Applications of Composite Materials

CHAPTER 1: INTRODUCTION TO COMPOSITE MATERIALS

1. Background

In recent years, high-stiffness, high-strength and lightweight composite materials have gained recognition as a significant cutting edge technology with a potential to generate efficient power, re-invent the high efficiency transportation sector, offer new carriages for storage and transportation of reduced carbon fuels, and enhance renewable energy production (Metals & Materials Society, 2012). It is imperative to harness the true potential of composite materials by utilizing the advanced engineering techniques to manufacture the cost-effective yet efficient products at commercial scale. Technology Assessment is an effective tool to modify the manufacturing processes by incorporating the modern advancements in technology.

A composite material is a blend of two or more distinct materials that retain their separate-structure resulting in a unique material which has improved properties than the original constituents (Campbell, 2010). Fiber reinforced polymers (FRPs) are composites prepared by joining a polymer resin with high strength reinforcing fibers. These lightweight composites are used in numerous applications where energy saving and reduced carbon emissions are desired. Major examples of energy conservation include light weight vehicles with lower energy demand, lightweight and high-efficiency wind turbines and utilization of compressed gas tanks for fuel gases.

Normally, a composite material comprises of matrix and fibers. The reinforcement or fiber material gives strength and distributes the applied load in the composite. The matrix material binds and upholds the arrangement or spacing of the fibers and shields the reinforcement from abrasion and environmental damages. The mingling of a matrix with high strength fibers results in the production of a composite material with high strength to weight ratio. The properties of composite materials are often comparable or even superior to the metals. Fibers and resin can be mixed in a significant number of ways and treated through a chain of forming and joining steps. The particular assembling procedure is reliant on the matrix material, the size and shape of the reinforcement, and the basic properties essential for the end use. Based on the nature of matrix material, the composite materials are classified into three categories which are listed below (Adrian & Gheorghe, 2010):

a) Organic/Polymer matrix composites

b) Metallic matrix composites

c) Ceramics matrix composites

The composite materials have following advantages over metallic materials:

i. Lightweight
ii. Low radar visibility
iii. Easy moldable to complex forms
iv. Low electrical conductivity and thermal expansion,
v. Part consolidation due to lower overall system costs
vi. Excellent fatigue resistance
vii. High specific stiffness and strength

As compared to metals, the composite materials also have some disadvantages which are listed below:

i. Difficulty manufacturing
ii. Cost of materials
iii. Solvent or moisture attack Fasteners
iv. Long development time
v. Temperature limits
vi. Low ductility
vii. Hidden damages and damage susceptibility

There are following three kinds of composites according to widespread occurrence:

1.1.Natural Composites

Natural composites are found in both plants and animals. Wood is also a composite – it consists of long cellulose strands (a polymer) held together by a substantially weaker material called lignin. Cellulose is also present in cotton, however without the lignin to tie it together, it is considerably weaker. The two frail substances –cellulose and lignin – combine to form a substantially stronger composite. The bones in our bodies are also composite materials. A bone is composed of a strong yet brittle substance called hydroxyapatite (contains calcium phosphate) and a delicate material called collagen (protein). Collagen is also present in fingernails and hair. Collagen alone is too weak to offer any strength to the bones; however, it can consolidate with hydroxyapatite to provide bones the properties that are expected to reinforce the body.

1.2.Early composites

Human beings have been creating composites since ancient times. One primary example is the manufacturing of mud blocks. Mud can be molded and dried out into a block/brick shape to provide a building material. It has high compressive strength, yet it breaks effortlessly if we attempt to twist it (i.e. weak tensile strength). Straw appears to be extremely strong when we try to stretch it; however, we can fold it up with ease. By combining mud and straw together, it is conceivable to create bricks that are impervious to both crushing and tearing and make fantastic building squares (Makar et al., 2005).

Another old-timer composite is concrete. Concrete is a blend of aggregate (gravel or small stones), sand and cement. It has an excellent compressive strength (it opposes squashing). Recently, it has been observed that adding metal wires or rods to the concrete can enhance its tensile and bending strength. Concrete containing wires or rods are called metal reinforced concrete.

1.3.Modern examples

The primary present day composite material is fiberglass. It is commonly utilized today for watercraft frames, sports gear, building boards and numerous auto bodies. The reinforcement is fiberglass while the matrix is a polymer; the reinforcement has been converted into fine filaments and often woven into a kind of fabric. Discretely, the glass is strong but also very brittle and it will break if twisted sharply. The polymer resin holds the glass filaments together and shields them from impairment by sharing out the stresses being applied to them. Some high-quality composites are presently manufactured by utilizing carbon fibers rather than glass fibers. Carbon fibers are stronger and lighter than glass fibers but more costly to manufacture. They are utilized as components of airplane structures and expensive sports equipment, e.g. golf clubs. Carbon Nanotubes (CNTs) have been used effectively to make advanced composites. CNTS based composites are stronger and lighter than the composites manufactured from conventional carbon fibers. They do, nonetheless, offer prospects for building lighter aircraft and cars (which will utilize less fuel than the currently used heavier vehicles).

The world's biggest airliner, Airbus-A380, contains modern composite materials in its structures. More than 20 % of the Airbus-A380 structure is made of modern composite materials; mostly plastic strengthened with carbon fibers. The Airbus design utilized fiberglass-reinforced aluminum on a large scale for the first time in the history of air crafts. The novel design is 25% stronger and 20% lighter than the conventional aluminum airframe.

2. Fiber Reinforced Plastics (FRPs)

FRPs for wind turbine blade, compressed gas storage, and automotive applications are considered as primary models for clean energy applications. There are different other applications of FRPs including industrial equipment such as pipelines and heat exchangers, geothermal power generation, structural building materials, flywheels for stability of electricity grid, hydrokinetic energy production, support assemblies for solar systems, transportation containers and different frameworks which can benefit from cost effective high strength, corrosion resistant, and lightweight composites to influence national energy objectives. Some of these applications benefit mainly from CFRP-based composites, which provide a high stiffness-to-weight ratio and excellent strength-to-weight ratio as compared to numerous structural materials (Tannous & Saadatmanesh, 1998). These lightweight composite materials can provide significant energy conservation and saving during the utilization stage that can't be accomplished with materials that don't possess high stiffness and strength properties. Comparison of properties for different categories of materials is shown in Fig.1.

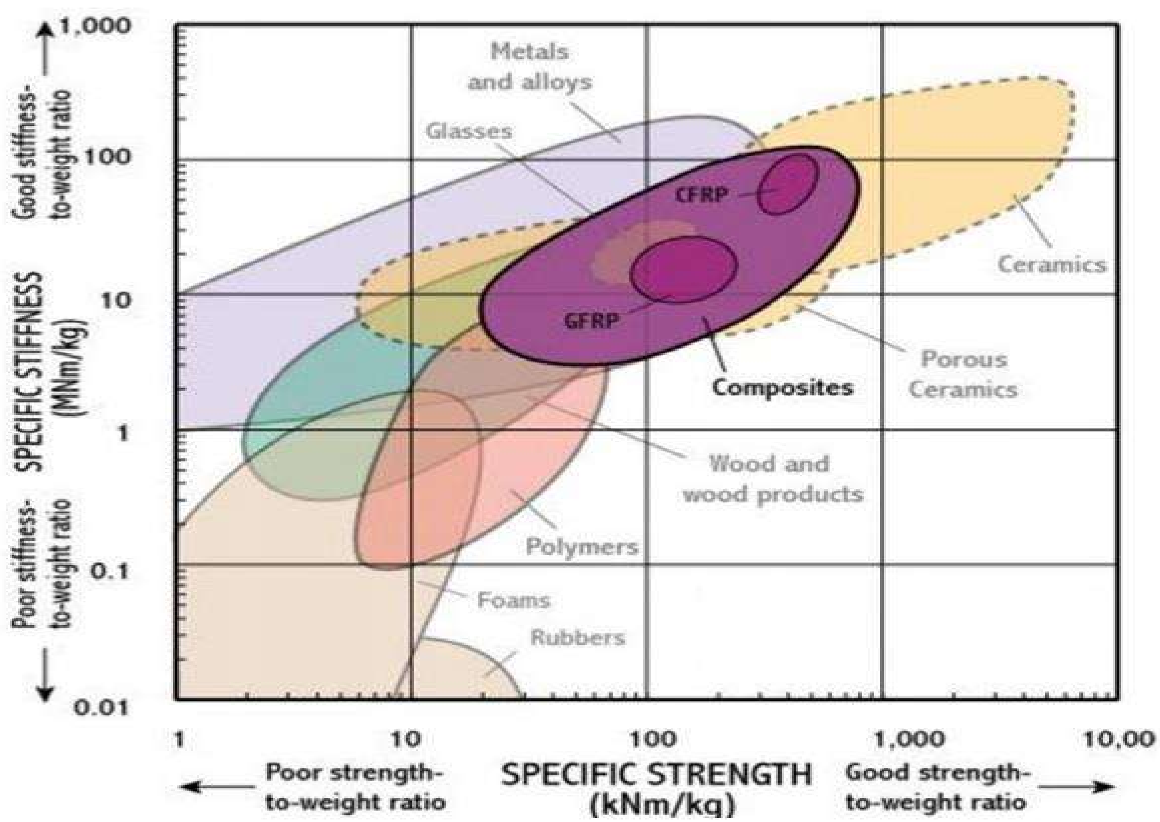

Fig. 1. Specific strength and specific stiffness for different materials, the figure also highlights Glass Fiber Reinforced Plastic (GFRP) and Carbon Fiber Reinforced Plastic (CFRP) Composites.

3. Science of Composite Materials

The reinforcing component provides the stiffness and strength in a composite material. In most of the cases, the reinforcement material is harder, stiffer and stronger than the matrix phase. The reinforcement is typically a particulate or fiber. Dimensions of particulate composites are nearly equal in all material directions. They might be platelets, spherical or any other symmetrical or asymmetrical geometry. Particulate composites have a tendency to be significantly less stiff and weaker than continuous fiber reinforced composites, yet they are less costly. Particulate strengthened composites generally contain less particulate content (40 to 50 % volume) due to brittleness and processing difficulties. The length of a fiber is significantly greater than its corresponding diameter. The length-to-diameter ratio of a fiber is called the *aspect ratio* (l/d) and can vary prominently (Halpin, 1969). Discontinuous fibers have small aspect ratios while continuous fibers possess comparatively higher aspect ratios.

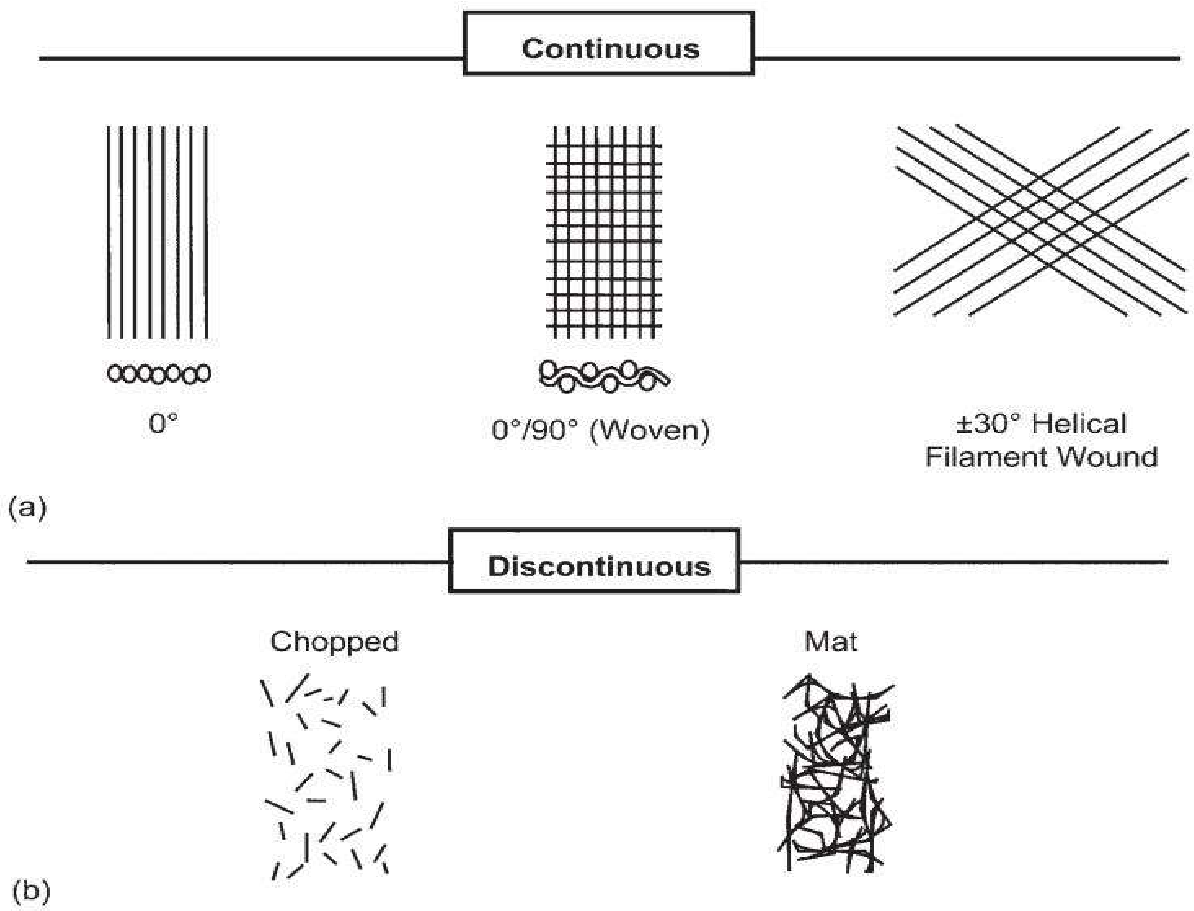

Fig. 2. Typical reinforcement types

Continuous fiber reinforced composites typically have a regular fiber orientation, while discontinuous fibers composites generally have an irregular fiber orientation in the matrix. Continuous fibers include unidirectional fibers, helically winded fibers and woven cloth (Fig. 2a), while discontinuous reinforcements are characterized as a random mat and chopped fibers (Fig. 2b).

Continuous fiber reinforced composites are generally converted into composite laminates by stacking continuous fiber sheets in various orientations to achieve the desired stiffness and strength properties with high fiber volumes, i.e. 60 to 70 percent. Fibers deliver high-strength composites on account of their smaller diameters; they contain far fewer defects (typically surface imperfections) as compared to the components manufactured by bulk materials. The diameter of fibers is inversely proportional to the strength of a composite, i.e. smaller the diameter, the greater its strength, however, smaller fiber diameters result in cost increment of the composite materials (Migneault et al., 2008). Additionally, high strength fibers with a smaller diameter are highly flexible and more responsive to manufacturing operations such as forming or weaving. Typical examples of the fibers include glass, carbon, and aramid which may exist as both continuous and discontinuous fibers. The continuous phase in a composite is the matrix, which is either a polymer, ceramic or metal.

Polymeric matrix has low stiffness and strength, metallic matrix possesses mild stiffness and strength but high ductility, and a ceramic matrix is brittle in nature but has high stiffness and strength. The matrix phase performs numerous important functions such as keeping the fibers in a proper alignment and shielding them from environment and abrasion. In metal and polymer matrix composites which make a solid bond between the matrix and the fiber, the load is transmitted from the matrix to the fibers through shear loading at the fiber-matrix interface. In ceramic matrix composites, the goal is to enhance the toughness of the composite rather than stiffness or strength. Therefore, a composite with a low interfacial (fiber-matrix interface) bond strength is desirable. Quantity and the type of the reinforcement define the final characteristics of a composite. Fig three demonstrates that the higher modulus and strength values are achieved with continuous-fiber composite materials. There is a practical limit (about 70 percent volume) for fiber content in a composite. Fiber content beyond that limit results in loss of strength and mechanical properties due to the inability of the matrix to support and hold the fibers properly.

The strength of the composite with discontinuous fibers can match that of continuous-fiber composite if the aspect ratios of discontinuous fiber composites are sufficiently high and they are regularly aligned. However, it is difficult to keep up a substantial arrangement with discontinuous fibers. Discontinuous-fiber composites are usually irregular in alignment, which significantly decreases their modulus and strength. On the contrary, discontinuous fiber composites are typically less expensive than the continuous-fiber composites. Consequently, continuous-fiber composites are utilized where higher stiffness and strength are required (quality driven), and discontinuous fiber composites are utilized where cost is the principal driver while stiffness and strength are less significant. Nature of both the fiber and the matrix influence processing parameters for composite manufacturing. There are two categories of polymer matrices, i.e. thermoplastics and thermosets (Blackketter et al., 1993). A thermoset is initially a low-viscosity resin (matrix) that reacts with environment and cures during the processing, resulting in a rigid solid.

A thermoplastic is a highly viscous resin which is prepared by heating it over its liquefying temperature. Since a thermoset resin sets up and eventually cures during the processing phase, it can't be recycled by reheating. There are processing methods for both categories of resins which are more amiable to continuous fibers while there are other processes which are more suitable for discontinuous fibers. Ceramic and metal matrix composites are usually more expensive than polymer matrix composites because of high processing temperatures and pressures. On the other hand, both metal and ceramic matrix composites possess higher thermal stability, which makes them an ideal candidate for high-temperature applications. Variation in strength for the different class of fibers is shown in Fig. 3.

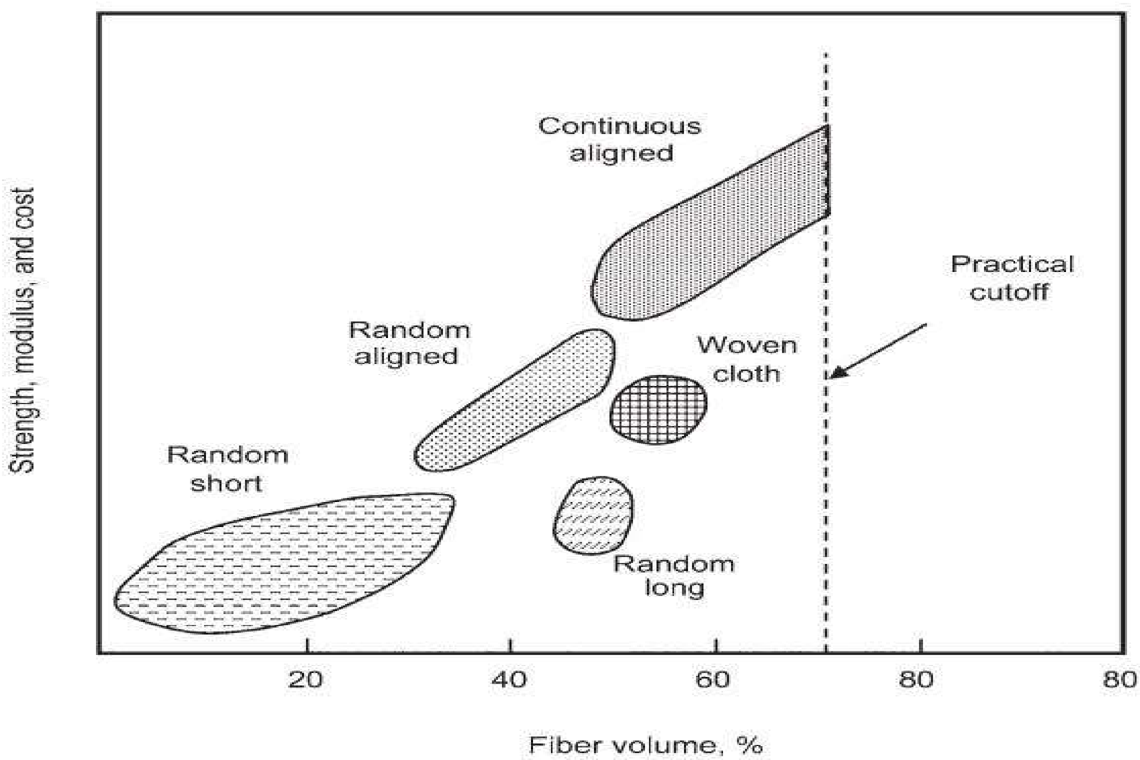

Fig. 3. Influence of reinforcement type and quantity on composite performance

4. Orthotropic, Isotropic and Anisotropic Materials

All the materials are categorized as either isotropic or anisotropic material (Jones, 1975). Isotropic materials possess the similar properties in all material directions, and perpendicular loads generate normal strains only. However, anisotropic materials usually have dissimilar properties in all material directions. There are no symmetrical planes in anisotropic materials, and normal loading conditions produce both normal and shear strains. Materials are categorized as isotropic if their properties are not direction dependent within the bulk material. For instance, if the material undergoes loading along 0°, 45°, and 90° from a specific reference point, the modulus of elasticity remains same in all directions, i.e. $E0° = E45° = E90°$. Different loading conditions for an isotropic material as explained in Fig. 4.

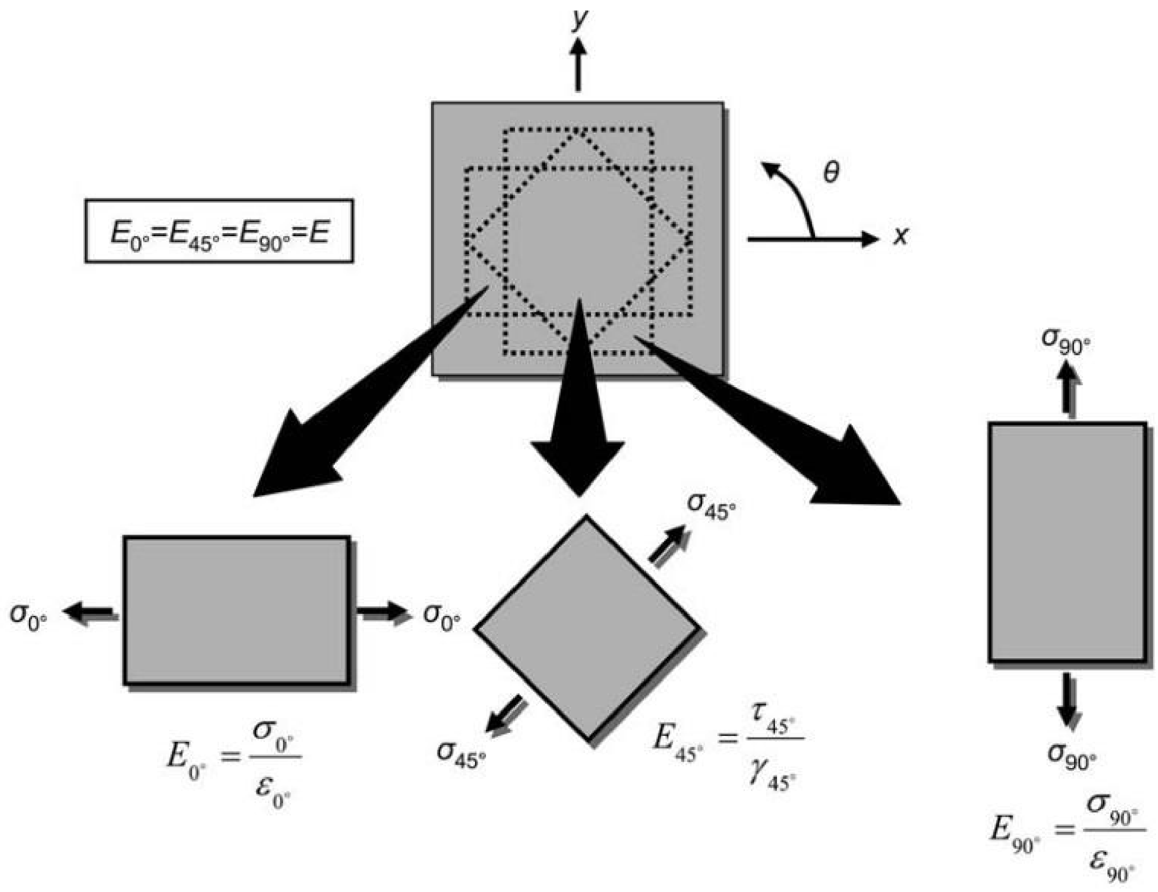

Fig. 4. Isotropic material under stress conditions

4.1. Element of isotropic material under stress

The properties of anisotropic materials vary significantly with change in material direction. The modulus of the anisotropic material also varies with the change in direction, i.e. $E0° \neq E45° \neq E90°$. Variation of other mechanical properties such as ultimate strength, thermal expansion, and poison's ratio are also direction dependent in anisotropic materials. Bulk materials (metals, polymers, and ceramics) are typically dealt as isotropic materials, and composite materials are classified as anisotropic materials. However, bulk materials, for example, metals and polymers can also become anisotropic, i.e. if these materials are treated (cold working, localized heating) to harvest certain properties in specific directions.

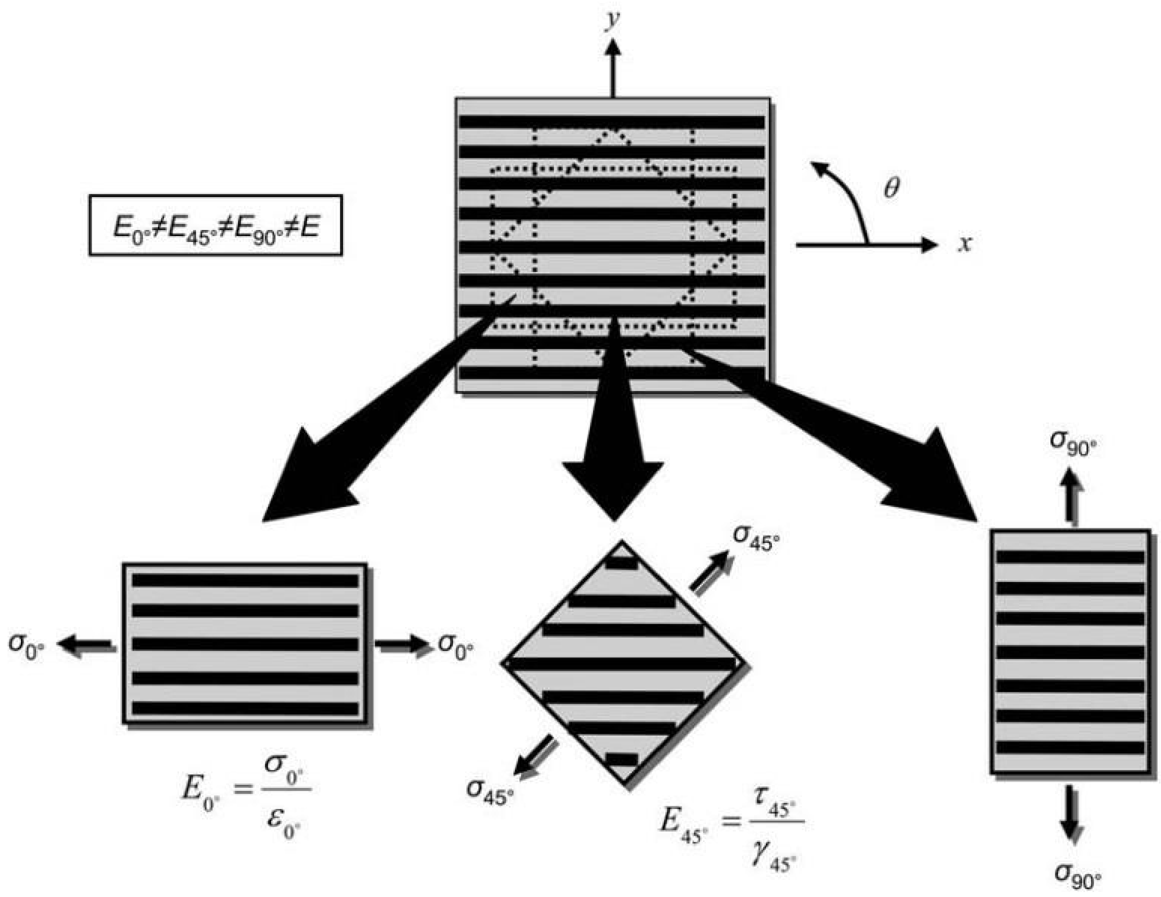

Fig. 5. Anisotropic material under stress conditions

4.2.Elements of composite materials under stress

Composites materials lie in the sub-category of anisotropic materials which are branded as orthotropic materials. Properties of orthotropic materials are different in all perpendicular directions. Their three axes of symmetry are mutually perpendicular, and only normal strains are produced by application of load parallel to these symmetrical axes. On the contrary, both shear and normal strains are produced if the applied load is not parallel. Therefore, orthotropic properties of the material are regulated by material orientation.

5. Rule of Mixtures and Curing of Composites

The longitudinal modulus of a continuous fiber laminate undergoing unidirectional loading, parallel to the fibers (11- 0° direction), can be calculated from the individual properties of constituents by utilizing Rule of Mixtures (Hui & Shia 1998).

5.1. Rule of Mixtures

$E_{11} = E_f V_f + E_m V_m$ (eq 1.1)

In equation 1.1, E_f is the modulus of fiber, V_f is volume percentage of fibers, E_m is the modulus of the matrix, and V_m is the volume percentage of the matrix. The longitudinal ultimate tensile strength (σ_{11}) can also be calculated by applying the rule of mixtures:

$\sigma_{11} = \sigma_f V_f + \sigma_m V_m$ (eq 1.2)

In equation 1.2, σ_m and σ_f are the ultimate strengths of matrix and fiber respectively. As the strength of fibers is extremely high as opposed to the strength of matrix at all fiber volume percentages, therefore, the strength values of matrix can be ignored:

$E_{11} \approx E_f V_f$ (eq 1.3)

$\sigma_{11} \approx \sigma_f V_f$ (eq 1.4)

5.2.Curing Processes

Structures composed of fiber-reinforced plastics (FRPs) necessitate the polymer matrix (resin) to attain and sustain solid-state properties in service. Thermoset resins polymerize irreversibly through cross-linking reaction, while thermoplastics are easily re-melted above their transition temperature. Thermoplastics and thermosets not only differ in physical properties but also undergo different fabrication processes for composite manufacturing. Traditionally, advanced composite materials have long been based on thermosetting polymer systems, and almost 80% of the composites are based on a thermoset polymer matrix, which requires a particular curing time to produce the desired properties.

Due to stringent certification and specifications methods, aerospace composite materials are based on epoxy resin systems in which the curing reactions follow a specific temperature profile to ensure a proper resin flow, consolidation, de-gassing, and ultimately homogeneous degree of polymerization to attain final properties (U.S. Department of Energy, 2011). The curing processes are usually slow (a few minutes to hours) and energy exhaustive because the huge thermal mass of autoclave and the tooling are also subjected to the same thermal sequence. Autoclave methods have also been utilized by the composites industries beyond aerospace applications. The modern developments and improvements in optimized cure cycles, selective polymerization techniques, and further innovations in the autoclave technique are prospective steps to diminish the energy consuming composite manufacturing processes. Currently, electro-technologies using radiation heat transfer principles are being utilized for selective heating or curing of composites materials. However, electro-technology requires composite systems which are responsive to applied radiation frequencies. Examples of responsive systems are explained below:

Dielectric heating techniques based on radio frequency (RF) or microwave (MW) where the electromagnetic (EM) radiation combines primarily with the matrix; for instance, the RF curing of epoxy-based composites are dependent on the dielectric response of the resin system (Feher et al., 2003).

i. Infrared (IR) heating is a cost effective and efficient technique of heating, pre-heating, melting and curing. Medium and long-wave IR heating has various potential applications; which have been successfully implemented by composite manufacturing industries such as partial curing of composites and pre-heating of fiber pre-forms during intermediary processing steps.

ii. Induction heating techniques are utilized to heat conductive matrix materials such as metallic matrices. Induction heating processes are broadly used in metal foundries for heat treatment and melting purposes (Cresko, & Roberts, 2002).

6. Composites versus Metallic Materials

As discussed earlier, the physical and mechanical characteristics of metals and composites are substantially different. Table 1 depicts the comparison of properties for composites against metals. Composite materials are exceptionally anisotropic, in-plane stiffness and strength of composites are typically high and vary in different directions, depending on the alignment of the fibers. There are some composite properties which do not show any improvement because of reinforcement, i.e. through-thickness tensile strength. The load is applied on the matrix rather than fibers in this thickness direction.

Condition	Comparative behavior relative to metals
Load-strain relationship	More linear strain to failure
Notch sensitivity	
Static	Greater sensitivity
Fatigue	Less sensitivity
Transverse properties	Weaker
Mechanical property variability	Higher
Fatigue strength	Higher
Sensitivity to hydrothermal environment	Greater
Sensitivity to corrosion	Much less
Damage growth mechanism	In-plane delamination instead of through thickness cracks

Table 1.The comparison of properties for composites as compared to metals (Campbell, 2010)

Comparison of the through-the-thickness mechanical strength of a composite laminate and an aluminum alloy is displayed in Fig.6**.**

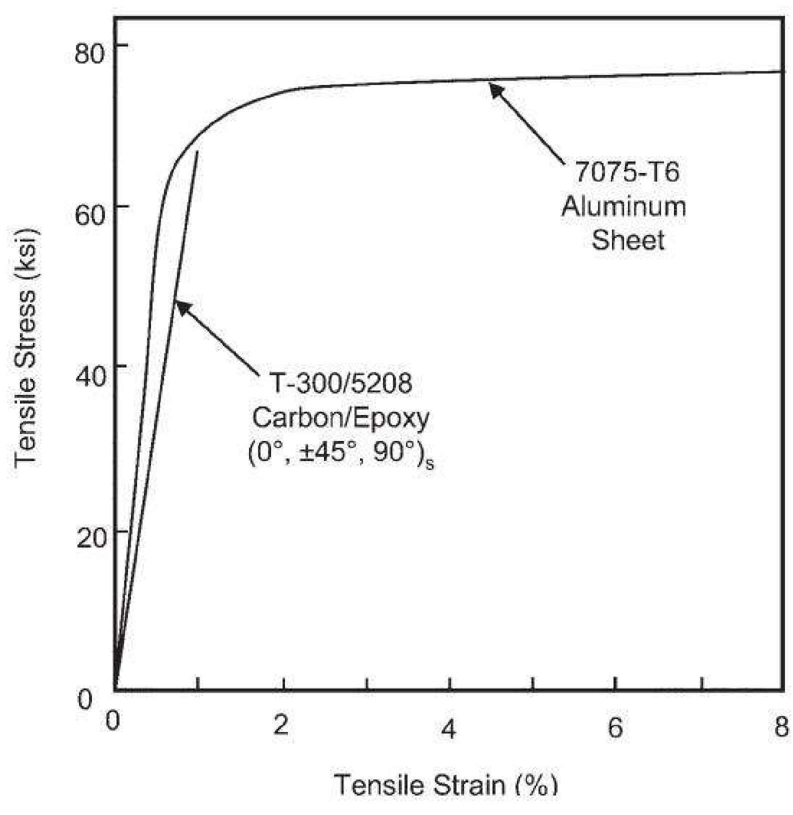

Fig. 6. Comparison of through the thickness strength for epoxy composite and aluminum alloy

Ductility of metals is typically high which makes them compress or elongate significantly, without fracture, under certain loading conditions. Ductile yielding has following two benefits:

1. Ductile yielding assists in local stress relief by distributing the stress to adjacent structure or material. Consequently, ductile metals possess a huge capacity to incorporate stress relief mechanism during static loading conditions.
2. Ductile materials have a great capability to absorb energy (area under the stress-strain curve). Therefore, ductile metals undergo plastic deformation under impact loading before fracture.

Composite materials are brittle as compared to metals. Brittle nature of the composites is characterized by its poor capability to withstand stress concentrations. Brittle composites also lack the ability to withstand impact loads. The response of notched composite materials to cyclic (fatigue) loading is also considerably different (high) from that of metallic materials. The capacity of composites to tolerate fatigue loading is greater than that of metals. However, the static strength of notched (damaged) composites is lower than that of metals due to the presence of defects.

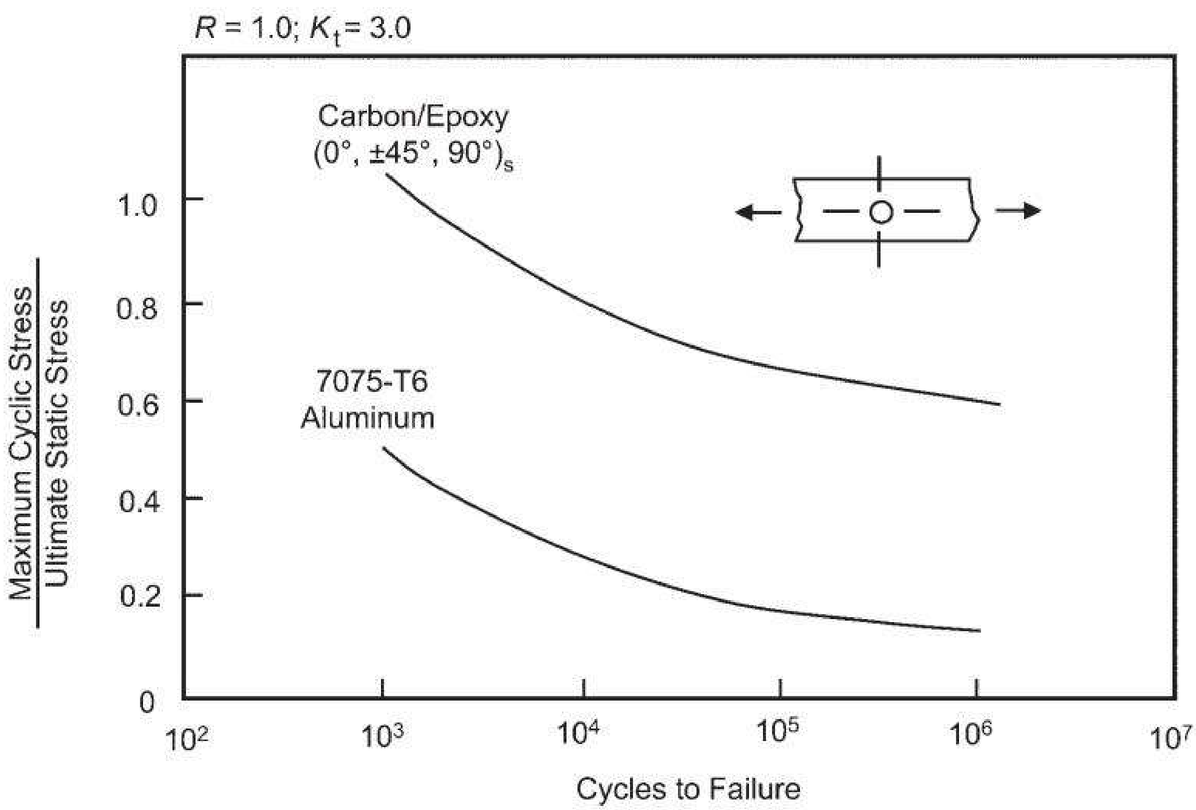

Fig. 7. Comparison of Fatigue properties for epoxy composite and aluminum alloy

Fig.7 shows that the fatigue strength of a notched composite material (carbon/epoxy composite) is considerably higher than that of space grade aluminum alloy (7075-T6). Structural materials usually require high static strength as compared to high fatigue resistance; therefore, the strength of the composites is improved by adjusting the fiber content and its orientation. However, fatigue is generally a critical design parameter.

7. Advantages and Drawbacks of Composite Materials

There are many advantages of composite materials such as lighter weight, improved fatigue life, high corrosion resistance, high stiffness and strength, and lower assembly expenditures due to lesser part and fastener components (Campbell, 2010). Specific modulus (modulus/density) and specific strength (strength ratio density) of highly strong fibers are generally greater than the mechanical properties of comparable aerospace alloys (Fig. 8). Higher mechanical composite materials are also lighter in weight, which result in improved performance, longer range, greater payloads, and fuel saving. Fig. 8 depicts the comparison of structural efficiency for carbon/epoxy composite, high strength aluminum alloy (7075-T6) and titanium alloy (Ti-6Al-4V).

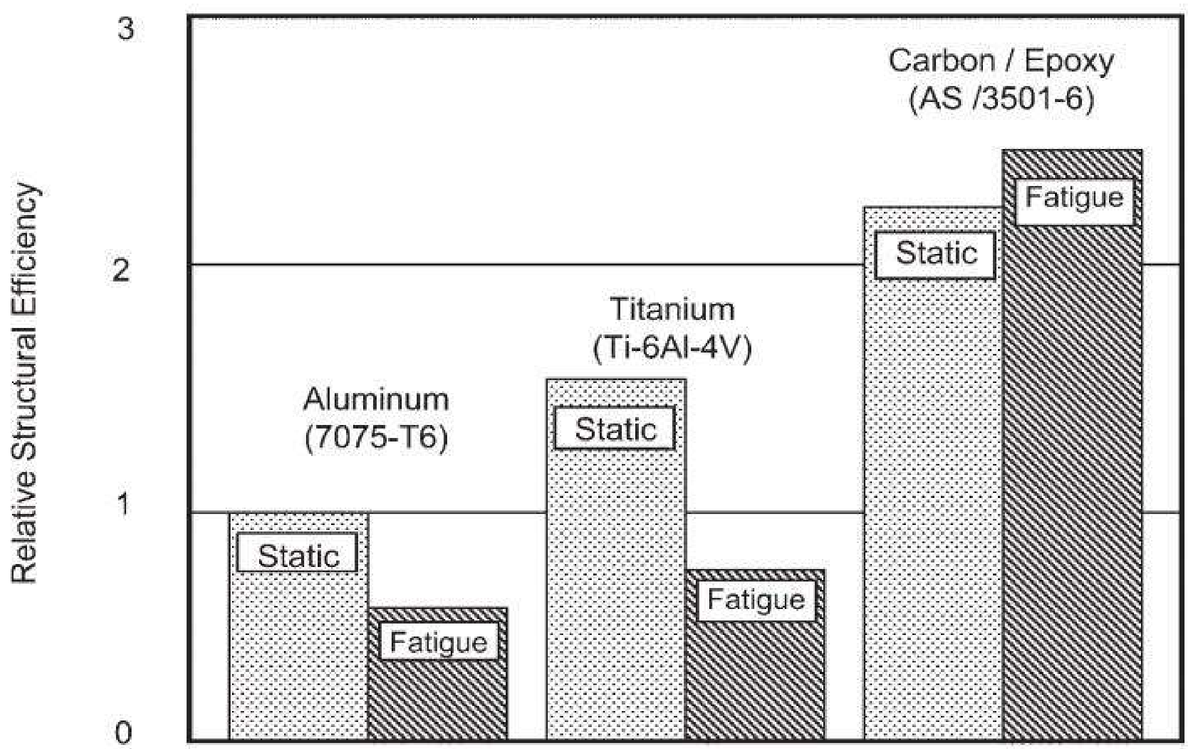

Fig. 8. Structural efficiency of different materials

8. Fabrication Process for Composite Materials

Composite fabrication normally accounts for manufacturing of following two structures (Strong, 2008):

a) **Laminates**

Some composites are fabricated as Laminates which contain bonded layers.

a) **Sandwiches**

Composite materials are also manufactured as honeycomb sandwich structures which consist of a low-density core sandwiched between faces of polymeric or metallic sheets.

Composites manufacturing can be carried out by various processes, some important fabrication processes are discussed in the appending text. Flowchart of the composite manufacturing processes is shown in Fig. 9.

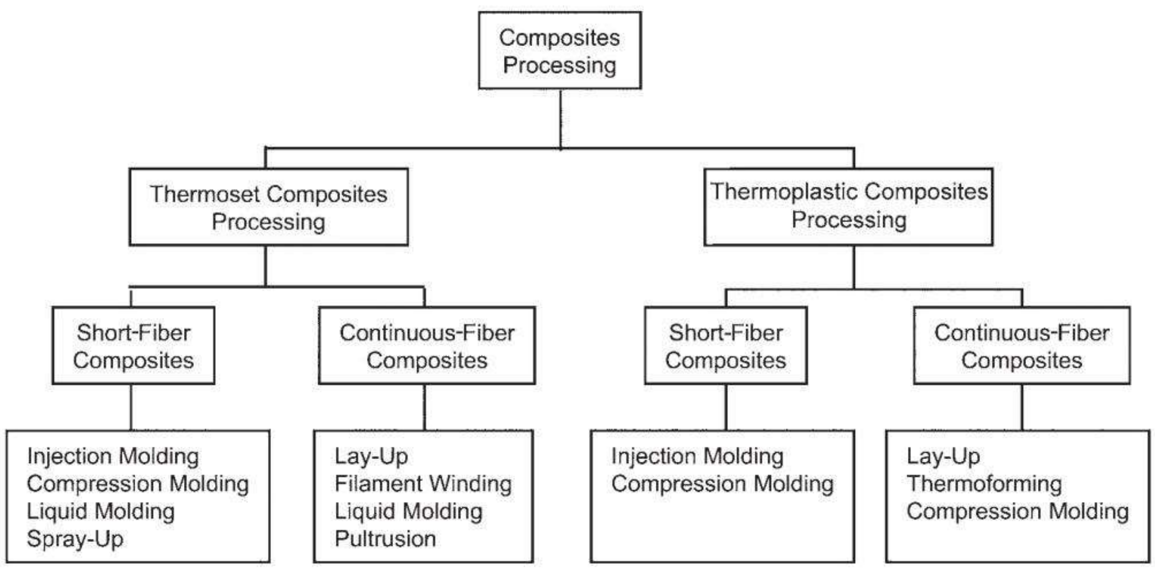

Fig. 9. Major polymer matrix composite fabrication processes

8.1. Injection Molding

Injection Molding is one of the most well-known and broadly utilized fabrication processes for high-volume development of thermoplastic matrix components reinforced with fibers (Thiriez & Gutowski, 2006). Almost 20% of all products fabricated these days injection molding because of its versatility, adaptability and lower cost. Solid blocks of resin (matrix) containing reinforcing fibers are fed into the heated barrel (containing rotary screw) through a hopper. The rotary screw produces heat shearing against the barrel, ultimately liquefying (melting) the resin. The rotating screw also behaves like a piston which forces the blend of molten resin and fibers into a metal mold, which aids the mixture to cool down and solidify.

After solidification process, the composite component is ejected by opening the mold cavity. The major benefits of injection molding include the short process durations (generally, a few seconds) and comfort of automating the manufacturing process. The combination of process automation and short process times results in higher production volumes. The principle drawback of injection molding includes the high cost of the molds and capital equipment. Additionally, the properties of composites also vary due to the absence of a mechanism for distribution and orientation of fibers. Furthermore, because of the limitations in the melt viscosity of thermoplastic resins, injection molding accounts for the production of particulate fiber reinforced composite materials which are utilized in the manufacturing of automotive components, such as dashboard components, seat backs, closures and control valves.

Long process durations for injection molding of parts are a major downside to the utilization of fiber reinforced plastics in high volume marketplaces, including typical automotive applications. Long process cycles are regulated by curing rate, resin flow rate and the time required to circumvent the formation of bubbles in the polymeric resin which converts into cavities after curing and result in structural flaws. Considering the competition in the market, the cycle times of composites manufactured from injection molding are typically less than two minutes which are considerably faster than the conventional pre-preg processes (usually one-hour cycles). Existing composites applications normally utilize glass fibers and a thermoplastic resin (instead of thermoset resins) for manufacturing of injection molded components with shorter cure times.

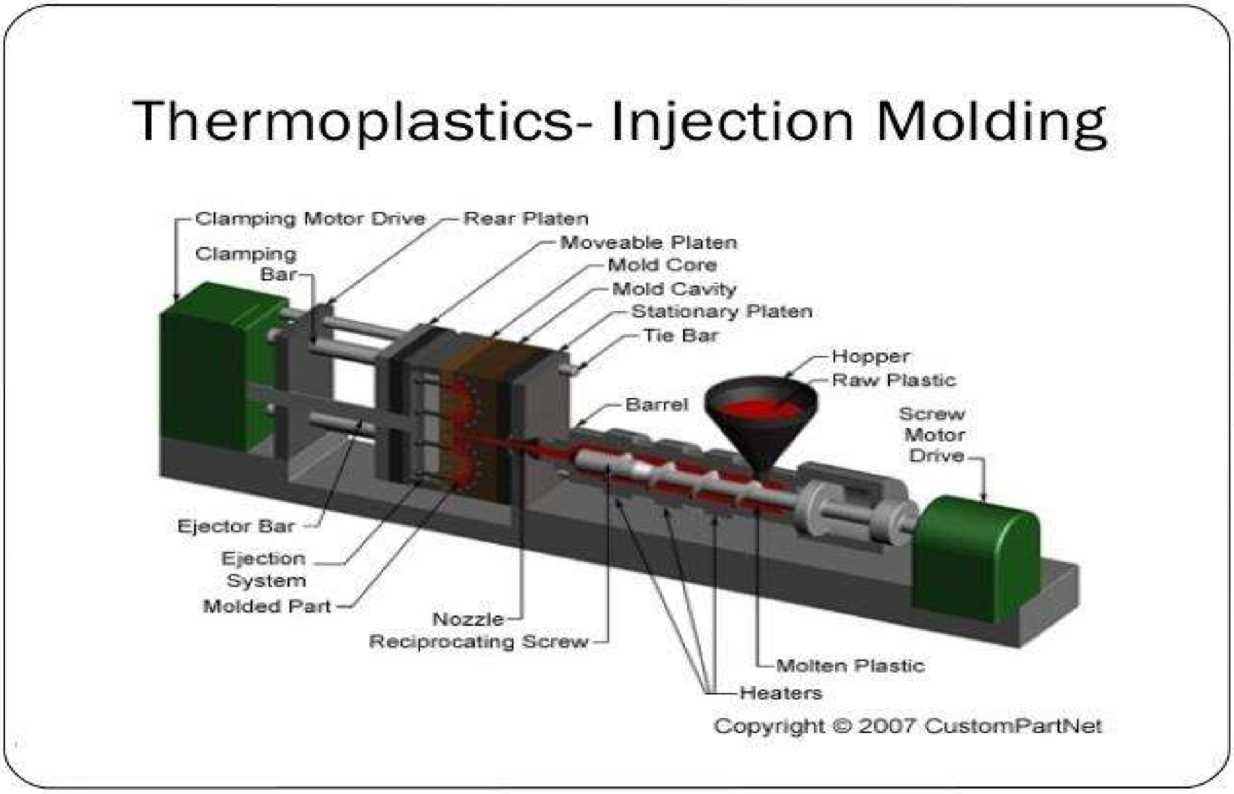

Fig. 10. Schematic of Injection Molding process

Substantial advancements are in progress to regulate the chemistry of thermoplastics and tailor the viscosity of resins to manufacture continuous fiber reinforced composites. This high volume fabrication process will remain the process of choice for fabrication of automotive components. Recently, Toho Tenax has developed a technology based on carbon fiber reinforced plastics which can produce high volumes of automotive components in less than a minute.

8.2. Resin Transfer Molding (RTM)

Resin Transfer Molding involves the packing of dry fiber reinforcement of fiber preform into a mold tool which has the desired geometry of the composite component. Both mold tools are clamped over one another and the resin in fed into the mold cavity (Potter, 2012). A vacuum process known as Vacuum Assisted Resin Injection might be utilized to facilitate the drawing of resin through the cavity. The key drawbacks of this process include the inability of the tool to manufacture large-sized components and high costs of mold tools, which can withstand high pressures. Moreover, un-impregnated zones can exist resulting in extremely expensive scrap parts. This composites fabrication method offers the most astounding capability of all fabrication processes in the manufacturing of intricate, large-scale automotive parts. The current BMW i3 utilizes RTM method in combination with the robotic alignment of fiber preforms to fabricate the frame of the car. The process is also a potential fabrication method for chassis/suspension and hood applications in auto vehicles.

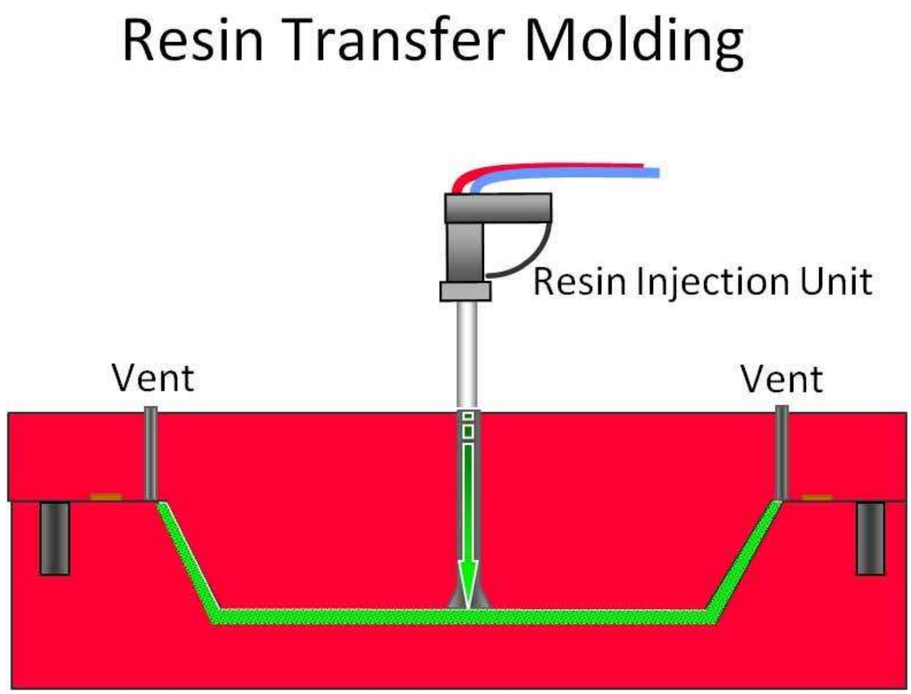

Fig. 11. Schematic of Resin Transfer Molding

The development of rapid curing epoxy and polyurethane resins are the key manufactured high-performance carbon fiber composites formed by utilizing RTM, infusion molding or compression molding processes. High-pressure RTM in conjunction with thermoforming is a promising latest development to improve the process cycle of the RTM procedure. Presently, the process time of RTM is approximately 20 minute with the utilization of high-pressure infusion of resin to reduce the injection time to seconds rather than minutes and takes into account the utilization of highly reactive thermoset resins. All the major worldwide providers of thermoset resins have formulated lab-scale resins having less than two-minute process durations. Currently, Scaling up the RTM procedure for high-pressure infusion and quick curing resin systems is the prospective challenge which is being addressed.

8.3. Vacuum-Assisted Resin Infusion

There are many minor variations in Resin Transfer Molding (RTM) which involve the replacement of the upper mold tool by a vacuum bag. These modified procedures include RIFT, SCRIMP, and VARTM. A permeable layer, for instance, a knitted non-structural fabric, is usually used to facilitate the dispersal of the resin in part (Goren & Atas, 2008).These advanced processes have substituted Resin Transfer