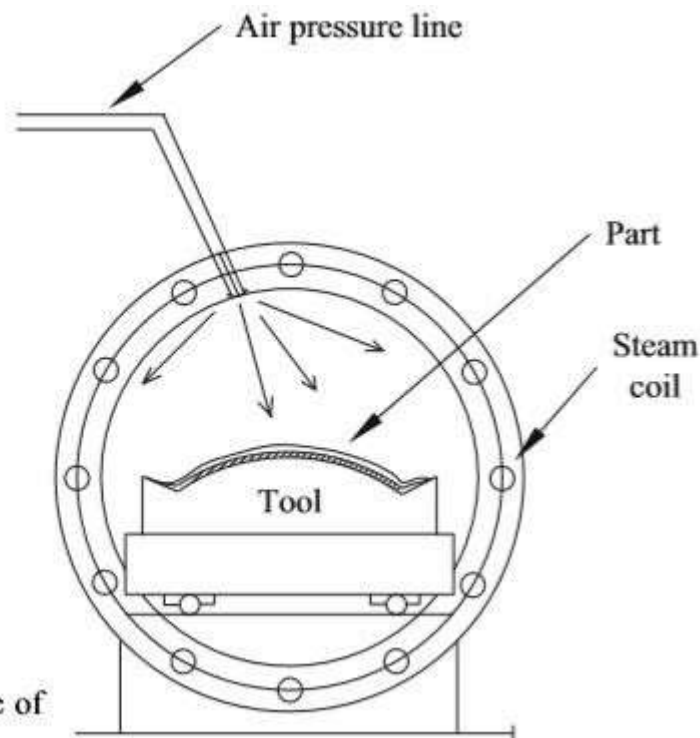


Fig. 1.5 Schematic of autoclave

The process of autoclave involves application of higher heat and uniform pressure on the component during curing, which results in a denser and low void percentage product. The autoclave equipment and tooling are expensive and it is only suitable for high-end applications. The pressures required for curing are typically in the range of one to six bars and takes several hours to complete the curing. This method accommodates higher temperature matrix resins having properties higher than the conventional resins, such as epoxies. Component size is limited by the autoclave size. It is mostly used in the aerospace industry to manufacture high-strength/weight ratio parts from pre-impregnated high-strength fibers for aircraft, spacecraft, and missiles.

4) Filament Winding

This process consists of a rotating mandrel on which pre-impregnated fibers or reinforcement is wound in the preset patterns. The method provides the best control of fiber placement. The wet method is shown in Fig. 1.6. Here, the fiber is allowed to pass through a bath containing low-viscosity resin. In the dry method, the pre-impregnated reinforcing layers are wound on the mandrel, and then the component is removed and postcured.

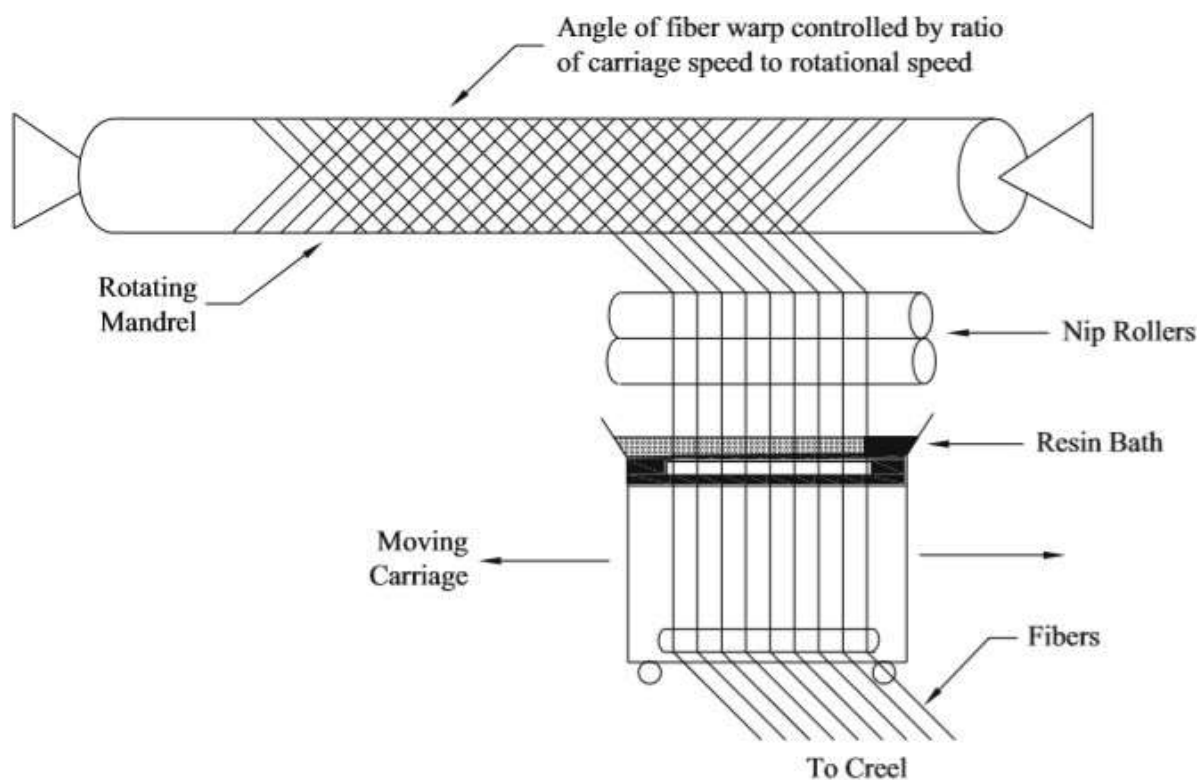


Fig. 1.6 Schematic of filament winding

Conventionally, this process is used to make pressure vessels, rocket motor cases, tanks, ducting, golf club shafts, and fishing rods. Recently, non-cylindrical and nonspherical composite parts are also produced by filament winding technology. Polyesters, vinyl esters, epoxies, and phenolics are the typical thermoset resins used in the filament wound parts. This process is best suited for parts with rotational symmetry, but it is possible to wind odd-shaped parts using a robotized winding. It requires special

equipment and may result in variation in the part thickness in case of tapered parts. The tooling and setup cost is high and it is only suitable for a limited variety of components.

5) Resin Transfer Molding

Resin transfer molding (RTM) is a low-pressure closed molding process for moderate- and high-volume production. This process basically involves placement of the dry stack of reinforcement in the bottom part of the mold, and then the other half is clamped over the bottom mold. For complex shapes, preforms are used. After closing the mold, a low-viscosity resin containing catalyst is pumped in, which displace the air through strategically located vents. The resin/catalyst ratios are controlled by metered mixing equipment and injected into the mold port as shown in Fig. 1.8.

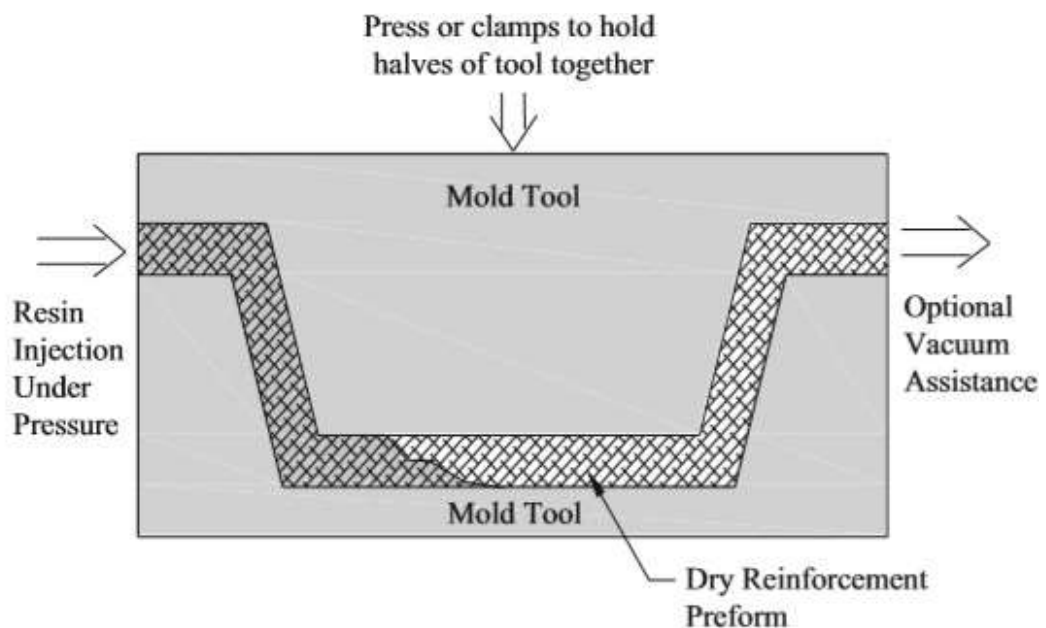


Fig. 1.8 Schematic of resin transfer molding

The commonly used matrix resins include polyester, vinyl ester, epoxy, and phenolics. Both injection and curing can take place at either ambient or elevated temperature. In order to have optimum surface finish, a gel coat is applied to the mold surface prior to molding. High-quality parts such as automotive body parts, bathtubs, and containers

are produced by this method. The variation in injection pressure has no effect on the quality of moldings. A wide range of resin viscosities has been successfully molded by this technique (RTM). It can produce laminates having high fiber volume with very low void contents. It is safe for the health and environment due to the enveloping of resin. Component prepared by RTM has molded surface on both sides. The disadvantages of RTM process are need of heavy and expensive tooling to withstand pressures, limitation in size of the components, and very expensive scrap parts due to un-impregnated areas.