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ADVANCED TECHNOLOGIES FOR FIBER REINFORCED POLYMER COMPOSITE MANUFACTURING: A REVIEW

ELYAF TAKVİYELİ POLİMER KOMPOZİT ÜRETİMİ İÇİN İLERİ TEKNOLOJİLER: DERLEME

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ABSTRACT

Developments for improving the effectiveness of the composite structures strongly depend on the manufacturing methods. Additionally, the composite manufacturers have put effort into cost-effective and automated fabrication with mechanization. Controlling the imperfections is also an important consideration for the production. This study presents several manufacturing methods for fiber-reinforced polymer composites. It also draws attention to novel techniques that use advanced technology required for the developed composite designs. Besides the conventional methods such as hand lay-up, vacuum bag, resin transfer molding, resin infusion, and autoclave, the advances in hot press molding, pultrusion process, and automated lay-up method were indicated. Moreover, the methods making difference for the hybrid composite designs such as the same qualified resin transfer molding and automated stitching processes were introduced. The advantages and limitations were indicated for the manufacturing methods and the usage purposes were addressed.

Keywords: Manufacturing techniques, composite manufacturing, advanced technology, out of autoclave, same qualified resin transfer molding

ÖZET

Kompozit yapıların etkinliğini artırmaya yönelik gelişmeler büyük ölçüde imalat yöntemlerine bağlıdır. İlâveten, kompozit üreticileri düşük maliyetli ve otomasyona dayalı imalat için de çaba göstermektedirler. İmalat hatalarının kontrol edilebilir olması da üretim için önemli bir husustur. Bu çalışmada elyaf takviyeli polimer kompozitler için çeşitli imalat yöntemleri sunulmuştur. Ayrıca gelişmiş kompozit tasarımlar için ileri teknoloji kullanmayı gerektiren yenilikçi yöntemlere de dikkat çekmektedir. El yatırması, vakum torbalama, reçine transfer kalıplama, reçine infüzyonu ve otoklav gibi geleneksel yöntemlerin yanı sıra, sıcak baskı kalıplama, pultrüzyon işlemi ve otomatik yerleştirme (istifleme) yöntemlerindeki gelişmeler de belirtilmiştir. Aynı kalitede reçine transfer kalıplama ve otomatik dikişleme işlemleri gibi hibrit kompozit tasarımlarında fark yaratan yöntemler de tanıtılmıştır. İmalat yöntemlerinin birbirlerine göre üstünlükleri ve sınırlamaları belirtilmiş ve kullanım amaçlarına değinilmiştir.

Anahtar Kelimeler: İmalat teknikleri, kompozit üretimi, ileri teknoloji, otoklav harici işlemler, aynı kalitede reçine transfer kalıplama

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INTRODUCTION

The demand for using fiber-reinforced polymer composites have gradually increased day by day in many engineering fields due to their attractive features. In addition, the developments of new polymers and reinforcement types have made the obtaining of the enhanced physical and mechanical properties possible. Besides the high strength and stiffness to weight ratio, the composites and other hybrid forms such as sandwich structures can provide better impact strength, higher fatigue resistance, thermal and acoustic insulation, good electrical and thermal conductivity, better electromagnetic shielding performance, and resistance to other environmental effects (Gibson, 2000). In order to achieve these features, the applied manufacturing method plays an important role in composites' design and construction (Uzay, 2020). Basically, fiber reinforcement is a dimensional (1D) strengthening process and it can be oriented in different directions in a certain matrix surrounding with a suitable forming process to obtain two or three-dimensional structural members (Baker et al., 2004). Therefore, the desired mechanical properties can be combined in a unique composite part based on the reinforcement type, stacking sequence, matrix materials, and manufacturing technique.

Genç (2006) produced glass fiber/vinyl ester composites with three different manufacturing techniques: hand lay-up, vacuum bag, and resin infusion. When the methods were compared, infusion provided the best results and the hand lay-up yielded the lowest results under the flexural, tensile, and impact loading conditions. The vacuum bag method was found a transition between the infusion and hand lay-up. The void content was observed for the specimens fabricated with hand lay-up. Better surface finishes were obtained with vacuum bag methods. It was also concluded that by using the hand lay-up method, a complete fiber wet-out cannot be reached with insufficient matrix materials and a satisfactory product quality strongly depended on the labor. Durgun et al. (2014) also compared the hand lay-up, vacuum bag, and resin infusion methods. They produced carbon/epoxy and glass/epoxy composite specimens and subjected them to tensile and three-point bending tests. For both loading conditions, the strength values increased in the order of hand lay-up, vacuum bag, and resin infusion methods, respectively. Sevkat et al. (2012) revealed the advantages of the VARTM method over the hand lay-up by investigating the bearing load capacity of pin-loaded woven glass/epoxy composites under the tensile test. Kim et al. (2014) produced both circular and square cross-sectional tubes made from carbon fiber prepreg with the autoclave process. The round structure provided two times higher bending strength under three-point flexural loading. Bere et al. (2019) applied the autoclave method to obtain the best tensile properties of carbon/epoxy prepreg composites. They also introduced the steps of the process.

The pultrusion method has also become an attractive technique with the growth of the improved performance of composite constituents. Application fields of the method are widespread particularly in infrastructure and include bridges and decks, cooling tower parts, marine construction, transportation, and energy such as wind power (2020). Several out-of-autoclave techniques such as RTM, VARTM, vacuum-assisted resin infusion method (VARIM) were developed, but in that application dry fabrics are used. In this case, resin impregnation and curing processes become a concern. Without sacrificing the process quality and robustness, an alternative method instead of the autoclave process was introduced called the Same Qualified Resin Transfer Molding (SQRTM). It was developed by Radius Engineering Inc. and SONACA (2020). The prepreg was cured in an enclosed mold with the resin transfer which is the same as prepreg resin. The process also has advantages over the autoclave. Because dimensional accuracy of the part geometry, structural integration, and internal quality may deteriorate since the technique is not carried out in a well-designed mold. Lumley et al. (2020) compared the SQRTM, autoclave, and RTM methods and applied the SQRTM for the manufacturing of moveable wing parts (slats and flaps). They stated that the complex geometrical shapes can be fabricated with better surface quality by applying the SQRTM method.

Briefly, composite technology continues to grow with developed fabrication techniques in which the parts are produced with higher performance and reduced cost. The present study firstly demonstrates commonly used composite manufacturing methods and then introduces the advanced techniques currently emerged for the manufacturing of composite structures. The methods were also discussed comparatively in order to reveal the negative and positive sides of each other.

CONVENTIONALLY USED METHODS

Several methods are available to manufacture fiber-reinforced polymer (FRP) composites and their hybrid types like sandwich structures. Typically, hand lay-up, vacuum bag, resin transfer molding (RTM), autoclave, resin infusion, pultrusion, filament winding, matching die set compression molding, etc. are the well-known manufacturing methods (Kar, 2017). But mostly, the followings are currently used methods for the fabrication of

composite materials: *hand lay-up*, *vacuum bagging*, *RTM*, *vacuum-assisted resin transfer molding*, *filament winding*, and *autoclave methods*.

Hand Lay-up Method

The hand lay-up method, the oldest process, is used for composite manufacturing carried out on an open mold. This process is simple, but a labor-intensive process, and suitable for low-volume production. For instance, in marine applications, large components like boat hulls can be fabricated with this method (Kar, 2017). Reinforcing materials such as chopped strand mats or fiber fabrics are placed manually onto the open mold, and resin is sprayed or poured over the reinforcement materials and the impregnation of them is provided manually. The required curing time is 24–48 hours at room temperature. A catalyst and accelerator that are called a hardener are mixed to the resin in a proper fraction in order to satisfy curing. The mixture is carefully stirred both to prevent void formations within the matrix and to obtain homogeneous matrix material. Figure 1 shows the schematic view of the hand lay-up process.

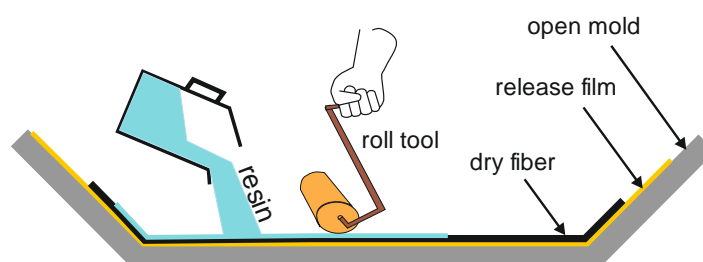


Figure 1. Schematic of Hand Lay-up Method

Vacuum Bagging Method

In the vacuum bagging method, the entrapped air during lay-up and excessive resin is removed with a vacuum. After stacking, a peel ply or perforated release film is laid onto the composite laminate. A breather cloth is placed onto the peel ply, in order to absorb excess resin from the laminate. Lastly, the entire system is enclosed with a vacuum bag and the mold surrounding is covered with sealant tape as presented in Figure 2. Then vacuum is applied to the composite material under the bag. This process is more suitable for laboratory applications (Uzay et al., 2019) and provides a high reinforcement with increased fiber volume fraction and improves adhesion bond strength between the composite layers compared to the hand lay-up process. Because the applied vacuum removes most of the air and volatile substance quickly from the laminate (Baker et al., 2004). When compared to the hand lay-up, the method has important advantages such as higher fiber content, better fiber wet out, lower void formation, and decreased volatile emissions. The aerospace industry mainly applies this method since the high production volume is not primarily considered. Moreover, racing car parts and large cruising boats can be fabricated by using a vacuum bagging method. However, the process has some drawbacks such as labor-intensive, a requirement of better labor skills, loss of seal, process cost due to the consumables and equipment (Kar, 2017; Mallick, 2007). In addition to this, Mehdikhani et al. (2019) investigated the reasons for voids in polymer composite materials. The void content within the composites is increasing with the relative humidity. Although the void content obtained with both vacuum bag and autoclave methods is similar up to a relative humidity of 60%, after 60 to 100, the void fraction is increasing exponentially for the vacuum bag method.

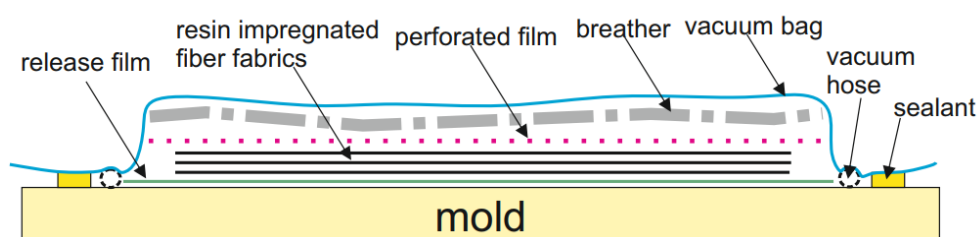


Figure 2. Schematic View of the Vacuum Bag Method

Resin transfer molding (RTM)

Resin transfer molding (RTM) is carried out in a closed mold, and suitable for moderate and high-volume productions. The process mainly contains stacking of the dry reinforcement materials in the base part of the mold, and the other half of the mold is placed over the bottom mold and clamped. The schematic view of the process is presented in Figure 3. After closing the molds, a resin including its hardener is injected. High-quality part requirements such as vehicle body parts, containers, bathtubs, etc. can be achieved by this method. RTM method can be modified with a vacuum assistant for effective resin transfer and impregnation of fiber elements (Kar, 2017). The method is also relatively more suitable for complex shapes compared to hand lay-up and vacuum bag methods (Mallick, 2007).

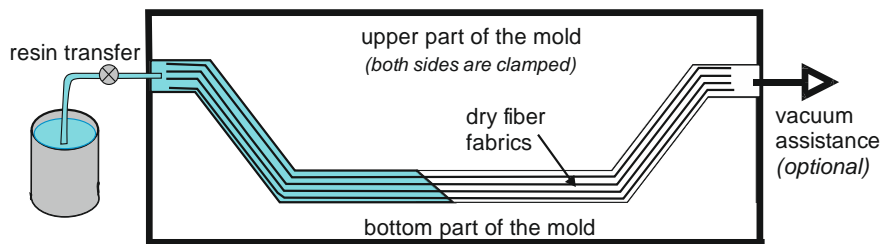


Figure 3. Schematic View of RTM Process

Torres (2019) reviewed the previous studies about monitoring and instrumentation of the process parameters for RTM. Due to its relatively higher ratio of mechanical performance to cost compared to autoclave, the method is still requested. The significant RTM fabrication parameters on surface roughness of the final part were indicated as low profile additives, injection pressure, filler content, a temperature gradient.

Vacuum-assisted Resin Transfer Molding (VARTM)

In vacuum-assisted RTM (VARTM), the manufacturing is carried out on a single mold in which the composite laminates are stacked on it as the case performed with vacuum bag technique. The process is carried out over the bottom part of the mold only. A peel ply and/or perforated release film is placed over the lamination, and the system is covered with a vacuum bag by using sealant tape. The resin impregnation of the dry composite layers is performed with the aid of a vacuum supply as seen in Figure 4. The vacuum process provides the resin movement. The entrapped air is also removed. The vacuum application increases the fiber concentration and improves adhesion bonding between the composite plies. VARTM technique provides several advantages when compared to the RTM method with lower tooling cost, shorter duration of mold filling by resin. The process efficiency and quality of the final product depend upon sufficient wet-out of the fibers which can be done successfully with a proper resin movement (Kar, 2017).

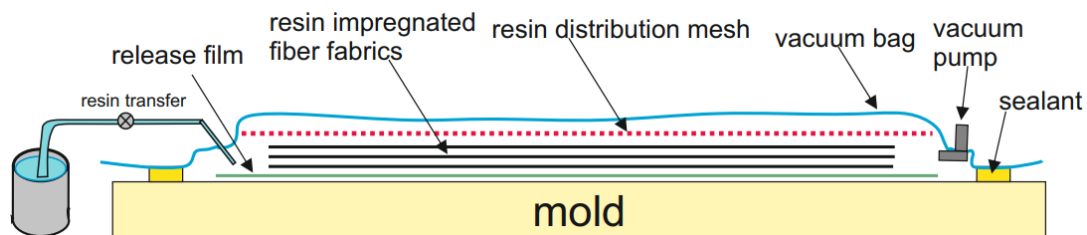


Figure 4. Schematic View of the VARTM Method

Autoclave Process

An autoclave manufacturing method can be applied where excellent quality is needed such as in aerospace industries. Because in this method, an increased fiber volume ratio is obtained with minimum void content in the matrix. The curing is carried out under pressure and in a heat-generated autoclave as seen in Figure 5. The process parameters of the computer-controlled method depend on the resin system used for lamination. Kermani et al. (2020) produced a honeycomb core sandwich structure with an autoclave oven by controlling the process parameters of autoclave pressure, vacuum bag pressure, and autoclave temperature. The preparation of the composite materials is similar to the vacuum bagging method. After preparing the composite for curing within the enclosed heat-resisted vacuum bag, the product is placed inside an autoclave. The external sources of vacuum,

pressure, and heat provide to densify and consolidate each lamina to form better lamination by removing air and volatiles with the aid of vacuum. In order to prevent the possibility of any internal fire, nitrogen, or carbon dioxide is used. The process is costly and requires labor-intensive production (Baker et al., 2004; Mallick, 2007; Carlsson and Kardomateas, 2011). Bere et al. (2019) specified the steps of the autoclave process for carbon/epoxy prepreg composite laminates as follows: (1) *Heating of the mold for 30 min. at 60 °C, then (2) heating at a rate of 2 °C/min and increasing temperature to 120 °C in 60 min. (3) dwell for 2 hours at 120 °C, (4) cooling of the composite at a rate of 2 °C/min for 60 min.* On the other hand, Plappert et al. (2020) achieved a 60% fiber volume density with a single ramp of temperature increase. The process was performed as follows: Increasing the temperature from ambient to 120 °C in 30 min. with a pressure of 3-bar, then constant temperature for 120 min., and lastly cooling to ambient temperature in 30 min. Also, the reported void fraction in the literature is below 1% for this kind of manufacturing method (Hassan et al., 2017; Mehdikhani et al., 2019).

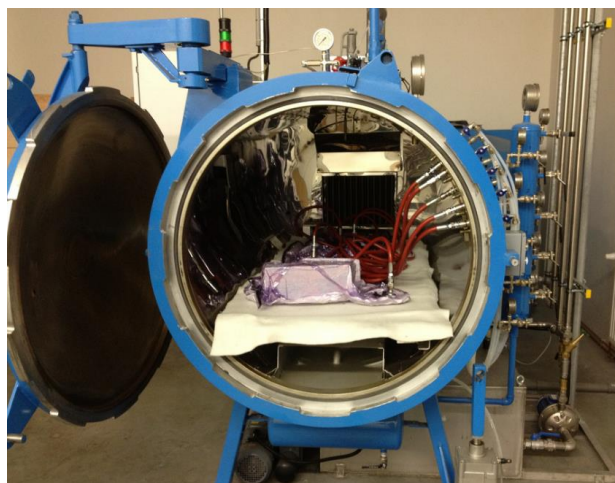


Figure 5. Representation of Autoclave Process (URL 3)

Filament Winding Process

In order to produce cylindrical parts such as pipes and tubes, filament winding is used effectively. The process includes wrapped bands of continuous fibers over a mandrel as seen in Figure 6. After the winding, the curing is performed at an increased temperature of a mandrel. The resin impregnation can be made before, during, or after winding operation. The strength and the stiffness of the finished product depend on the compaction of fiber layers. The major factors have been specified as helix angle, winding tension, conditions of strand bandwidth, resin content, and its distribution, winding speed, and curing cycle (McIlhagger et al., 2015). A sufficient fiber tension is required on the mandrels to keep the arranged orientation and to prevent fiber misalignments. Low-viscosity resin types are preferred or the resin bath temperature is increased to control the appropriate resin flow. In other cases, there might be voids within the structure that worsen the mechanical properties. Delamination and fiber wrinkles are other defects that could be encountered. The significant parameters affecting the strength of fiber composites are indicated as winding angle, fiber orientation and its sequence, fiber volume fraction, mechanical and physical properties of fiber and matrix, respectively (Prabhakar et al., 2019). Pressure vessels, pipelines, blades, automotive drive shafts, oxygen tanks, the rocket body, etc. are the common examples of filament winding technique (Mallick, 2007).

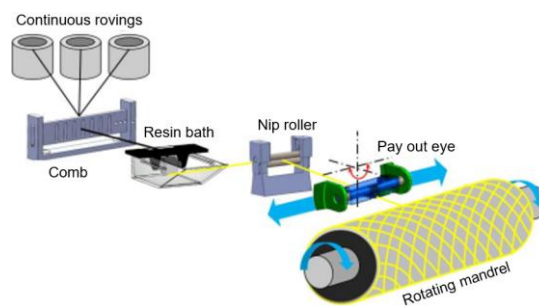


Figure 6. Filament Winding Method (Quanjin et al., 2019)

ADVANCES FOR COMPOSITE MANUFACTURING

As stated by Fan et al. (2010), the further developments for improving the effectiveness of the composite structures strongly depend on the manufacturing methods based on cost-effectiveness, automated with mechanization, and controlling the imperfections. The advanced processes are presented in the following sub-sections.

Advances in Lay-up Processes

When the lay-up process of resin impregnation is applied by handling, it can be messy and may cause health and safety problems due to the hazardous effect of the polymer resins (Baker et al., 2004). Therefore, the hand lay-up process has been automated by using a chopper gun and a spray. As seen in Figure 7, a machine tool that can be used by hand-held or a robot arm. The process can accelerate the manufacturing time with the low-cost operation and reduce the manual work and labor cost. It is possible to mix the resin and its hardener in a reservoir and allow it to distribute chopped fibers and matrix material simultaneously directly onto the mold surface. Although continuous fiber is feeding to chopper guns, the fibers are sprayed as chopped glass fiber which is the main drawback and cannot provide homogeneous mechanical properties for the finished product.

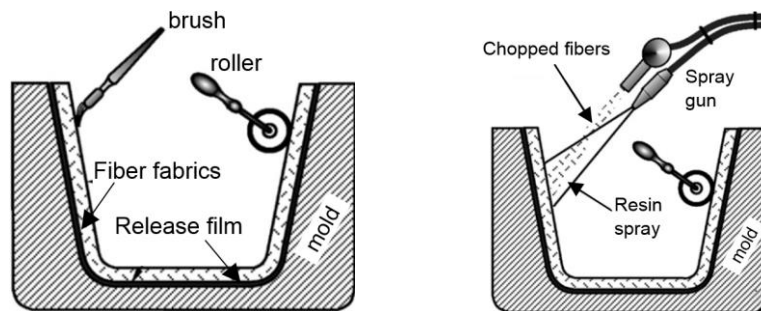


Figure 7. Hand Lay-up vs. Spray-up Manufacturing Methods (Swift and Booker, 2013)

Using prepregs is also a better alternative to wet lay-up processes for advanced structures such as sandwich panels for obtaining well-impregnated resin, and increased mechanical properties for the final product. Low void contents are obtained in composite face sheets laminated by prepregs (Karlsson and TomasAström, 1997). For aircraft structures such as wing skins and fuselages, the production and mechanical properties must be excellent. Therefore, prepreg materials with autoclave curing are the best process combination for that kind of application fields. In order to increase production rates, improved shape tolerances, and dimensional accuracy, automated processes have been developed such as automated fiber placement (AFP) and automated tape layup (ATL). AFP process was developed to overcome the drawbacks of ATL (Crosky et al., 2015) that lays up the prepregs either onto a flat or a cylindrical mandrel by using multi-head robot machinery (Carlsson and Kardomateas, 2011) as represented in Figure 8. It was reported that the significant gain for the cost-effectiveness of AFP is low material scrap rate besides reduced labor cost (Crosky et al., 2015).

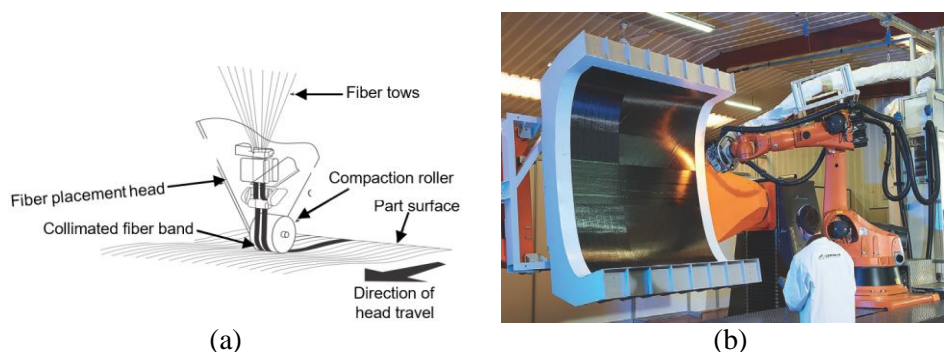


Figure 8. a) AFP process (McIlhagger et al., 2015), b) Image of the AFP (Crosky et al., 2015)

Advances in Pultrusion Method

The term “pultrusion” is used to define a continuous process for manufacture where the combination of pull and extrusion is applied. The continuous fibers are taken in a polymer matrix resin bath then pulled via heated dies and extruded (Hota et al., 2009). It is a cost-effectively used and automated manufacturing process for continuous and

constant cross-sectional composite profiles. This technique is essentially suitable for the fabrication of long and straight structural parts such as cylindrical rods and tubes, beams, shells, etc. (Mazumdar, 2009). It was also reported that a pultrusion process was patented with a new concept. The new technique allowed to produce nonlinear profiles with the aid of curved moving dies (Vedernikov et al., 2020). As presented from Figure 9, continuous fibers are drawn through a resin tank and moved to a heated die having a final shape of the product. As the resin-impregnated fibers pass through the die, the composite material is assumed to form to final shape and cured. After curing and leaving the die, the product is cut properly. Utmost attention must be given to the fiber wet-out to control the mechanical effectiveness of the pultruded part. Because, the amount of resin in the resin bath, its viscosity, bath temperature, the time allowed for resin impregnation of the fibers, and the workability of the mechanical system are the major factors to be considered (URL 3).

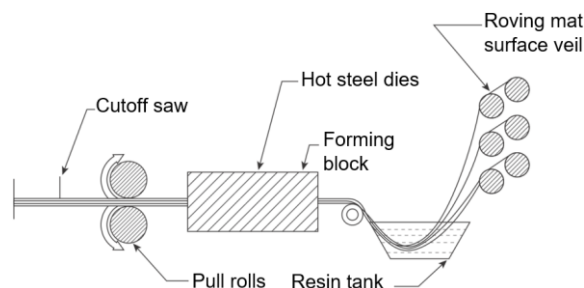


Figure 9. Schematic View of Pultrusion Method (McIlhagger et al., 2015)

Advances in Stitching Machines

Santhanakrishnan et al. (2018) designed a stitching machine for the sandwich core materials as shown in Figure 10. The machine also provided to make different pile orientations in the stitching process, which allows to find out optimal mechanical properties. Table 1 shows the shear properties of the glass fiber reinforced PVC foam core sandwich. The stitching was performed to the core material with various orientations by using glass fiber yarns.

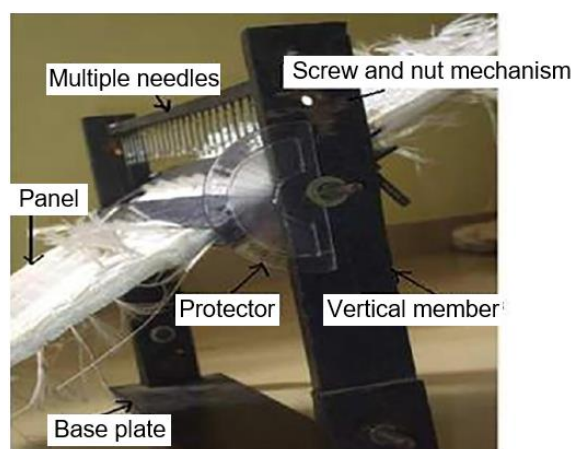


Figure 10. Image of Stitching Machine (Santhanakrishnan et al., 2018)

Table 1. Shear properties of stitched and unstitched foam core sandwiches (Santhanakrishnan et al., 2018)

Sandwich Panel	Ult. Shear Strength (kPa)	Shear Modulus (MPa)
Unstitched	420	1.75
Stitched- 45°	1686	11.24
Stitched- 90°	963	8.78
Stitched- 90°/45°	2443	13.75
Stitched- 90°/45°/90°	2844	16.32

Stitching of the core materials also enhanced the tensile and compressive strength of the polymer foam core sandwich structures compared to as-received core materials (Yalkin et al., 2017).

Advances in Hot Press Molding Method

Mei et al. (2017) developed a novel manufacturing method by hot press molding for fabricating carbon fiber reinforced tetrahedral truss core sandwich panels. The process is illustrated in Figure 11.

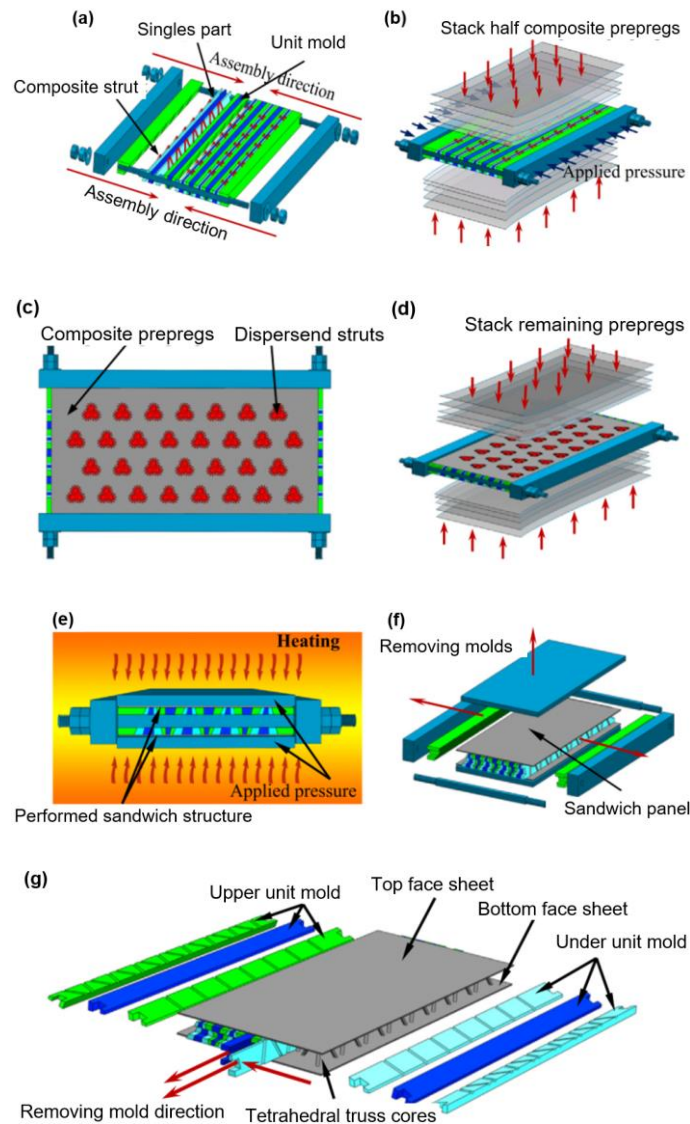


Figure 11. Manufacturing process with developed hot press molding; a) placing the prepared composite strut into corresponding position, b) lay-up of five layers of carbon/epoxy prepregs on the mold, c) dispersing end of the struts by penetrating them into prepreg, d) lay-up of another 5-layer of prepregs, e) curing of preformed structure, f, and g) demolding and removal of the composite structure (Mei et al., 2017)

Same Qualified Resin Transfer Molding (SQRTM)

SQRTM is a newly developed composite manufacturing method consists of the prepreg lay-up and liquid resin transfer molding. The method was first developed and commercialized by Radius Engineering (2020) in order to provide net shape composite products. Figure 12 presents the difference between traditional and net shape productions.



Figure 12. a) traditional production of composite parts, b) net shape, single part composite production (URL 4)

SQRTM is also known as the out-of-autoclave process and it has several advantages over the autoclave process. With the aid of SQRTM, large and complex parts can be produced with final shapes with reduced cost. The method differs from the RTM method with prepreg lay-up and the injected resin to the RTM system is the same as that existed in prepreg as shown in Figure 13. This allows using of high qualified toughened materials such as tough resins and toughened agents. The injected resin creates hydrostatic pressure to composite laminate and eliminates the formation of void contents, which improves both quality of the final product and its mechanical properties. By the way, control of the composite quality is easier than the autoclave process due to its complex dependent variables. In addition, the curing in the SQRTM method is approximately two hours shorter than in autoclave as seen in Figure 14. On the other hand, the method has advantages over the RTM technique. Thickness variations in the final part, dimensional accuracy, and surface quality are improved with the aid of SQRTM. The process is currently under the commercialization process by Radius Engineering Inc. (2020). The main difference between the RTM and SQRTM is the used fiber fabrics. While the RTM technique uses dry fabrics, the SQRTM method uses prepregs. The resin material used for the impregnation of prepregs is also used for resin injection of the SQRTM process. Therefore, the SQRTM process has been most suitable and preferable for aerospace industries to produce structural members (URL 2, URL 4).

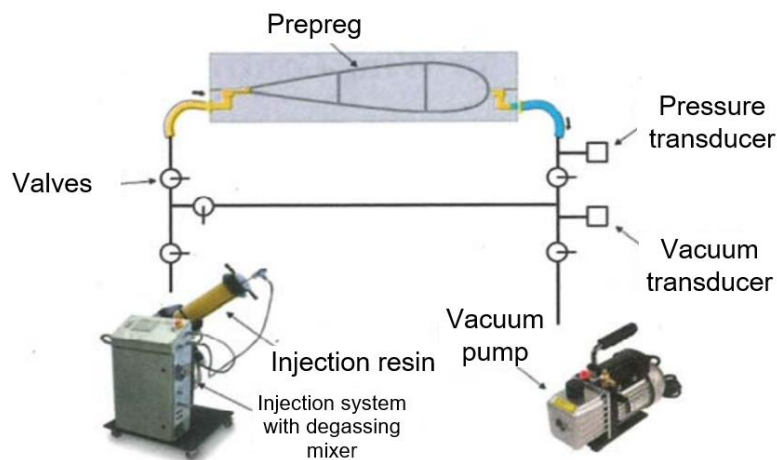


Figure 13. Schematic Presentation of SQRTM Process (Gueuning and Mathieu, 2016)

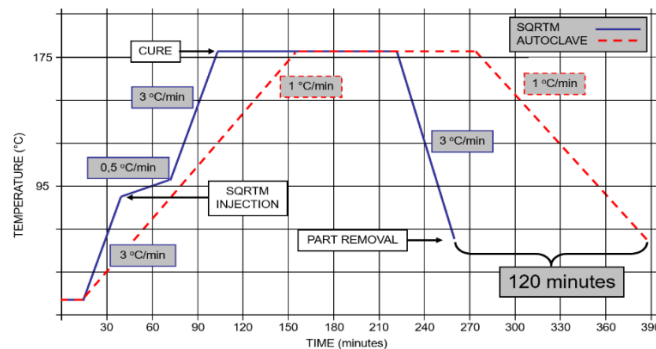


Figure 14. Comparative demonstration of curing cycles both in SQRTM and autoclave (URL 4)

DISCUSSION

The most limiting factor to the use of fiber-reinforced polymer composites and the hybrid materials systems is the cost of constituents. Although the aerospace industry uses composite structures in high volumes, cost reduction is still a challenging task (Mallick, 2007). For instance, honeycomb core sandwich panels with carbon/epoxy face sheets are used for indoor applications, but, due to sudden thermal changes during the operations, honeycomb cells may be filled with water in certain conditions, and it may freeze under cold temperatures. This can cause significant damage which leads to repair costs (Herbeck et al., 2002). Therefore, the closed-cell rigid polymer foams can be offered for indoor sandwich panel applications to reduce both maintenance and materials costs. Contrary to the aerospace industry, there is an obligation to consider the cost of both materials and manufacturing processes in the automotive sector in order to produce large quantities of vehicles with reduced costs. This is why, the use of carbon fiber technology is restricted and glass fiber and polyester, and/or vinyl ester are preferred as the reinforcement and the polymer matrix, respectively.

The advantages and limitations of the manufacturing methods are evaluated and summarized in Table 2 based on the literature review.

Table 2. The Advantages and Limitations of the Manufacturing Methods

Methods	Advantages	Limitations
Hand lay-up	Simple, cheap, versatile, suitable for mechanization	Oldest, labor-intensive, low-volume productions, poor surface finish and dimensional accuracy, low mechanical properties
Vacuum bag	Moderate cost, good mechanical properties, better interface adhesion	High labor skill, low-volume production
RTM	moderate and high-volume productions, complex shapes, good surface finish	Tooling cost, dimensional accuracy of the tool, possibility of insufficient resin impregnation
VARTM	Elimination of void contents, low tooling cost, fast resin wet-out, relatively resin-rich	Additional cost of consumable materials for vacuum process, moderate surface finish compared to RTM
Autoclave	High mechanical properties,	Costly, complex process, require computer control, relatively simple shapes, requires secondary finishing operation
Filament winding	Better mechanical properties, fast, suitable to automation, high volume production, less labor dependent	Simple shapes and profiles, machine and process cost, proper selection of the resin,
Pultrusion	Automated, fast, suitable for nonlinear profiles, long and straight parts, less labor dependent	simple and moderate shapes, costly,
SQRTM	Net-shape, no need for secondary operation, better surface finish and dimensional accuracy, improved product quality, better mechanical properties, large and complex parts, relatively easy to control, and shorter process compared to autoclave	Complex process, high cost, tooling, accuracy of mold

The manufacturing methods are still not completely suitable for mass production, e.g., the parts in the automotive field. Generally, the methods are applied manually, they take hours dependent upon the shape and dimensions of the product, and well-skilled laborers are needed. However, with the advances in the fabrication process, reductions in application time and labor cost are possible. For instance, the prepreg fabrics can be cut with computer-controlled machines to shorten the processing time. Also, the tape lay-up machine eliminates the labor work of hand lay-up. Besides these, the quality of the final product is affected by the manufacturing techniques. Obata et al. (2020) confirmed that the autoclave process almost removes the entrapped resin within the composite laminate and thus higher load capacities can be obtained. However, Haluza et al. (2020) reported that the process of out of autoclave, i.e. SQRTM, is emerging as an alternative to autoclave which requires higher capital expenses. Pultrusion and filament winding techniques are relatively less labor-dependent, automated and a large number of parts can be produced. The most important drawback in pultrusion, only the production of simple shapes, has now been overcome with the fabrication of nonlinear profiles thanks to the curved dies (Vedernikov, 2020). Quainjin et al. (2019) determined the favorable and restricted features together with the current problems of the filament winding technique. Then they addressed the industrial fields where the technique can be used for particular applications.

Although the RTM method is more suitable for relatively complex shapes, the tooling cost is another concern. Robust molds considering the molding materials, design of the molds, determined tolerances, assembly, and demolding, and handling of the parts are required to achieve high production rates.

CONCLUSION

In this study, the conventionally used composite production methods, and the advances in composite manufacturing technology based on the particular techniques were presented and discussed comparatively. It can be concluded that conventional methods such as hand lay-up, vacuum bag, vacuum-assisted resin infusion, or resin transfer molding techniques are more suitable for laboratory applications, prototype productions, and other purposes where low batch products are demanded or perfect surface quality is not desired. On the other hand, methods such as filament winding, pultrusion, RTM, and SQRTM are more appropriate for commercial purposes since such methods are open to automation and mechanization developments particularly for both flexible and mass productions.

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