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A review on the fabrication method of bio-sourced hybrid composites for aerospace and automotive applications

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Abstract: Development of bio-sourced materials over the recent years has shown growing interests due to their eco-friendly characteristics. The combination of bio-sourced material such as kenaf, jute, sisal and many more into current synthetic fibres such as glass and carbon fibre, which is also known as hybrid composites, offers several significant benefits including sustainability, cost reduction, product variety and high specific mechanical properties. There are many methods used to fabricate composite parts nowadays. However, each method has its own requirement and usability. This review paper intends to focus on suitable technique to be adopted in order to fabricate bio-sourced hybrid composites. Some of the fabrication methods are customized in order to suit with the application of natural fibres. The selected methods are also highlighted with the application in aerospace and automotive industry. The process and outcomes are presented comparatively.

1. Introduction

In recent aerospace manufacturing, nearly 50% components of the aircraft are made from composites [1]. Composite material comprises of two or more different materials integrated through a certain process to obtain a resultant material with new physical and mechanical properties [2]. Resin, either from natural or synthetic polymer, is used as a binding mechanism that holds the composite together to achieve the desired strength [3]. The major benefit of composite components is strength-to-weight ratio, which is ideal for aerospace application [4]. Increasing global awareness on the environmental sustainability has led to numerous development on renewable materials such as natural fibres in the fabrication of composite parts. Hybrid composites, which is a combination of two or more materials in a common matrix [1], has been implemented since natural fibre composites do not have adequate strength to substitute conventional synthetic fibre [2]. By having hybrid composites, the advantages of one type of fibre could complement what is lacking in the other, resulting in a balance in performance and cost through proper material design [3]. The mechanical properties of natural fibre reinforced composite (NFRC) such as stiffness, strength and moisture resistant behaviour are also significantly improved by incorporation of stronger and more corrosion-resistant synthetic fibre such as glass or carbon fibre. A study by M. Ramesh *et al.* [4] indicated that hybridization of glass fibre into sisal/jute reinforced epoxy composites showed good tensile strength of 68.55MPa. Another study by M. Thwe *et al.* [5] depicted that incorporation of glass fibre up to 20% by mass with bamboo fibre increased tensile and flexural modulus by 12.5% and 10%, respectively. Sanjay [6] investigated flammability behaviour and degradation of PP/banana and glass fibre-based hybrid composites and found out that hybridization with glass improved flame retardant characteristic. T. Subash *et al.* [7] discussed about bast fibres reinforced hybrid composites for aircraft indoor structures applications. These materials provide the benefits in the making of the body panels such as in seat cushions, cabin linings, parcel shelves and many more. The natural fibres such as jute, kenaf, bagasse, bamboo, coir, sisal proved that these materials have a greater strength in aerospace and automotive industry. These composites show lower density as compared to metal composites and have a higher potential to make lightweight sustainable finished parts that can reduce tremendous amount of energy consumption in the industry.

There are various fabrication methods applicable for producing bio-sourced composites for usage in aerospace and automotive applications. This review paper will discuss processes involved using open and closed moulding technique. The correct selection of process, based on the geometry of the part, production scale, cost, and mechanical properties is vital in order to achieve optimum outcome for composite parts produced.

2. Composite fabrication method

Composite fabrication method in general can be divided into two main processes, namely open and closed moulding. For open mould technique, the top layer of the laminates and matrix are exposed to the atmosphere, resulting in uncontrolled surface condition [8]. Since the tooling fabrication process is relatively simple and low cost, rapid product development cycle is possible to be implemented using this method. This review will discuss three main processes under the open moulding method: manual hand lay-up, spray-up method and filament winding. On the other hand, closed moulding or also called liquid composite moulding (LCM) [9] is a process when fibres are laid on two-sided mould or within a vacuum bag. A liquid resin is supplied into the mould cavity to fill up the spaces within the laminates. Due to the fact that the process is normally automated and requires special equipment, it is capable of producing large part and high volume. The closed mould process that is discussed in this review include vacuum infusion process, resin transfer moulding, pultrusion, compression moulding and vacuum bag moulding. The fabrication techniques are summarized in Table 1. The selection of fabrication method depends on several factors such as material, resin system, part complexity and application. Table 2 shows suitability of fabrication method with respect to the production amount.

Table 1. Fabrication method for open and closed mould

Open Mould	Closed Mould
Hand Lay-Up	Vacuum Infusion Processing
Spray-up	Pultrusion
Filament Winding	Resin Transfer Moulding (RTM)
	Compression moulding
	Vacuum Bag Moulding

Table 2. Fabrication method according to volume production

Low Volume	Medium Volume	High Volume
Hand Lay-Up	Filament Winding	Compression Moulding
Vacuum Bagging	Resin Transfer Moulding	Pultrusion
Spray Up	Centrifugal Casting	Continuous Lamination
Vacuum Infusion Processing	Wet Lay Up Compression Moulding	Reinforced Reaction Injection Molding (RRIM)

2.1. Open mould

2.1.1. Hand lay up. Hand lay-up is the most popular fabrication process in composite manufacturing [10]. This process is widely practiced due to the low set up cost compared to other process like resin transfer moulding that requires high investment for tooling and material [8]. Hand lay-up involves application of laminate ply manually into an open mould until desired part thickness is achieved. The diagram of hand lay-up is shown in Figure 1. The use of different types of polymer is a determining factor for curing time. Epoxy resin, for instance, required 24 hours curing time at room temperature [11]. Hand lay-up is normally used with thermoset polymer based material. Although hand lay-up requires less capital investment, it is limited to relatively low production rate and low volume fraction of reinforcement [12]. Various aircraft and automotive parts can be fabricated using this method including aircraft seats, non-structural parts, car dashboards and also interior cabin parts [13]. The characterization of hand lay-up, its advantages and disadvantages are summarized in Table 3.

2.1.2. Spray up method. Spray up is a process where compressed air supplied through the spray gun is used to spray both resin and fibre onto an open mould [23]. The fibre, usually in yarn form, is cut simultaneously and mixed with the sprayed resin at the tip of the spray nozzle before both of them fall into the mould. In order to remove the air trapped in between the layers, a roller is usually applied over the sprayed material. The curing depends on the resin system used, which is normally occurs at room temperature. The cured part is detached from the mould for further manufacturing process. The process might be repeated in order to achieve desired part thickness. Due to the nature of the process, the fabrication method is efficient, hence easy to accommodate design alteration. The final quality of the composite part produced by spray up technique depends heavily on the worker’s skill. In terms of application, this method is more suitable for lower load carrying components such as boats and trucks fairing. Spray-up method can accommodate a variety of part size, as well as capable of providing high volume fraction of reinforcement. Figure 2 illustrates the set up for spray-up process.

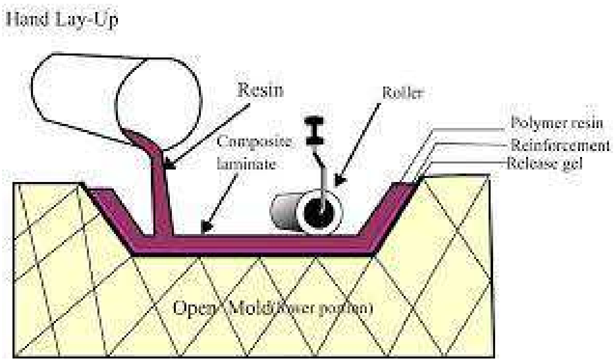

Figure 1. Hand lay-up set up

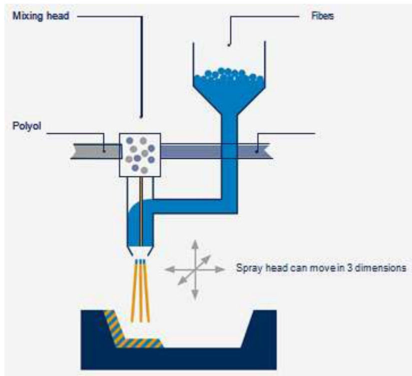

Figure 2. Schematic diagram of spray up method

Table 3. Characteristics of hand lay-up process

Resins	Fibres	Advantages	Disadvantages
epoxy, polyester, vinylester, phenolic [12, 14, 15]	Any, e.g. glass, carbon, aramid [11, 12, 16], jute [17], kenaf [11], coconut spathe [18], sisal, cotton, banana, oil palm, bamboo, wheat, rice, and bagasse [19, 20]	1. Most famous conventional method [21] 2. Relatively easy to learn process [20] 3. Low capital investment [12] 4. Variety of material types [12] 5. Higher fibre volume, and longer fibres size [22]	1. Resin mixing is very dependent on the skills of operators [23] 2. Health and safety considerations of resins [24] 3. High styrene contents of resins [22] 4. Require low-viscosity resin[10] 5. Require long curing times and the mould release characteristics are poor [25]

Although spray-up is an effective fabrication method for composites, exploration of mechanical properties for parts produced using this method is still limited. In a study by Xiao *et al.* [17], 3-point bending test was conducted to study bending properties of laminated plate with the detached acrylic resin and glass reinforced unsaturated polyester layer (GFRP). The acoustic emission, as well as thickness calculation of jute fibre reinforced plastic (JFRP), were also measured simultaneously. The experiments illustrated that JFRP laminates can obtain 75% bending modulus with the same thickness as the laminate with GFRP, suggesting possibility for JFRP to replace GFRP in industrial application. Table 4 summarizes the characteristic of spray up method.

Table 4. Characteristic of spray up method

Resins	Fibres	Advantages	Disadvantages
Matrix epoxy, polyester, polyvinyl ester, phenolic resin, unsaturated polyester, polyurethane resin	Glass fibre, carbon fibre, aramid fibre, natural plant fibres (sisal, banana, nettle, hemp, flax, coir, cotton, jute etc.) (all these fibres are in the form of chopped short fibres, flakes, particle fillers etc.)	1. Low investment for high volume capacity 2. High fibre volume	1. Inconsistent part thickness 2. Difficult to obtain thorough resin distribution

Another research done by Kikuchi *et al.* [23] on mechanical properties of jute composite by spray up fabrication reported large variation of tensile strength despite stable elastic modulus values. It was depicted that the quality of products is proportional to the operator's skill. There are several factors affecting the outcome of spray up process. Liakus *et al.* [26] investigated microstructure-property predictions for short fibre reinforced composite structures based on a spray-up process. In the study, variations in fibre length, as well as spray disposition pattern have been identified as two major factor contributing to the mechanical strength of the composite part produced.

2.1.3. Filament winding. Filament winding is mainly used for fabricating open (cylinders) or closed end structures (pressure vessel or tanks) due to high stiffness-to-weight ratios. In a filament winding procedure, the fibre tows are wetted in a resin bath before being wound onto a mandrel in different orientations. The winding process is controlled by fibre feeding mechanism and rate of rotation of the mandrel. The schematic diagram of typical filament winding process is illustrated in Figure 3.

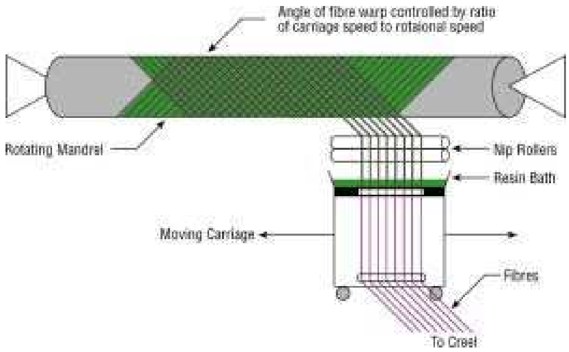

Figure 3. Schematic diagram of typical filament winding process

One of the well-known product of filament winding process is composite overwrapped pressure vessels (COPVs), which are vital to spacecraft propulsion, attitude control systems and life support applications. The COPV design requires integration between the analysis of the liner and the fibre overwrap [27]. Ductile materials are usually used as the liners, such as soft aluminium, with only minimal load-sharing capabilities. The fibre is generally applied as ribbon of multiple tows wetted in resin bath. In previous research conducted by Madhavi *et al.* [28] on design and analysis of filament wound COPV with integrated-end domes, material characterization of FRP of carbon T300/Epoxy for various configurations are determined using filament winding technique. It is found out that having alternate hoop and helical layers with hoop layers as the top and bottom most layers, gave the burst value of 12.4 MPa in the cylindrical zone. Vargas Rojas *et al.* [29], on the other hand, developed a numerical computing tool to simulate the filament winding process for various mandrel geometry, including axisymmetric mandrel. The numerical tool developed solves the general path equation that could be used as a basis for further mechanical behaviour models by integrating onto the filament winding parameters. Cherniaev *et al.* [30] conducted both experimental and numerical study of hyper-velocity impact (HVI) damage by orbital debris in the composite materials fabricated by filament winding. The result showed that the filament winding pattern with higher degree of interweaving of filament bands demonstrated better ability to hinder the dissemination of HVI induced damage, even in the presence of pre-loading. The characteristic of filament winding process is presented in Table 5.

Table 5. Characteristic of filament winding process.

Resins	Fibres	Advantages	Disadvantages
Matrix epoxy, polyester, polyvinyl ester, phenolic resin	Glass fibre, carbon fibre, aramid fibre, natural plant fibres (the fibres are used straight from a creel and not woven or stitched into a fabric form.)	1. Economic way of laying material down 2. Resin usage can be controlled 3. Minimum fibre cost 4. Good structural properties of laminates	1. Limited to convex shaped components 2. Difficult to lay fibre exactly along the length of component 3. High mandrel cost for large components

2.2. Closed mould

2.2.1. Vacuum infusion. Vacuum infusion refers to a process when the resin is driven into a laminate using a vacuum pressure [31]. Reinforcement are draped onto a mould and flow media is placed on top of it to allow equal distribution of resin throughout the laminates [32]. The vacuum is applied prior to introduction of resin. Once a complete vacuum is achieved, which is normally at 25 mmHg, resin is allowed to enter into the laminate via carefully placed tubing. Typical resin set up is shown in Figure 4.

Previous study done by Kim *et al.* [12] on hybrid glass fibre reinforce plastic (GFRP) showed that the vacuum infusion process resulted in higher ultimate strength and modulus, shear strength, and displacement over thickness value than the hand layup samples in both tension and compression tests. Another investigation carried out by Scalici *et al.* [33] on basalt fibre reinforced composites using different vacuum assisted impregnation techniques suggested that vacuum assisted resin infusion exhibited lower aptitude to thoroughly impregnate the laminates as compared to the vacuum bagging process. This results in higher fibre volume fraction, hence yielded in higher stiffness values for the composite part. However, the lack of full impregnation of the dry fabric architecture could result in under-performance outcome due to low fibre/matrix adhesion. The characteristic of vacuum infusion process is described in Table 6.

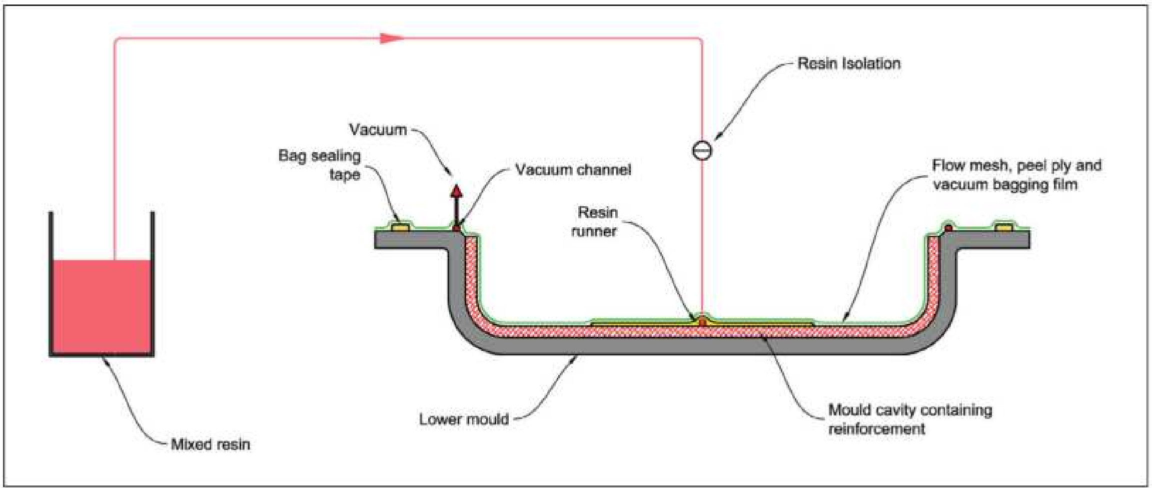

Figure 4. Schematic diagram of vacuum resin infusion process

Table 6. Characteristic of vacuum infusion process

Resins	Fibres	Advantages
Ortho, Iso, DCPD, Vinyl Ester [31], Epoxy	Any, e.g. glass, carbon, aramid, jute, kenaf, coconut spathe, sisal, cotton, banana, oil palm, bamboo, wheat, rice and bagasse	1. Better fibre-to-resin ratio 2. Less wasted resin 3. Consistent resin usage 4. Light weight, due to minimum resin contain 5. Lower tooling cost 6. Large components can be fabricated

Yenilmez *et al.* [34] investigated about variation of part thickness and compaction pressure in vacuum infusion process. Getting a consistent part thickness is a big challenge in vacuum infusion process due to the effect of varying compaction pressure on the upper mould part, a vacuum bag. Based on the experiments, it can be summarized that the final part thickness depends on the durations of initial vacuuming and gelation time for the resin, resin pressure at the location, and shrinkage ratio of the resin system used. Md Afendi *et al.* [35] studied about degassing process prior to resin infusion for reducing void formation from gasses dissolved in the resin. At 90 mbar, this method of degassing may eliminate 40-50% of the dissolved gas with the assistance of bubble thin films.

2.2.2. Pultrusion. Pultrusion is a manufacturing process for hybrid composite that offers continuous production of profile with a constant cross section [36]. In the thermoplastic pultrusion molding, resin and reinforcement fibres are pulled through a heat die. As the heat and pressure generated, resin starts to melt and impregnate into the reinforcement fibre. There are several parameters such as preheating method, die temperature and pulling speed that represent determining factors regarding a potential industrial application. The normal set up of pultrusion is shown in Figure 5 and Figure 6.

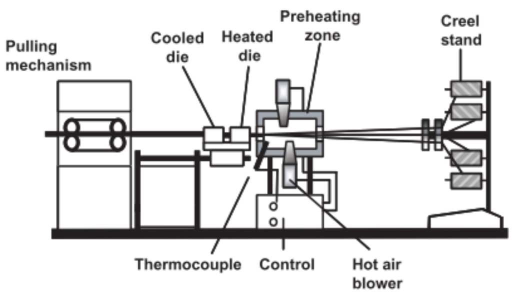

Figure 5. Schematic diagram of pultrusion process

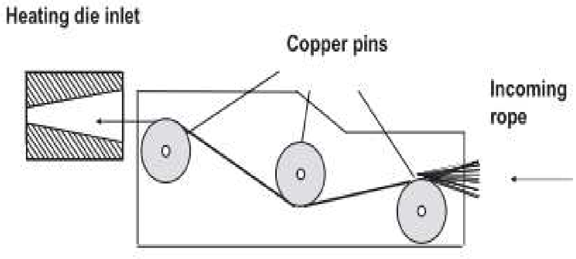

Figure 6. Pulling mechanism in pultrusion process

There are a number of studies have been carried out on pultrusion process to fabricate composite parts. Memon and Nakai [37] investigated the mechanical properties of jute spun yarn reinforced PLA tubular braided composite using pultrusion moulding. The experimental results showed that the configuration of the intermediate material and the moulding temperature influenced the mechanical properties of the part produced. It was reported that the impregnation quality increased with the size of moulding and increasing temperature reduced the mechanical properties due to deterioration of jute fibre. Another study was carried out by Peled and Mobasher [38] to investigate the use of pultrusion technique as a cost-effective method for production of thin-sheet fabric reinforced cement composites. The pultrusion process required a relatively simple set-up using low cost equipment while at the same time it was able to maintain laminates alignment, resulting in relatively smooth surface and uniform products. It was found that pultrusion had significantly improve the mechanical performance of the cement composites compared with cast composite. The mobilization of the filaments in the pultrusion process yielded in a strain hardening composite even when the yarn modulus is relatively low. The characteristic of pultrusion process is explained in Table 7.

Table 7. Characteristic of pultrusion process

Resins	Fibres	Advantages	Disadvantages
Epoxy, polyester, vinylester, phenolic	Any, e.g. glass, carbon, aramid, jute, kenaf, hemp, coconut spathe, sisal, cotton, banana, oil palm, bamboo, wheat, rice, and bagasse [39]	Fast and economic way of impregnating and curing material, minimised fibre cost, good laminates structural properties, enclosed resin impregnation area, thus limiting volatile emissions	Limited to constant or near constant cross-section components and high cost for heated die

Properties of hemp fibre composite made by pultrusion process was studied by Peng *et al.* [39]. Natural fibres generally depend on factors such as source, age, retting and separating techniques that give rise to difficulties in the property control of their composites. The diversity of compatibility to adhere to matrix required additional process such as treatments and chemical modification [40]. The result of the experiment showed that the thermosetting polymer-based composites reinforced with hemp and wool fibres have higher tensile strength compared to the common plastics at a comparable density. With the benefits of low cost, availability, and process, the polyester composite made by pultrusion process would be a good choice for manufacturing construction board, insulation board, or being used as reinforcement for other structural materials.

2.2.3. Resin transfer moulding. Resin transfer moulding (RTM) is a closed-moulding method in which reinforcement material is laid into a closed mould and resin is pumped in (through injection ports) under pressure. This process produces complex parts with smooth finishes on all exposed surfaces [41]. The lay-up of materials onto the dry mould enables any combination of different materials and orientation. The desired part thickness can be obtained by setting up the tool cavity volume and the process can achieve a fast cycle time in temperature controlled tooling. Typical set up for RTM is as illustrated in Figure 7.

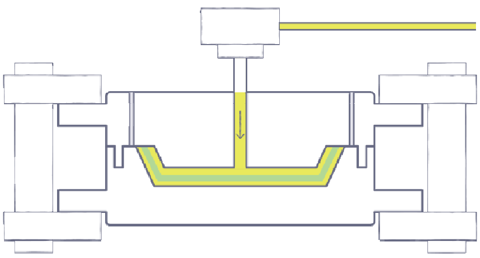

Figure 7. Schematic diagram of resin transfer moulding

Vacuum assist can be used to improve resin flow inside the mould cavity. There is a wide range of tooling variety, from low-cost composite to temperature controlled metal tooling that can be used for RTM. Mould release agent is applied prior to positioning the reinforcement (and core material) onto the mould. As the mould is closed and clamped, the resin is injected under pressure using mix/meter injection equipment and the part is cured in the mould. RTM can be done at room temperature but the heated moulds are required to achieve fast cycle times and also product consistency. Clamping can be accomplished by perimeter clamping or press clamping.

There have been many developments of hybrid composite being done using RTM process. Liu *et al.* [42] investigated the mechanical performance and failure mechanism of thick-walled composite connecting rods using RTM technique. From the study, it was recorded that the tensile failure was originated from the delamination at the round angle transition areas of the T-joints at either end of the connecting rod and the failure strength was determined by the interlaminar strength. Meanwhile, the compressive failure was due to the fracture of fibres in the main bearing beam, hence determining the failure strength of the structure. The characteristic of resin transfer moulding process is shown in Table 8.

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Table 8. Characteristic of resin transfer moulding

Resins	Fibres	Advantages	Disadvantages
Epoxy, polyester, vinylester, phenolic, bismaleimides	Any, e.g. glass, carbon, aramid, jute, kenaf, hemp, sisal, cotton, banana, and bagasse, stitched material	1. High fibre volume and low void contents 2. Controlled surface on both sides of panel 3. Good health and safety, environmental control	1. Expensive tooling cost 2. Limited to smaller components 3. Unimpregnated areas can occur resulting in costly scrapped parts

Another research on mechanical and damping properties of RTM jute-carbon hybrid composites was carried out by Ashworth *et al.* [43]. The study investigated carbon (CFRP), jute (NFRP) and hybrid (HFRP) fibre reinforced polymers fabricated using RTM process. Kim and Lee [44] studied about structural behaviour evaluation of composite side beams by comparing between autoclave cure and RTM method. It was reported that the side beam made by RTM appeared to be slightly softer than the autoclave cured one due to lower fibre volume fraction. The environmental resistance of flax/bio-based epoxy and flax/polyurethane composites manufactured using RTM method was investigated by Cuinat-Guerraz *et al.* [45]. From the study, they found that for cellulosic fibres reinforced composites, the usage of polyurethane resin leads to environmental stability, durability and material's moisture resistance. It was also illustrated that the nature of the fibre/matrix interface played a key role in the moisture absorption mechanisms. Papargyris *et al.* [46] compared mechanical and physical properties of a CFRP manufactured by RTM using conventional and microwave heating and found out that there was a 9% increase in the interlaminar shear strength (ILSS) for the microwave cured composites in comparison to the conventional ones.

2.2.4. Compression moulding. Compression moulding refers to a process where composite materials are laid between two matching moulds under high pressure (up to 2,000 psi) and heat (from 120°C to 200°C) in order to cure the part. This technique is used to rapidly cure large quantities of complex fibreglass-reinforced polymer parts [47]. There are several types of compression moulding that are defined by type of moulded materials: bulk moulding compound (BMC), thick moulding compound (TMC), sheet moulding compound (SMC) and wet lay-up compression moulding. Matched metal dies are mounted in large hydraulic moulding press. Compression moulding enables part design flexibility and features such as inserts, ribs, bosses and attachments. Typical set up of compression mould is illustrated in Figure 8.

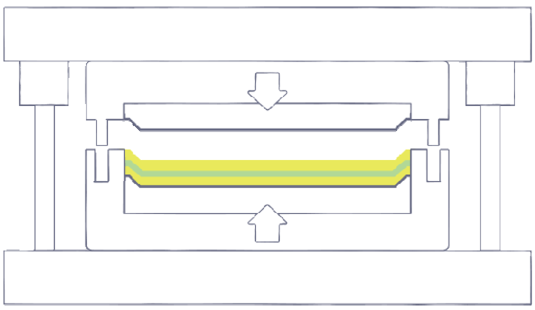

Figure 8. Set up for compression moulding

Curing time normally depends on shape of the part, size and thickness. Cured parts are removed from the mould for the next process. Compression moulding offers one of the fastest routes for the manufacturing of the composite components from thermoset matrices. This makes sheet moulding compounds (SMC) the most widely adopted material format of fibre reinforced composites within the automotive industry, accounting for 70% of composites by mass. Numerous works have been carried out to study compression moulding method as a mean to fabricate composite parts. Wulfsberg *et al.* [48] combined the carbon fibre sheet moulding with prepreg compression and found out that the combination yielded load-bearing and autoclave-quality component without being cured in autoclave.

However, each material combination has to be properly developed to comply with the requirement for particular application. There are also some parameters that need to be looked into such as flowability, moulding pressure, moulding temperature and time in order to ensure consistency in parts produced. The characteristic of compression moulding is illustrated in Table 9.

Table 9. Characteristic of compression moulding

Resins	Fibres	Advantages	Disadvantages
Epoxy, polyester, vinylester, phenolic, bismaleimides	Any, e.g. glass, carbon, aramid, jute, kenaf, hemp, sisal, cotton, banana, and bagasse, stiched material	1. Low initial set up cost 2. Fast set up time, allow intricate parts 3. Good surface finish, can apply to composite thermoplastics with unidirectional tapes, woven fabrics, randomly orientated fibre mat or chopped strand	1. Expensive tooling cost 2. Limited largely to flat or moderately curved parts with no undercuts 3. Less than ideal product consistency

In terms of the surface analysis, there is a study carried out by Serré *et al.* [49] pertaining to the morphology of the outermost layer of a compression moulded composite based on the unsaturated polyester resin. Wakeman *et al.* [50], on the other hand, conducted a systematic study of the effects of charge composition and process parameters for automotive part (door cassette) produced through the compression moulding from glass fibre and polypropylene composites.

2.2.5. Vacuum bag moulding. Vacuum bagging refers to a process that applies mechanical pressure on a laminate during its cure cycle. Vacuum bagging is an extension to the current hand lay-up. It serves important role to remove any trapped air in between the laminates, securing the position of fibre orientation during curing, reduce humidity and optimize fibre to resin ratio in the composite part. The elements consist in vacuum bagging system include vacuum pump, fitting and connectors, vacuum gauge, bagging film, sealant tape, release film, peel ply, breather, bleeder and vacuum tubing. In a typical vacuum bagging process, a release film or peel ply is draped onto the mould as first layer, followed by composite laminates, release film, bleeder, breather and bagging film as the final layer. Vacuum gauge is then installed on the bagging film and vacuum suction pressure is applied up to normally 25 mmHg. Normal set up of vacuum bagging is shown in Figure 9.

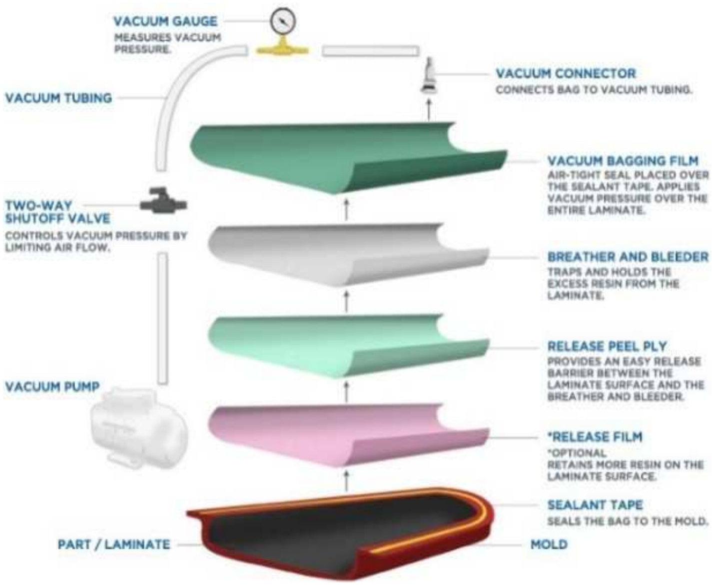

Figure 9. Set up for vacuum bagging process

Present study by Dominguez and Madsen [51] on development of new biomass-based furan/glass composites fabricated by the double-vacuum-bag technique showed that, in the optimal case of no matrix porosity, the composites yielded a well comparable stiffness with conventional thermosetting / glass composites, despite lower strength. Hamill *et al.* [52] investigated the surface porosity factors during vacuum bagging process and identified several parameters that affect air evacuation including freezer and out time, vacuum hold time, material and process modifications. The characteristic of vacuum bagging process is illustrated in Table 10.

Table 10. Characteristic of vacuum bagging process

Resins	Fibres	Advantages	Disadvantages
Epoxy, polyester, vinylester, phenolic,	Glass, carbon, aramid, jute, kenaf, hemp, sisal, cotton, banana, and bagasse, stiched material	1. Higher fibre content laminates 2. Lower void content 3. Reduce the amount of volatiles emission	1. Additional costs for bagging material 2. Higher level of skill operator 3. Resin usage depend highly on operator skill

Zahid and Chen attempted manufacturing of single piece textile reinforced riot helmet shell using vacuum bagging technique [53]. They managed to develop a technique to manufacture single-piece riot helmet shells that is usable for the development of different varieties of bi-curvature composite structures and almost any composite geometry. They also conducted a research on impact evaluation of Kevlar-based angle-interlock woven textile composite structures using vacuum bagging method [54]. The result indicated that laminate thickness plays important role in energy absorption and force transmission capabilities. Mariatti *et al.* [55] focused on investigating the properties of unsaturated polyester reinforced with banana and pandanus woven fabric. It was observed that banana woven composites show better flexural and impact properties as compared to pandanus woven fabric due to different cross section structure and higher cellulose content. As the fibre volume fraction increased, both flexural modulus and strength rose up until the maximum limit of 15 volume fraction of fibres. Sudheer *et al.* [56], on the other hand, investigated the effect of potassium titanate whiskers on the mechanical and tribological properties of glass/epoxy composites. From their study, it was reported that the addition of potassium titanate whiskers has significantly improve the property of glass/epoxy composites such as density, hardness, stiffness, wear resistance as well as friction coefficient.

3. Application

Summary of application for open and closed moulds is listed in Table 11 and Table 12, respectively.

Table 11. Application of open mould method

Hand Lay-up	Spray Lay-up	Filament Winding
Aircraft seats, non-structural parts, car dashboards and interior cabin parts	Lightly loaded structure, car bonnet, truck fairings, car bodies	Composite overwrapped pressure vessels (COPVs), pipelines

Table 12. Application of closed moulding method

Vacuum Infusion	Pultrusion	Resin Transfer Moulding	Compression Moulding	Vacuum Bag Moulding
Vehicle floor, interior cabin part, customized car body panels	Rods, tubes, interlocking floors, stiffeners, fencing, simple beams	Vehicle seat, spar, rib element, hovercraft rotor blade	Vehicle body parts, jet engine parts, nacelle structure	Helmet, door panels, vehicle body parts

4. Future overview

A significant leap in the development of composite manufacturing technologies might not be really foreseeable in the near future. However, a lot of improvement in the current manufacturing method is currently being studied and a few new manufacturing concept are in the progress. The introduction of the automated tape lay-up (ATL) and the automated fibre placement (AFP), for examples, indicates the integration of computer-guided-robotic with current composite material to perform lay-up process for large composite parts such as aircraft wing skin and fuselages. With this development, it opens up another opportunity for current manufacturing method to be integrated with automation such as spray-up and filament winding. With the view that natural fibres are becoming more substantial nowadays to replace depleting petroleum based products such as carbon fibres, emphasize should be given to the development of manufacturing technology to suit with bio-sourced hybrid composite material. This is to ensure the sustainability of the whole manufacturing ecosystem as well as the dependency on the synthetic materials.

5. Conclusion

This study sums up the current manufacturing of hybrid composites for both open and closed mould techniques. Each method is unique and some of them can be combined or integrated to achieve better results. For large size aircraft components, methods such as hand lay-up, spray-up, vacuum bagging and vacuum infusion are suitable due to their ability to suit with a big mould and working area. Meanwhile, for intricate geometry part, methods such as pultrusion, compression moulding and resin transfer moulding are more appropriate due to the pressure applied during fabrication process. The development of the composite manufacturing technologies should also take into account the growing importance of natural fibres as a substitution for current synthetic materials.

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