Chapter 4

Polyester Usage in Manufacturing of Electrical and Mechanical Products and Assemblies

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Abstract

This chapter focuses on the processes in which polyester is usually used for the manufacturing of mechanical components and assemblies. Various methods of manufacturing these products are mentioned in this chapter. These methods include wet layup method, filament winding, pultrusion, vacuum bagging and autoclave curing, resin transfer molding (RTM) and vacuum-assisted resin transfer molding (VARTM). Various production levels and properties can be achieved by polyester resin using abovementioned processes. Each process has its own benefits and disadvantages, which are discussed in this chapter. Furthermore, the use of polyester in making electrical insulation is also discussed in the chapter. Advantages and disadvantages of each impregnation technique are also explained.

Keywords: mechanical components, polyester, manufacturing, electrical insulation

1. Introduction

Polyesters are used in several applications related to high-tech applications. Polyester is used as a raw material in manufacturing of several products in several applications including automotive dashboards, panels and light covers. Similarly, in aerospace applications, polyester has been used in various assemblies and parts of airplanes, space ships and rockets. Structure and body of boats and ships are also fabricated using this material. Several techniques are practiced in industries for manufacturing of abovementioned products and applications. These techniques mainly involve mechanical parts, assemblies, and electrical insulations.

2. Manufacturing of mechanical components

Resin transfer molding (RTM) and vacuum-assisted resin transfer molding (VARTM) are used to manufacture various parts related to ships and automotives [1]. Vacuum bagging and autoclave curing is another technique mostly used in aerospace industries. In addition, filament winding and pultrusion process have the capability to manufacture cylindrical shapes, pipes, and pressure vessels using polyester and fibers. However, high-voltage and frequency insulation applications are also performed using polyester. Seven techniques are known for high-voltage insulations. In the next topics, initially RTM, VARTM, vacuum bagging and autoclave curing, matched die molding, filament winding and pultrusion are discussed. Afterwards, impregnation or insulation of electrical devices is explained.

2.1. Wet layup method

Wet layup is the most commonly used technique. In this technique, polyester resin is poured over the reinforcement [2]. In addition, usually a tool is used to properly distribute polyester resin (in polyester resin initiator and accelerator are mixed). This proper distribution of polyester fills the air pockets and spaces before getting cured. Afterwards, other reinforcements are also added with calculated resin quantity. The abovementioned procedure is repeated until desired thickness of the product is achieved. Optimum amount of resin is necessary to impregnate the fiber or reinforcement. Afterwards, proper environment and conditions are provided to cure and harden polyester resin. Glass fibers are used as reinforcement in this method.

Various sequences are also used in this procedure. Traditionally, dry fibers are also placed in the mold and resin is poured upon them. However, to achieve resin uniformity, some industries altered the procedure by predipping fibers before placing in the mold. Additionally, resin is also introduced in mold by pressure casting, capillary action and vacuum infiltration which has improved this technique. This technique is cost-effective and used to produce parts at a mass level. However, several complex shaped components cannot be manufactured using this technique.

2.2. Vacuum bagging and autoclave curing

Aerospace industry predominantly uses this technique to manufacture several components related to aircraft [3–5]. In this technique, the inner surface of mold is usually covered with a nonsticking material, usually Teflon (PTFE) (**Figure 1**). Above this nonsticky surface, prepreg plies and porous cloth are positioned. In addition, to prepreg plies and porous cloth, another cloth known as bleeder cloth is also placed [4]. This entire vacuum-based bagging mechanism is placed inside an autoclave. Inside the autoclave, a combination of optimum or suitable temperature and pressure is maintained to cure the resin. This technique cures the resin uniformly in shortest possible time. Moreover, the pressure is kept higher inside the autoclave to remove the excess resin. This technique is relatively costly in comparison to other techniques due to its lower production capacity.

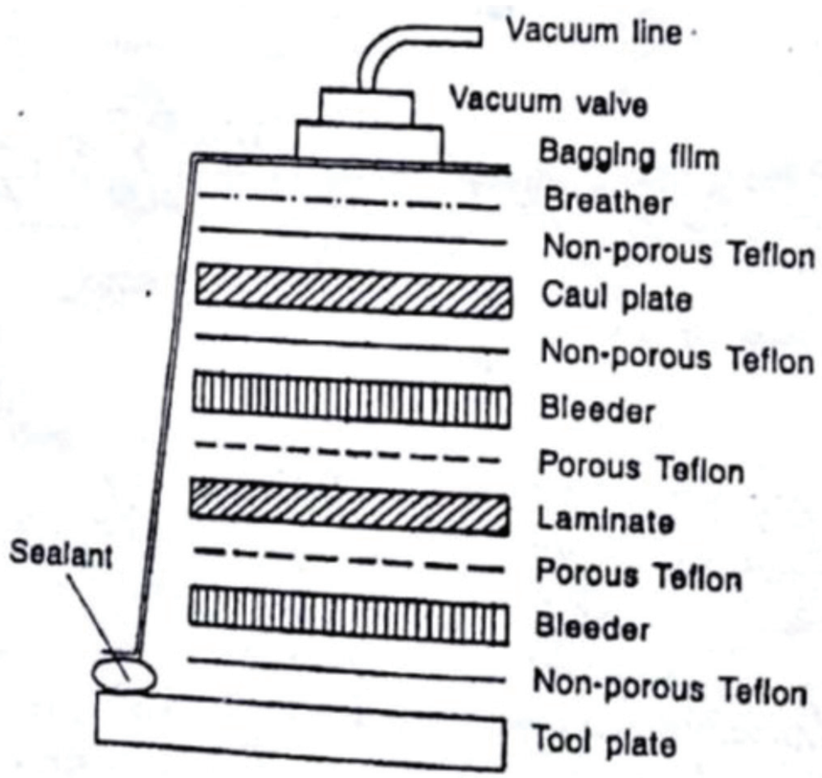

Figure 1. Schematic diagram for vacuum bagging and autoclave curing process (courtesy [4]).

2.3. Filament winding and pultrusion

Filament winding is also a composite manufacturing technique having cylindrical or tubular structures. Generally, a steel-based mandrel is manufactured in specified dimensions. Fibers are wounded upon this mandrel in a hoop, helical or polar manner. Windings are performed adjacent to one another in hoop winding (**Figure 2(a)**). However, winding can be performed at specific set of angles in the helical winding (**Figure 2(b)**) [4, 6, 7]. In contrast to helical and hoop winding, the desired product is obtained by winding between two opposite poles at specific angles (**Figure 2(c)**). Besides, there are two types of filament winding, that is, wet and dry winding. Prepreg tow is used as a winding medium in the dry winding process. On the contrary, reinforcement is properly impregnated with resin in the wet winding process. Furthermore, reinforcement impregnation is usually performed in resin bath. Later, these impregnated reinforcements are wound on the mandrel surface in a helical, hoop or polar manner.

In the filament winding process, epoxies, polyesters and silicones are usually used as polymeric resins. Water tanks, pressure vessels, automotive driving shafts, helicopter blades and rocket motor cases are generally fabricated using this technique. Furthermore, this is an economical technique which can produce these parts in varying sizes and geometries. Moreover, composites manufactured using this technique are usually void free or having less void contents.

Pultrusion is a method for production of tubular sections, rods and cylindrical type profiles in a continuous manner [2, 4]. The fundamental difference between pultrusion and filament

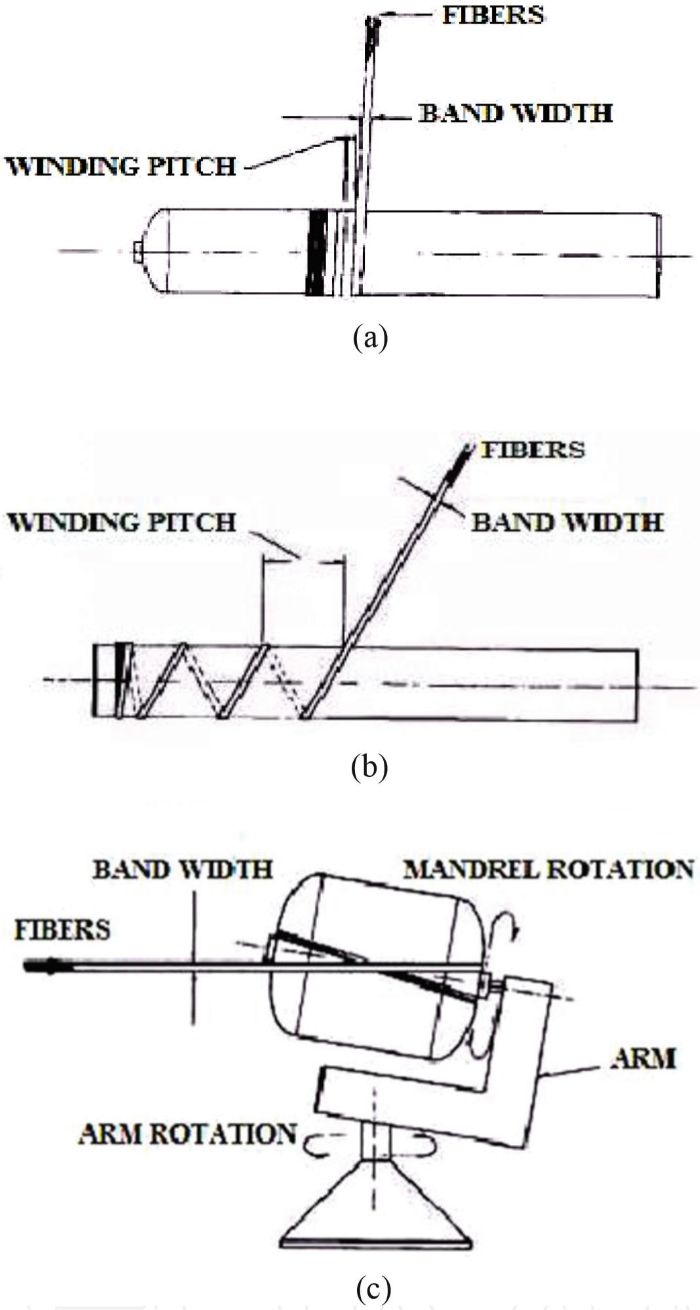

Figure 2. Schematic for filament winding patterns a) hoop, b) helical and c) polar winding (courtesy [7]).

winding is the winding pattern. In the filament winding process, the winding pattern can be hoop, helical or polar. However, pultrusion follows a longitudinal winding pattern, that is, the winding pattern is in longitudinal direction (**Figure 3**). Epoxy, vinyl ester, polyethylene and polyester-based resins are generally used in the pultrusion process. Polyester resin has been considered suitable for the pultrusion process to achieve continuous production in a short curing time. Additionally, polyester shrinks and does not stick with the mold surface after curing. Therefore, polyester resin must be preferred over other resins in pultrusion.

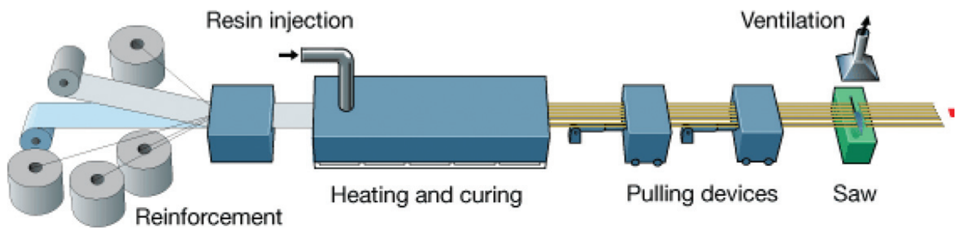

Figure 3. Schematic showing pultrusion process (courtesy Fiberline composites).

2.4. Matched die molding

To obtain uniform distribution of premixed resin, matched die molding process has been used. Reinforcement preform is placed inside the closed die mold. Afterwards, injection of premixed resin (resin in which hardener/accelerator or both are added and mixed) takes place due to externally applied pressure. Moreover, the resin enters the mold under pressure and spreads in radial direction. During the filling process, reinforcement is permeated slowly. However, operational control over the filling process is required. Improper flow leads to falling behind or racing ahead of resin. As a consequence, reinforcement is not uniformly wetted or impregnated. The final product will not be fabricated in this case. Therefore, proper understanding and prediction of flow paths are necessary for the abovementioned process. Besides, understanding the flow path, positioning of vents and injection points are also very crucial to avoid nonuniformity in flow pattern of premixed resin.

2.5. RTM and VARTM

An improved technique for producing high-quality products is RTM [8]. This technique involves insertion of low-viscosity resin into the mold. Prior to insertion in the mold, resin and hardener are mixed in the mixing chamber. Additionally, reinforcements and fabric are also placed inside the mold. Furthermore, resin is injected in mold where it impregnates the reinforcements and fabric (**Figure 4**). Afterwards, mold is heated at specific pressure and temperature to achieve the

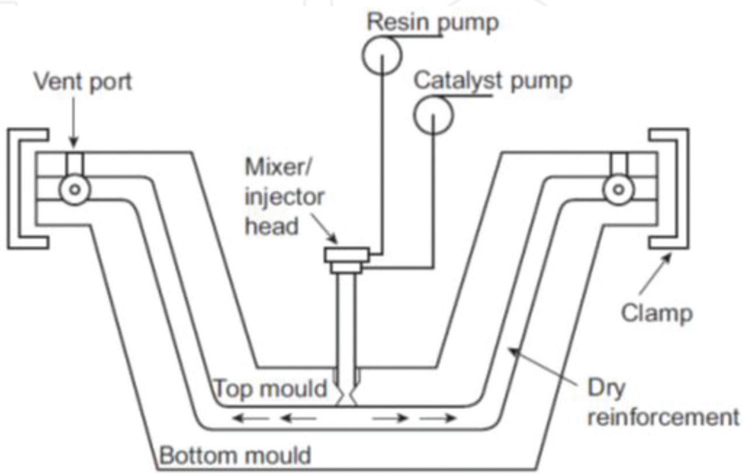

Figure 4. Resin transfer molding (RTM) process (courtesy [2]).

desired products. RTM relatively takes less curing time in comparison to other available processes. Epoxies, polyesters and vinyl esters are generally used as resins in RTM.

RTM is feasible for mass production of complex 3D shapes in comparison to prepreg processes. High-strength products are achieved using this process. No autoclave is required; therefore, RTM is a cost-effective procedure. Exposure of chemicals to workers and environment is minimized in this process. Surface finish of components made from RTM is also adequate. Training and handling costs are also reduced due to easy processing of raw material in this process. However, RTM initially involves higher tooling and investment costs. Process parameters also need to be properly controlled [1, 8, 9].

VARTM process consists of layup sealed in a vacuum bag [10]. By application of vacuum pressure, the resin is drawn inside the vacuum bag where fiber preform is placed (**Figure 5**). Resin impregnates fiber preform and starts curing. High-quality products are achieved using VARTM process due to reduction in void contents.

2.6. Electrical insulation

High-voltage power equipment is insulated by using various methods of impregnation, practiced across the globe. Selection of the process is based on the quality and production requirement. The various processes for impregnation are vacuum impregnation (VI), vacuum pressure impregnation (VPI), dip and bake impregnation or flood impregnation, trickle impregnation, B stage tapes, wet windings and full encapsulating and potting.

2.7. Dip and bake or flood impregnation

It is a very simple technique used for impregnation of electrical machines. In this technique of impregnation, the part to be impregnated is dipped inside the resin or varnish (**Figure 6**). The system is given constant heating till the varnish enters into vacant spaces of the equipment to be insulated. Heating continues till the formation of bubbles halts. This further depicts curing of polymer or evaporation of solvent. The advantage of this method is that it requires very less labor training. It is easy to implement and execute for preparing impregnated parts. A

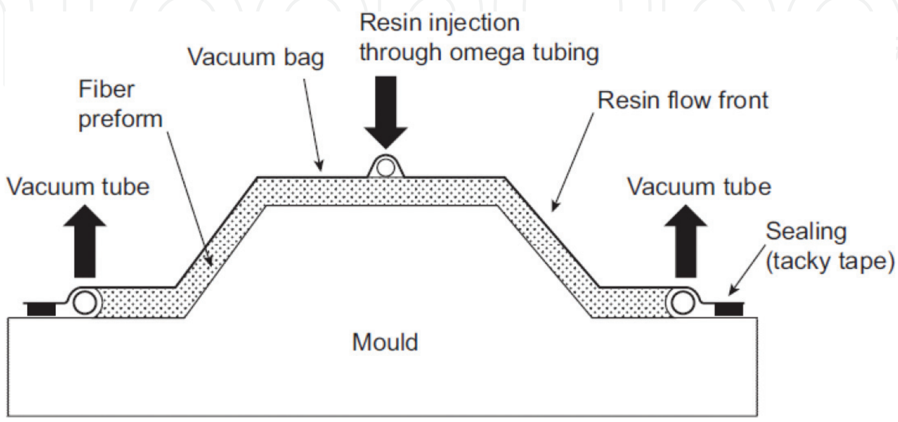

Figure 5. Vacuum-assisted resin transfer (VARTM) molding process (courtesy [2]).

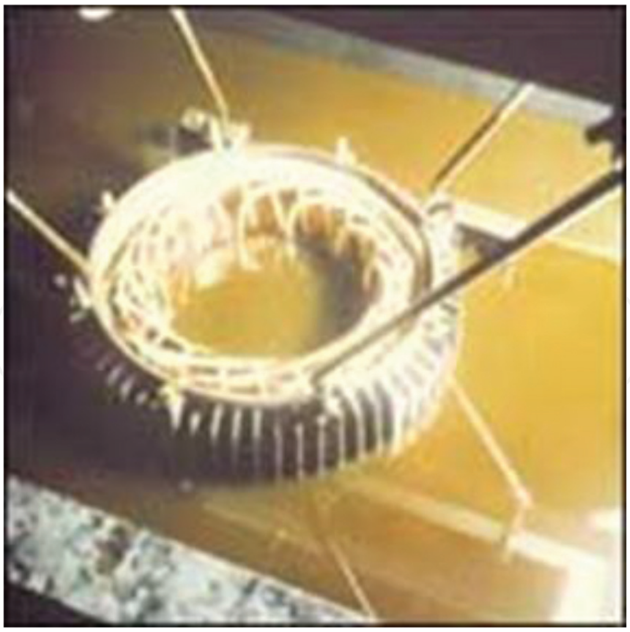

Figure 6. Insulation of stator assembly with polyester resin using dip or flood impregnation (courtesy from Elantis electrical insulation pvt ltd.).

relatively less amount of investment is required in preparing manufacturing setup. It includes resin processing tank, baking oven and pneumatic system for dipping the part in varnish [11].

The disadvantage of this process is that polymer resin is dissolved in solvent. This solvent comprises 60% of volume. However, during curing process solvent evaporates and leaves behind polymer which is usually left less than 40%. As a consequence, desired insulation is not achieved. Formation of voids and bubbles is another problem in dip or flood impregnation. In other words, bubble formation percentage in insulated parts produced by dip and bake impregnation is comparatively higher than any other process. As an outcome, probability of occurrence of corona effect in voids and bubbles increases. Therefore, this process results in poor chemical and dielectric properties. Gelling of varnish or irreversible separation of varnish can be done due to the presence of acids or bases in smaller amounts. This method cannot be used in significantly high voltage insulation due to the high amount of bubble and void formation [11].

However, by using solvent-less resin, in dip and bake impregnation process, bubble percentage can be reduced to certain extent. In this process, relatively lesser material loss is observed compared to solvent-based resins. Very small amount of resin gets evaporated, that is, less than 0.5%. This makes the process also less hazardous for labor as compared to solvent-based process. Water-based solvent systems can also be used in dip impregnation, which makes it less hazardous for the labor, and there is no chance of flammability during process. In spite of using solvent-less resin, the process relatively produces insulations having higher voids and bubble contents.

2.8. Trickle impregnation

Trickle impregnation is another process performed to insulate generators, wound motors and coils. The polymer blend is poured usually with the help of nozzle on the electrical component

Figure 7. Stators insulation by trickle impregnation technique (courtesy from Elantis electrical insulation pvt ltd.).

to be insulated. Desired volume of blend is poured on the product and allowed to trickle. Turn by turn, pouring of polymer is performed by trickling (**Figure 7**). Operator usually uses paint brushes to level the polymer which is used for lamination in this specific case. In this process, windings are heated electrically to evaporate moisture contents and to reduce viscosity in certain range. In this technique, a turntable is employed to rotate the electrical components which need insulation [11]. This turntable also helps in accomplishing process quickly. In this process, void or bubble contents are reduced in comparison to dip and bake process. However, rapid changing in mixing tank makes the process less economical. Additionally, rigorous training sessions and demand for skilled labor make the process highly uneconomical. The percentage of voids in this case depends upon the process sequence (pretreatment, mixing and curing), parameters (premixing temperature, curing temperature, heating procedure and pressure during process) and the skill level of labor. The components manufactured or insulated from this technique cure more rapidly in comparison with dip and bake impregnation.

2.9. Vacuum impregnation

There is very close resemblance between dip and bake and vacuum impregnation (VI) process. Additional step in VI for proper penetration of pretreated polymer or polyester resin inside the mold is achieved by application of vacuum pressure. VI process is composed of two types of tanks [11, 12]. One is process tank, and the other is known as storage tank. A fix volume of polymer or varnish is placed inside storage tank to minimize the chances of air entrapment. Electrical components in manufacturing phases are placed inside the process tank. These electrical components are heated to eliminate the possible volatile components or wet vapors prior to resin infusion. Solvent-based resins are not recommended in this type of impregnation because when vacuum is produced in the chamber the volatile solvent starts evaporating. Vacuum is created in the process tank for a long time, ranging from 0.5 to 1 h. After that a valve which joins the storage tank with process tank is unlocked. Varnish starts entering from storage tank into process tank due to pressure difference. The valve is closed as the desired level of varnish in the tank is achieved. Vacuum effect will remain for some time, and bubbles will rise in the products. Vents are generally provided in process tank to remove the entrapped

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air. Products are drained and placed in an oven to bake. This process needs high initial investment. Strict maintenance activity is required at different intervals. Therefore, production is halted during the maintenance of process and storage tanks. Hence, maintenance cost of this process is relatively higher than other impregnation techniques.

Vacuum potting technique is also adopted by several industries which is a specific case of VI. In this, thermoset cross-linking polymers, that is, polyesters, vinyl esters and epoxies, are used in order to impregnate the product. Cross-linking polymers impregnate at room temperature. Here in VI, pouring in pots is done under vacuum to get bubble-free parts. Usually, ignition coils are prepared using this method. But vacuum potting is expensive compared to normal potting procedure. Furthermore, problem of bubbles and voids still remains in vacuum potting and VI process. The reason behind this bubbles or voids is due to the partial pressure which causes resin to evaporate. Evaporation of polymer also causes formation voids and bubbles in the polymeric insulation of the electric component.

2.10. Vacuum pressure impregnation

Vacuum impregnation (VI) process is used usually in tightly wounded windings. Impregnation with this process is done with highly viscous resin [11, 13]. It needs high investment and is time-consuming process. The parts manufactured by this process have high quality and are expensive due to high cycle time.

VPI shows adequate similarity with VI process. The main difference of VPI from VI is the application of higher pressure, that is, 90–100 psi after vacuum. This higher pressure is usually exerted with relatively inert gas usually nitrogen gas. In contrast, in VI process, no higher pressure is applied after vacuum (**Figure 8(a)** and **(b)**). Instead in VI, atmospheric pressure is achieved after vacuum is released. This technique shrinks bubbles and reduces their size. The process tank in VPI is designed to withstand higher pressures. Existing literature suggested that VPI is considered the best process in comparison to other known processes. VPI method is also used for making field coils (heavy coils). Reaction accelerator is also poured on the outer periphery of the insulating polymer. Due to accelerating agent, outer layer of polyester/polymer cures very quickly; this prevents polyester from spilling out of the mold or capsule. Reaction accelerator shall not be soluble in polymer resin. If reaction accelerator dissolves in polymer resin can disturb the curing and degassing process. Furthermore, accelerating chemical or agent should be reactive with resin.

2.11. B-stage tapes

B-Stage tapes are special type of insulating material which consists of partially cured resin. It is also used to insulate high voltage windings. This partially cured resin is in solid phase at low temperatures but liquefies again at room temperature. The procedure involves wounding of tapes on coils. After that it is placed in hot press machine in which it is heated and compressed. The resin is fully cured after heating up to curing temperature, which is recommended by the manufacturers. This impregnation method is used in high-voltage transformers, voltage coils, motors, and generators.

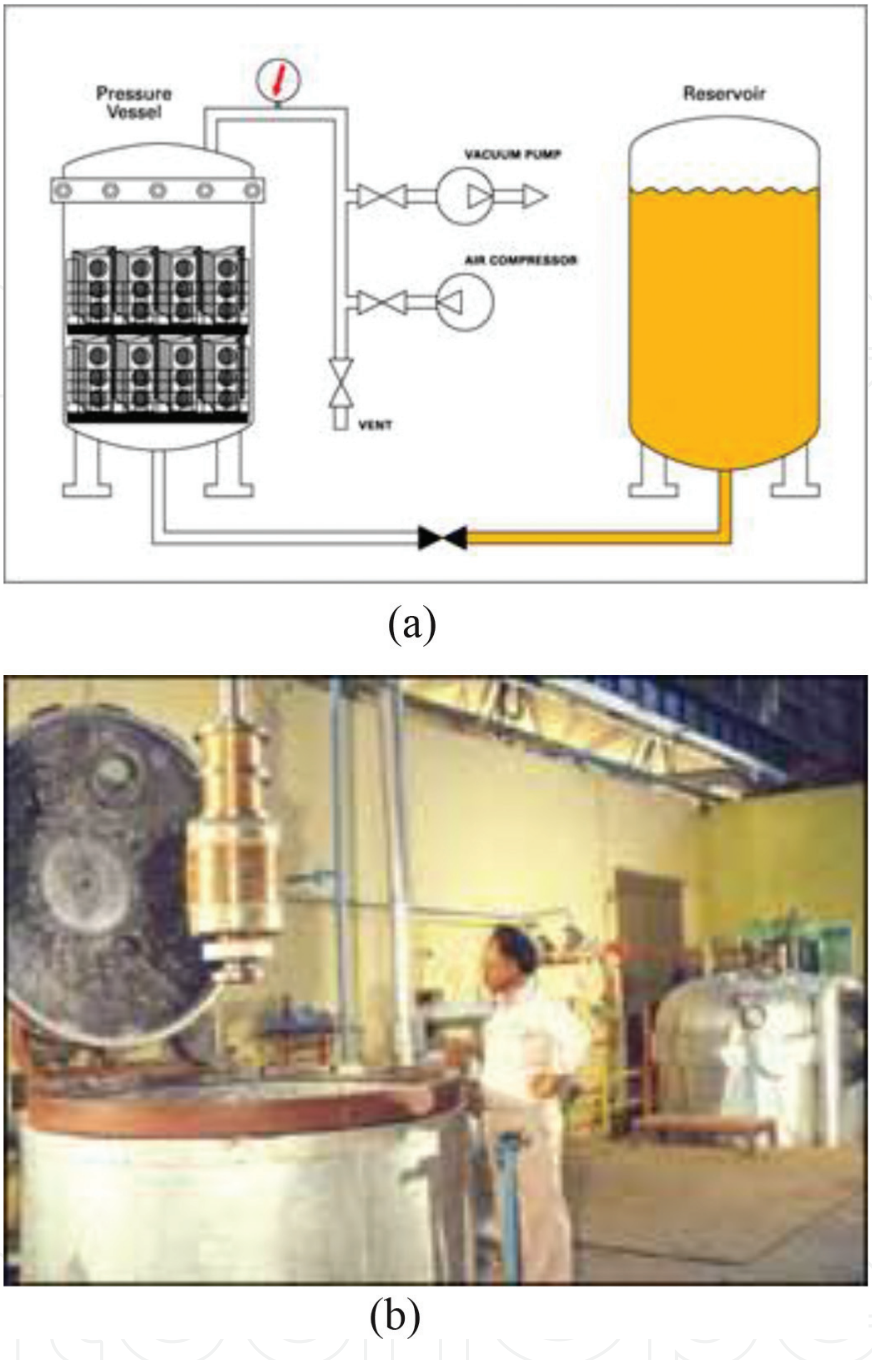

Figure 8. (a) Schematic of VPI process (Courtesy from Godfrey and Wing Inc.) (b) High-voltage assembly insertion in vacuum chamber during VPI (courtesy from Elantis electrical insulation pvt ltd.).

The problem in this type of impregnation is the high investment on hot press machine. Proper worker training is required while using this type of impregnating technique. Thirdly, this process is not labor friendly. Usual skin contact with tapes can cause skin problems. Another significant problem faced in this technique is proper cooling of tapes and taking care of their shelf life. After a certain period of time, it becomes waste and cannot be used in impregnation. So higher inventory loss is expected when compared with other processes [11, 14].

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2.12. Wet windings

Wet winding is a labor-intensive and time-consuming method used in manufacturing and onsite repairs of field coils. In this impregnation process, high-viscosity pastes are applied to the windings. For curing, two types of polyester or epoxy resins are used internationally. The first type of resin is cured at a specific temperature, and the second type is cured at room temperature. It is useful in big-size coils which are difficult to prepare by other methods. Second, optimum quantity of resin is used in this wet winding process, that is, no extra resin required. Good heat transfer is observed in parts made by this method. Wet winding is a very uneconomical technique for producing smaller parts, that is, ignition devices used in automobiles, boilers, generator coils, stator and rotor insulation and so on. It requires consistent labor training. It is totally an operator-dependent process. Wet winding process is not environmental friendly [14].

2.13. Encapsulation and potting

Full encapsulating, potting and casting are similar type of processes. In all these processes, impregnation is done around a subassembly with thick and viscous resin. There is a slight difference between potting and encapsulation. In casting and encapsulation polymer (usually polyester resin premixed with hardener and accelerator is used), resin is poured in the mold in which electrical component or subassembly is also placed. Polymer cures after a certain time at room or specified temperature. Usually transformers, ignition coils and circuit boards can be made from this method. In addition, the mold or capsule does not become part of the final product (after polymer cures inside mold). On the contrary, in potting method mold or capsule usually becomes part of the final component. Heating or vacuum can be used in both these processes, but usually this type of impregnation technique is conducted at normal atmospheric conditions. The potting method is suitable for lot production of electrical components operated at higher voltages, that is, ignition coils (**Figure 9**). This process is also environmental friendly, provided hazardous solvents are not added with the resin. Potting and encapsulation are highly economical processes in comparison to the other six processes [14, 15].

Figure 9. Polyester insulated ignition coil by potting method enclosed inside polypropylene capsule (courtesy from Pecs industries Lahore (pvt) ltd.).

3. Parameters affecting quality and production

Quantity and quality of components produced from polyester using the abovementioned techniques depend upon several crucial parameters. These parameters include type of polyester resin, hardener/initiator, accelerator, inhibitor, temperature and pressure. Unsaturated polyester resins (UPE) are generally used in several applications like automotive, aerospace, boats, ships, pressure vessels and high-strength pipes. These UPE are synthesized at mass production scale by addition reaction in which glycol, that is, propylene glycol (CH_3-CH(OH)-CH_2(OH)), is reacted with unsaturated acid, that is, maleic acid (HOOC-CH=CHCOOH). Afterwards, the resultant product (alkyd polyester resins) is blended with another unsaturated monomer usually styrene or chloro-styrene. The blending ratio between styrene and unsaturated polyester resin is generally 1:2 [4]. Finally, these unsaturated polyester resins can be cured by the addition of initiator and accelerator. Methyl ethyl ketone per oxide (MEKP) and cobalt naphthionate are used as initiator/hardener and accelerator, respectively [15]. In addition, anhydrides, dimethyl and diethyl anilines are alternative materials that can serve the purpose of hardeners and accelerators (**Figure 10**).

$$ROOH + Co^{+2} \xrightarrow{Step1} RO^{*} + OH^{-} + Co^{+3}\,(decompostion)$$

$$ROOH + Co^{+3} \xrightarrow{Step2} ROO^{*} + H^{+} + Co^{+2}$$

$$UPE + RO^{*} \xrightarrow{Step3} UPER \xrightarrow{Step4} +styrene \xrightarrow{Step5} Polymerization$$

Figure 10. Chemical reaction for Synthesis of polyester at commercial level.

4. Conclusion

This chapter mainly discusses about various manufacturing procedures for manufacturing of composite-based mechanical and electrical parts. Prime conclusions which can be drawn from this chapter are mentioned as follows:

- Increasing or decreasing hardener and catalyst significantly affects mechanical properties of the fabricated component.
- Similarly, temperature and pressure also affect the mechanical, thermal and electrical properties of the resultant product.
- In addition, curing cycles also depend upon abovementioned parameters. Optimum ratios of these parameters can give the desired properties (mechanical, electrical, thermal and optical) and production rate.

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parts for automobiles and generators. Furthermore, Pecs is vendor company of Honda, Suzuki, Fiat, Millat and Hyundai assembling plants in Pakistan. Moreover, Mr. Khalid Mehmood is CEO of Fiber craft which is leading company to manufacture composite parts and assemblies in Pakistan. However, the funding has not been provided due to certain financial crisis and higher education commission (HEC) policy.

Conflict of interest

No conflict of interest exists between the authors and their affiliations. Furthermore, no conflict of interest exists between authors and suggested potential reviewers.

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