A Review on Fabrication of Thermoset Prepreg Composites using Out-of-Autoclave Technology

Feroz SHAIK*[,1], M. RAMAKRISHNA[1], P. Dhaval VARMA[2]

*Corresponding author
[1]Department of Mechanical Engineering,
Vignan's Foundation for Science, Technology and Research,
Vadlamudi, Guntur, Andhra Pradesh-522213, India,
sferoz.in@gmail.com*, professormramakrishnaa@gmail.com
[2]School of Mechanical, Materials and Manufacturing Engineering,
University of Nottingham, United Kingdom,
narnevarma@gmail.com

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Abstract: *Autoclave is the technology that has been extensively used to manufacture high-grade performance composite parts for aerospace applications. This technology has been limited to aerospace industries only, primarily due to its high cost in manufacturing parts. The researchers then considered an alternative approach "Out-of-autoclave" (OOA) process, aiming at cost and time optimization. Non-autoclave methods such as OOA cure processes have been developed lately. The OOA process has a high potential for a drastic cost reduction in the manufacturing of composite aerospace structures. It processes parts that have a quality similar to that of parts cured using the autoclave technology. Specially designed OOA prepregs are available in the market for OOA processing, some of which are certified for aerospace manufacturing. This review paper briefly focuses on OOA prepregs and OOA processes that are used for aerospace components manufacturing. Future areas of development in the aerospace sector based on cost optimization and faster cycle times are also discussed in this paper.*

Key Words: *aerospace, OOA composites, prepregs*

1. INTRODUCTION

In the current scenario, the aerospace industry is much focused on developing high-performance carbon fibre composites to solve the main challenges which are lightweight aero-components/ structures, their cost reduction and improved durability. In this regard, composites are the key materials that can provide a solution to these problems. The use of them has resulted in reduced costs, light weighed components and improved durability in aero structure components. There are many processes available for the manufacturing of composites. It is a challenge for the manufacturing engineer to select the right process to manufacture a composite part as the selection of the process for fabricating composite components depends on many factors such as the rate of production, strength, cost, shape and size requirements for that particular part. Aerospace industries require high-end structural composites because high-temperature resistance is required for such parts. The processes to manufacture parts can be categorized as Autoclave cured and Out-of-Autoclave cured techniques in terms of aerospace structures. Autoclave processes have been commonly used to fabricate high-performance composites parts for aerospace applications. However, high capital and tooling costs make these autoclave cured composites very expensive. The operational costs of the autoclaves are also very high. The quality of the parts manufactured using an autoclave is high compared to other processes. But the parts to be cured using autoclave are constrained by available autoclave vessel sizes. Large autoclaves cannot be used at any time for small parts. So they have relatively inflexible manufacturing environments. In primary aero structures, advanced composites made of carbon fibre reinforced thermoset polymers have been extensively used to manufacture aero components. Not only in aerospace, but they have been also utilized in various applications such as the automotive industry, civil structures, sporting equipment etc. As the requirement for these CFRP (carbon fibre reinforced thermoset polymers) grows, we need new methods which are faster and more cost-effective. Many OOA methods have come up to meet those requirements. The widely used non-autoclave processes in the aerospace industry are Vacuum Assisted Resin Transfer Moulding (VARTM) process, Resin Transfer Moulding (RTM) process, Filament Winding and OOA vacuum-bag-only prepreg process.

Despite autoclaves capacity to manufacture better quality parts, they are very costly and require a high investment. Also, large parts cannot be manufactured easily as they are dependent on the capacity of the autoclave. Therefore, researchers developed a type of prepregs that could be cured under the vacuum only, i.e. using a traditional oven. From this OOA manufacturing process was born, with carbon epoxy prepregs that could be cured at a lower temperature than autoclave prepregs. This process obtains the same quality as in the case of an autoclave, but through a different fabrication process. However, the mechanical properties were not as good as with the autoclave prepregs. New prepregs were then produced using toughened epoxy resin, resulting in parts with improved mechanical properties and a higher glass transition temperature (Tg) which allowed for a higher service temperature [1]. It is the temperature above which a thermosetting polymer changes itself from a hard and rigid state to a rubbery or glassy state. However, for the OOA process to be considered as an aerospace composite manufacturing process, it should be capable to produce composites having lesser void content as compared with autoclave-cured composite parts.

2. COMPOSITE MANUFACTURING PROCESSES

To eliminate these difficulties, present in the autoclave curing process, alternative composite fabrication techniques, with the objective of manufacturing composite parts which are cost-effective and can be produced within a shorter period of time are developing rapidly. These are known as LCM (Liquid Composite Moulding) processes:

- Resin Transfer moulding (RTM).
- Vacuum-assisted RTM (VARTM).
- Resin Infusion moulding (RIM).
- Same Qualified Resin Transfer Moulding (SQRTM).
- Resin Film Infusion (RFI).
- Usage of OOA prepreg with an advance resin system.

2.1 Liquid Composite Moulding (LCM) processes

LCM processes consist of all the composite fabrication techniques, in which the (liquid state) matrix material, especially epoxy resin will be mixed with the dry preformed reinforcing material mostly carbon fibre fabric. The main aim of this process is to have a full impregnation of the dry fibres as the resin goes in between the fibres and fibre bundles. This impregnation driving force results usually from the pressure difference [2]. Thus, many different processes originate in the pressure difference, as shown in Table 1.

Table 1. Selection of different LCM processes by category

Vacuum based	**Vacuum and pressure based**	**Pressure based**
VARI	VARTM	RTM
VAP (Vacuum assisted process)	LRTM (light resin transfer moulding)	Inflatable tube process
SCRIMP (Seeman composite resin infusion moulding process)		GAP impregnation
RFI (Resin Film Infusion)		TERTM (Thermal expansion resin transfer moulding)
RST (Resin spray transfer)		URTRI (Ultimately, reinforced thermosets in injection)

2.1.1 Resin Transfer Moulding (RTM)

It was adopted in the mid-1980s for composite manufacturing. The automotive industry used it more as large structural parts can be made with high production volume. The RTM process begins with placing the dry fibres on to a metal mould. A liquid thermosetting resin according to our choice is then injected under high pressure. Before injection, they both can be preheated, or the mould can be heated before curing, i.e. after the injection of resin.

RTM process setup is shown in Figure 1.

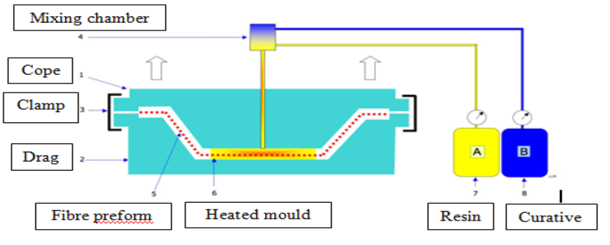

Figure 1. RTM process

Issues such as race-tracking channels [3, 4 & 5], fibre structure deformation during draping were found to cause variation in flow patterns. This fibre structure deformation was investigated by Rudd et al. [6]. Bickerton et al. [7] investigated the effect of resin flow based on draping of a compound curved preform. The relationship between outer and inner bend radii of the mould and fibre fraction volume was investigated [8, 9]. For several last decades, mathematical modelling of various stages in the RTM process was designed and applied. The details of this process modelling were observed and studied in many books [10-13].

2.1.2 Vacuum Assisted Resin Transfer Moulding (VARTM)

In VARTM process, environmental pressure is used to provide pressure against the fibre preforms which are kept in vacuum bag and mould. Mould temperature needs to be elevated depending on the resin system used during the cure cycle. For complex and large composite parts, multiple vents and injection lines can be used to improve the resin flow in it [14]. Figure 2 shows a basic VARTM tooling setup.

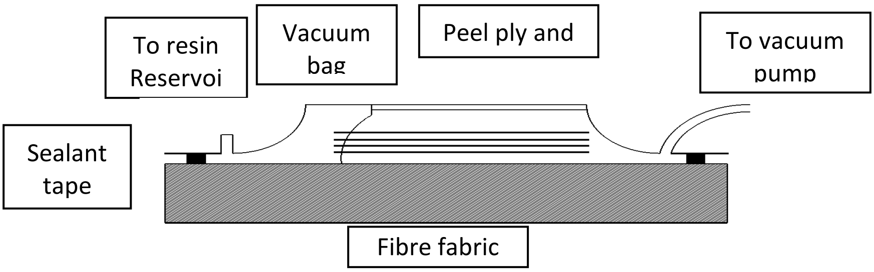

Figure 2. VARTM process

The following design considerations should be kept in mind during the design of the VARTM process:

- Mould temperature selection.
- Flow process design.
- Fibre volume fraction control [15].

Air entrapment is one of the major defects in this VARTM process. During mould filling, if the air doesn't get displaced by the liquid resin, then the chance of the air entrapment in the final composite part is high. The improper mould filling design is one of the main reasons for dry spot formation that causes the resin to come out from vents before displacing the entrapped air in the fibre preform. A proper mould filling design mitigates the dry spot issue considerably. There are many optimization methods for complex mould geometry to eliminate the dry spot formation [16-18]. Johnson and Pitchumani heated the resin in the mould during the mould filling stage so that the viscosity of the resin reduces and it accelerates the resin flow. This is the new flow control method done by them [19]. Dry spots may occur even if the time taken to fill the mould with resin is too long as the resin becomes too viscous to flow. Another type of air entrapment is micro-voids. They are formed due to the flow of incompatible resin inside a fiber tow. The resin flow in the gap between two fibre toes is given by Darcy's law. The relationship between formations of micro-voids and Darcy's flow equation has been investigated by many researchers [20-25]. The latest advancement in this process is IDVARTM (Injection and double vacuum-assisted resin transfer moulding) introduced by Fan et al. [26].

2.1.3 Resin Infusion Moulding

RIM is a process in which liquid resin is filled in the voids which are present in the stack of porous material. The assembly of materials forms into a rigid composite when the solidification of the resin matrix binds them together. Thermosetting resins are usually used, but thermoplastic resins are also being used for the RIM process [27]. The removal of air is the main part of RIM to avoid voids in the final laminate. Before injecting the resin, the air should be evacuated. The air should be evacuated from the porous material so that the resin can fill the air cavities present before evacuation. In a simple form, the process can be divided into the following stages:

- Pre-evacuation.
- Admission of resin.
- Maintaining vacuum during cure.
- Infused rigid part.

2.1.4 Same Qualified Resin Transfer Moulding

SQRTM is one of the closed moulding methods that utilize both liquid moulding and prepreg processing which produces net-shaped and complex aerospace components. The advantage of

SQRTM over the general RTM process is that, instead of laying dry fiber preforms over the mould, a prepreg layup is laid. Before closing the mould completely, the prepreg is arranged systematically within the mould and then the liquid resin is injected into the mould. Gating and channel systems are embedded within the tool to facilitate the evacuation of air from the layup before the injection of resin and to enable the injected resin to flow uniformly within the mould to fill all the cavities [28].

2.1.5 Resin Film Infusion

RFI is a fabrication process in which resin and fibre are kept on the mould but are not combined initially [29]. It has the same principle as that of VBO prepregs. It also contains paths for the removal of air during processing. By applying pressure and temperature, both the resin and the reinforcement are combined together. In this technique, the fibre remains dry most of the times and the resin remains outside the cloth. The research was done by Loos and Springer to develop new curing models for this process [30]. Researchers developed models which depicted the permeability among the fibre tows and spaces within them in a composite [31-34]. A simple relation for dry compressibility of the woven fibre preform was later proposed by Chen et al. [35]. Nano-materials are being used instead of resins. Anoop et al. [36, 37] fabricated glass composites with carbon nanofibers dispersed in epoxy resin. The viscosity of the resin was unaffected and the glass transition temperature of epoxy was improved when nanofibers were used. Even interlaminar shear and compressive strength was significantly improved. Issues such as filtration have been eliminated by using nanomaterials such as silica [36-38].

3. MECHANICAL PROPERTIES OF OOA COMPOSITE LAMINATES

Laminates fabricated using proper VBO techniques have shown properties equivalent to the panels fabricated in an autoclave. Many researchers have compared the mechanical properties of OOA processed laminates and autoclave processed laminates. Tencate TC-350 prepreg was cured using both autoclave and VBO methods, and their properties (mechanical properties) were examined by Villareal H et al. [39].

The mechanical properties (Tensile, compressive and flexural properties) were found to be equal for both sets of panels. Toray's T700G/2510 unidirectional VBO prepreg was cured using VBO and autoclave methods by Courter J et al. [40]. In this scenario, the oven-cured composite panels showed greater void content and thickness than autoclave cured composite panels and decrease mechanical properties. Cytec VBO prepregs (5215 and 754), which are first-generation have also shown mechanical property equivalence to traditional autoclave materials. Both woven fabric preforms and unidirectional fibres have shown equivalent properties in terms of glass transition temperatures as well as other mechanical properties [41]. Later-generation prepregs (Cytec 5320 and 5320-1) have also demonstrated property equivalence [42]. The National Aeronautics and Space Administration (NASA) conducted a detailed study on the comparison of properties of OOA laminates and autoclave cured laminates. Two autoclave carbon fibre epoxy composites (IM7/8552-1 and IM7/977-3) and two OOA carbon fibre epoxy composites (IM7/MTM45-1 and T40-800b/5320) [43] were used for their study. They were fabricated using both hand layup and fibre placement processes. When fresh VBO prepregs were used to cure panels, it was found that they had a quality equivalent to that of autoclave processed parts in the tests that were performed. Parameters that affect the quality of VBO cured laminates were also studied. The effects of post-cure temperature on compressive properties on Cytec 5320 prepreg were investigated by Vo et al. [44]. Laminates were fabricated using a two-hour cure at 93°C and post-cure at 100°C - 145°C.

Combined loading compression (CLC) testing was used to analyse the performance of the laminate. Results showed the existence of a relation between the degree of cure, CLC strength and glass transition temperature. These properties increased with high post-cure temperature and showed improved resin properties.

The above findings indicate the ability to fabricate autoclave quality parts using OOA process techniques. However, these relate to small and flat panels only. The manufacture of large and complex composite parts creates additional challenges.

4. OUT-OF-AUTOCLAVE (OOA) PROCESS

Traditionally, while manufacturing composite components for the aerospace industry, autoclave curing is used for achieving the desired resin-to-fibre ratio and void-free components to produce light and durable parts as per our requirement.

The general process involves laying up the fibres (prepregs), enclose them in a vacuum bag and then cure them in the autoclave while applying three parameters namely, temperature, pressure and vacuum.

It offers excellent reliability and high part quality, but this process requires high capital investment and energy costs. In addition, the component size is also limited to the capacity of the present autoclave [45].

Thus, the industry is engaged in further research and development for manufacturing processes that do not make use of autoclaves.

Special low-temperature curing prepregs have been recently designed for the fabrication of aerospace-grade composite components by OOA processing. In the present scenario, OOA technology is being used to make structural components at a comparatively lower price [46].

In the OOA manufacturing process, a defect-free part is produced by the application of temperature and vacuum only. By eliminating the external pressure during the autoclave curing process, the costly autoclave is no longer necessary.

The temperature application and vacuum application can be achieved by using a relatively smaller, simpler and portable oven. The investment cost of an oven is much less than that of an autoclave and hence it is more economical and in turn, helps to reduce the overall manufacturing cost of the part.

The OOA manufacturing process utilizes special prepregs that are designed specially to remove any entrapped air during the laying up process of prepregs. These partially impregnated prepregs create a surface which is porous in nature, to ease the evacuation of any of the entrapped air between the laminates prior to the transformation of resin into the liquid and then infused with the fibres [47].

The main defects in the OOA process that affects the part quality are ‘Voids’ and ‘Resin Rich Areas’. Both of them significantly affect the load-bearing capabilities of the part by hindering the transfer of loads from one fibre to another.

Resin rich areas usually have fewer fibre counts (the load-bearing component of the composite) compared to other areas in the component and hence stress concentration will be high in such regions, which in turn, will result in failure.

Inherently, the manufacturing process using OOA prepreg system requires more process control than other traditional prepreg lay-up process, and hence proper de-bulking, experienced labour and technical knowledge play crucial roles in manufacturing a high-quality part using the OOA process. [48]. Figure 3 shows the steps to obtain a void-free composite laminate manufactured using OOA process.

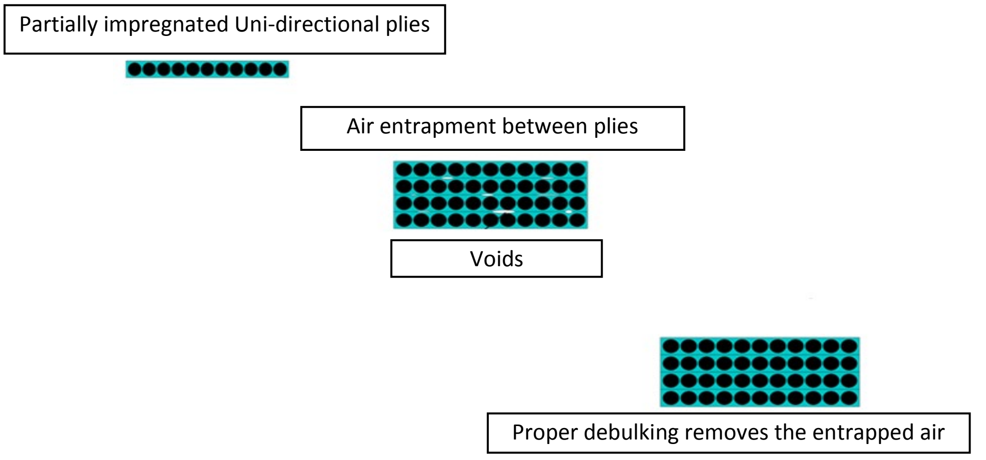

Figure 3. Steps for obtaining a void-free laminate

4.1 Reason for using OOA process

Mostly all the high-quality components made using composites are being produced using epoxy resin-based prepreg laminates which are cured using an autoclave at elevated temperatures and high pressures. Many prepreg materials were developed for autoclave curing. Parts with better quality can be manufactured using these prepreg materials. Autoclave curing has become a primary source in high-performance composite manufacturing as these parts have good stability and reliability. Though the autoclave curing process can produce high-quality parts, it has numerous disadvantages that make it inoperable in various fields of application. These disadvantages include:

- High capital investment.
- Lower temperature control.
- The overall component cost will be high.
- Longer cycle time.
- The high maintenance cost of equipment.
- High pressure is required.
- Energy consumption is excessive.

Let us examine the disadvantages in detail. Longer cycle times for the curing of the laminates (~8 hours or more) won't be a problem, but during the curing process for a batch, when longer cycle times are combined with the cost of many tools used for each batch curing, costs are much high and this process becomes unaffordable for many part manufacturers. Such high expenses cannot be taken up by all the industries [49]. The variable costs associated will also be considered while manufacturing the components using an autoclave. For heating such a large quantity of inert gas (Nitrogen) and then transferring it to such a massive tool to cure a composite prepreg laminate, which is quite inefficient and obviously time-consuming for the manufacturer. At last, all the above factors combine and result in a very high cost to fabricate the parts and restrict their manufacturing volume to relatively low numbers per day. Thus there was a continuous development to reduce the autoclave processing costs so that lower performance applications could be manufactured where higher production costs of the autoclaves cannot be incurred. These developments have significantly changed the entire course of the composites manufacturing market for small sector industries. The reinforcing fibre market, particularly the carbon fibres, has seen exponential growth in the past few years and will also be used extensively in the future (Figure 4). A lot of companies are interested in more cost-effective alternatives for autoclave curing. Not only this is linked to market and cost, but it is also controlled by government policies and regulations. Carbon emissions should be controlled as they degrade the environment. This point should be followed mainly by composites manufacturers. By considering all these implications, there is a need for the composite industry to develop some other composite fabrication techniques for different markets, so, preferably, the usage of the OOA process is well defined.

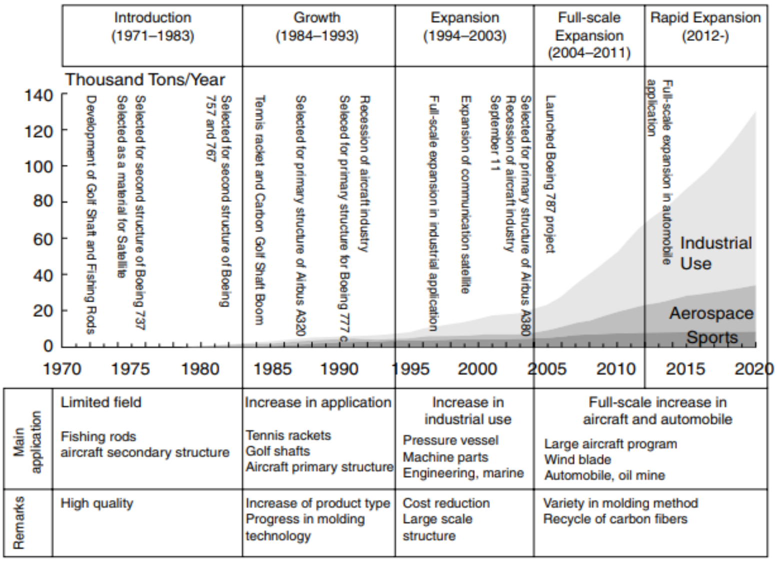

Figure 4. Growth for different markets in Carbon fibres. (Source: Toray)

4.2 The difference between autoclave and out of autoclave

Designers of aerospace composite components have taken granted the need for autoclave curing. Despite the cost and time advantages of out of autoclave processes, there is still a perception that they cannot produce parts with the same mechanical performance that autoclave curing produces. The main difference between a typical Autoclave and OOA and VBO batch oven is how the vacuum is generated. In an autoclave the entire chamber is under vacuum, in a batch oven, the composite work-piece is under vacuum since it is kept in the vacuum bag [50]. There are some knock-down factors for composite laminates associated with OOA processes such as “fibre volume” as there won’t be pressure parameters in out of autoclave process as present in an autoclave process. But this knockdown can be very small when the VARTM process is followed for producing composite laminates. The percentage of fibre volumes achieved with unidirectional and woven fibres are almost the same as that of the autoclave prepregs. Many factors are taken into consideration such as the overall weight, surface quality, processing time and costs for producing composite laminates. There are various alternatives to the autoclave process. The classic RTM process needs a two-part closed mould which is usually made of steel and is expensive. Dry fibre reinforcement is laid on the bottom half of the mould. They should be strategically laid on it. It is then closed and sealed. Then through the injection ports, the liquid resin is injected into the mould. Low viscosity resins are used in this process. Both resin and catalyst are measured and are mixed before they are introduced into the mould. Fast curing takes place due to this. Moulds are heated which reduces the cycle cure time when compared to that of an autoclave. This process can manufacture complex parts which are accurate dimensionally with good surface finish and lower void contents in the final composite part.

VARTM achieves aerospace-grade composite components without using the autoclave process. This process is commonly used in the marine, automobile industry and infrastructure sector. Dry fibre reinforcements and core materials are laid over the mould and then vacuum bagged. The laying of dry fibre preforms should be such that it should get impregnated by resin completely. The liquid resin is introduced through the ports which are placed in the mould. The ports should be strategically placed in the mould such that the liquid resin should impregnate the dry fibres completely. VARTM doesn't require high heat and pressure as required for an autoclave. Comparatively, VARTM has low tooling costs when compared with that of an autoclave which makes it possible to produce huge, complex parts at a time at lower costs. Approximating the net shape of the component, preforms are used in RTM and VARTM processes. Reinforcements are built outside the mould in the form of preforms for better quality components. Various automated preform processes are available such as braiding, AFP (Automated Fibre Placement). While manual layup can allow for a high degree of detail in preform manufacturing, automatic processes have proven to be more economic and less prone to human error during the critical pre-mould steps. The latest method is oven curing of prepregs. Specially designed prepregs are available for oven curing. Prepregs offer significant savings in terms of production cost and time compared to other methods. The high-quality aerospace components are made using carbon epoxy prepregs to achieve autoclave quality using a conventional oven. Oven curing doesn't require finishing costs and have reduced weight and improves the surface finish of the final component. Some of these prepregs are certified for use in aerospace manufacturing. These prepregs can be cured at lower temperatures. Excessive bagging material should be used in the autoclave to avoid its puncture during an autoclave process. Almost 25% of the overall cost can be reduced using OOA processes. The tooling is easier and less expensive to fabricate as well as using OOA processes. The surface finish is comparable to those achieved using the autoclave. The amount of surface porosity has been reduced, which reduces the post-operation time for producing high grade painted surfaces. "The Degree of impregnation" is important in oven curing than in autoclave prepregs, and the impregnation must be carefully controlled. If low viscosity resins are used, during curing the resin can flow easily and can lock the escape paths for entrapped air. This is crucial for OOA processing. When compared with an autoclave these gases will dissolve in the resin as the autoclave pressure acts on it. Latest prepregs are being developed for low-temperature oven curing which produces fibre volume equivalent to that of the autoclave cured parts and can achieve almost zero void content. OOA processes are not only cheaper and faster, but manufacturers also have optimized them for greater manufacturability and reduce secondary processes. Complex shaped parts can also be made using them.

4.3 Complex geometry

Complex composite structures contain curvatures and other features which complicate the layup process consolidation process. These introduce new challenges which are not observed in flat panels. The problems are shown below in Figure 5.

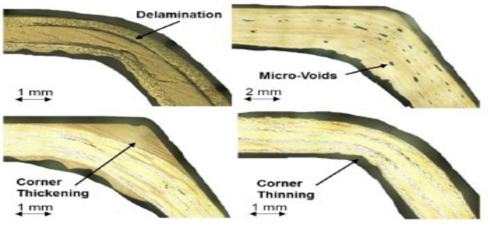

Figure 5. Problems in complex composite structures

4.4 OOA prepregs

New types of prepregs have been introduced for the OOA process. By using these types of prepregs it is possible to achieve parts with quality almost equivalent to that of the autoclave parts using the VBO process. These materials prevent the use of autoclaves and can be compatible with lower cost set-ups. The defects which are incurred in autoclave manufacturing can be eliminated in this process as low cure pressures are supplied during VBO curing of the composite laminate. Even honeycomb core composites can be cured in this, unlike the autoclave where honeycomb core crushes under autoclave pressure [51]. The prepreg formation is shown in Figure 6.

Figure 6. Prepreg formation

Earlier VBO prepregs were fabricated for low initial cure temperatures only (~70°C) and then followed by high post-curing temperatures, and were used for lower production rates [52-54]. There are three major drawbacks in using these prepregs:

- High porosity composite parts due to inconsistent resin flow [55].
- Only about a week allowable room temperature storage times [55,56].
- Low mechanical performance (mainly in toughness) compared to autoclave cured parts [55,56].

So to cope up with these drawbacks of prepreg resins for the VBO process, advancements in understanding resin chemistry and properties of matrix enabled the researchers to develop a new type of VBO resin systems. When resins can be impregnated properly with fibres, the parts processed from such prepregs were comparable with autoclave parts in terms of mechanical performance, porosity and out-times etc. [51, 57 & 58]. Several such aerospace grade resin systems are shown in table 2 [59].

Table 2. Current generation aerospace grade OOA prepreg resin systems

Prepreg Manufacturer	Resin family	Type of Resin	Description	Typical applications	NCAMP certified
Hexcel	Hexply M56	Epoxy	High-temperature performance from OOA cure, low density	Primary and secondary structures in commercial aircraft and military jets	No
	8552	Epoxy	Preferred product for aerospace structures	Structural parts for commercial aircraft, military jets and space applications	Yes
Cytec	MTM45-1	Epoxy	Medium temperature moulding toughened epoxy	Secondary and tertiary structure for commercial aircrafts	Yes
	5320-1	Epoxy	Toughened epoxy and have increased out-life	Primary structure applications	Yes
	EP2202	Epoxy	Specifically for vacuum bag	Fabrication of aerospace structures	Yes

			autoclave cure for high strength and stiffness	and tooling substrates	
Toray	TC250	Epoxy	Specifically for OOA cure for structural applications requiring high strength and stiffness	Fabrication of aerospace structures and tooling substrates	Yes
	BT250E-6	Epoxy	Specifically for OOA cure for structural applications requiring high strength and stiffness	Fabrication of aerospace structures and tooling substrates	Yes

4.5 NCAMP certification for prepregs

NCAMP[1], works together with FAA (Federal Aviation Administration) and industry partners to qualify material systems and can be viewed publicly.
Aircraft manufacturers can take information from their database about material systems to be used by them and can prove equivalency and can gain FAA certification in a quicker and cheaper way than a typical qualification approach [59].

Materials that are currently NCAMP certified

- Hexcel 8552.
- Newport NCT4708.
- Cytec MTM45-1.
- Toray TC250.
- Cytec 5320-1.
- Cytec EP2202.
- Toray BT250E-6.

The removal of air which is entrapped between the layers of prepregs during the lay-up process will result in low porosity VBO cured parts. VBO prepregs are “breathable”, featuring both resin-rich areas and dry areas [60]. The entrapped gases migrate towards the edges of the laminate during the processing of lay-up and when temperatures are elevated, the resin tends to flow into these channels and make it a void-free part. The entrapped gases should be able to escape out through the prepreg laminate into the breather film, so the boundary of the vacuum bagging assembly should be permeable and connects the breather and composite laminate without excess resin flow. Edge breathing dams (Figure 7) are also present for in-plane gas evacuation. To separate the laminate and the breather, release films (perforated or non-perforated) or peel plies can be used. A typical VBO layup is shown in Figure 8.

This type of prepreg doesn’t mean faster production rates as the extraction of the air that is entrapped is a time taking process. OOA prepregs require slow ramp rates as it reduces the resin viscosity if faster ramp rates are used and due to this resin can penetrate through the fibres quickly, due to which removal of air from the laminates becomes difficult. Many factors

[1]NCAMP-National Center for Advanced Materials Performance

affect the amount of void content in VBO cured parts. Nutt et al. systematically studied the effects of relative humidity in the formation of voids in VBO cured parts [61].

The OOA prepreg materials available right now in the market are at almost the same cost as autoclave prepreg materials. By taking into account the reduced manufacturing and operational costs of the OOA composite laminates, these OOA prepregs could be better compared to existing standard prepregs.

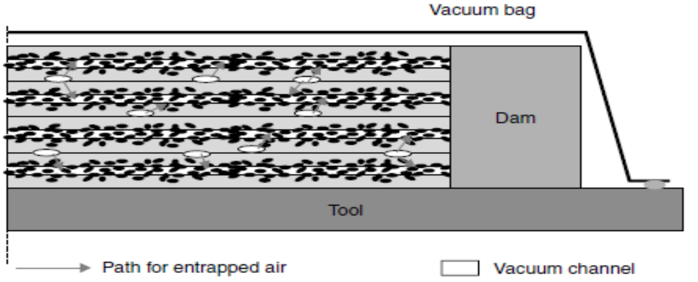

Figure 7. Edge dam principle (Evacuation of entrapped air from VBO prepreg)

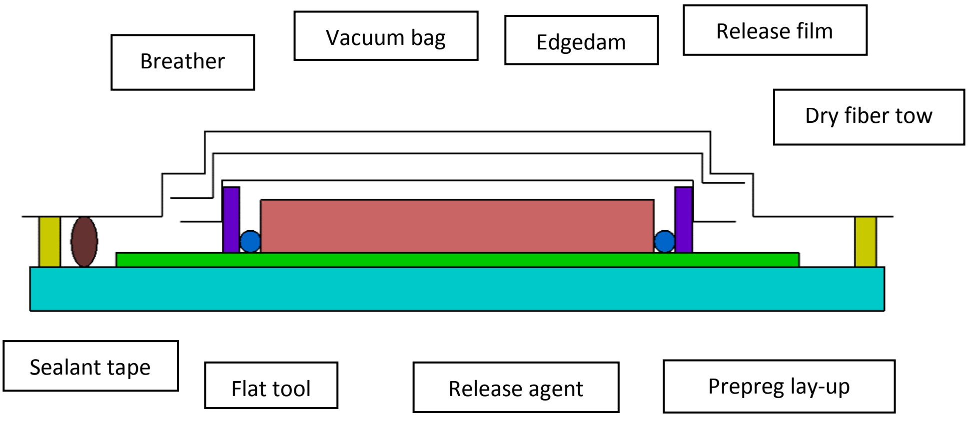

Figure 8.VBO layup schematic

5. OVEN CURING

The main idea behind the OOA process was to eliminate high-pressure curing so that we can use more cost-effective equipment with low operational and maintenance costs. Usually, thermoset resins can only be used for VBO processes, not thermoplastic resins due to low-pressure curing cycles [6]. The main areas in the industry where the oven curing process is used frequently are:

- When pre-impregnated materials (Prepreg) are used in the VBO process.
- LCM (Liquid composite moulding) processes in which the Thermoset resin system is infused with the fibre preform.

The principle of heat transfer of both autoclave and oven processes are the same. They are based on convection heating. The medium of heat transfer is different in both processes. Compressed nitrogen is used in the autoclave and normal air will be used in oven curing. Slowly ramping up the temperature in the oven will reduce the risk of exothermic reactions. Figure 9 shows a convection oven for composite curing. Table 3 shows the pros and cons of convection oven curing. Advanced ovens are coming into existence which has many attachments: [62]

- Combined airflow and having nozzles to direct the airflow to a specific area of the work piece for complex parts.
- Vacuum and thermocouple ports.
- Auxiliary cooling aids such as dampers.
- Number of work pieces processed.

Figure 9. Convection oven (Source: aschome)

Table 3. Pros and cons of convection oven

Pros	Cons
Very easy to use	Long process time (especially cooling)
A large number of parts can be cured per cycle	The rate of heat transfer is lower than that of an autoclave
Lower cost material	Limited space
Skilled labour is not required	Relatively high energy consumption
Longer out-time	

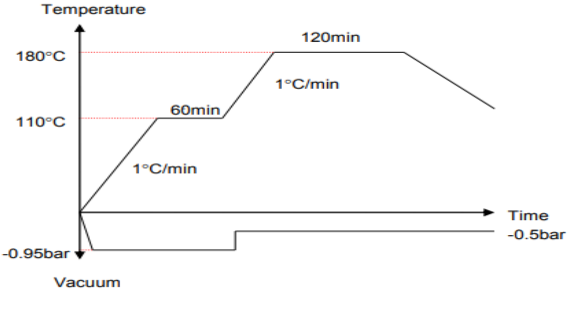

Figure 10. Cure Cycle for Out-of-Autoclave Process Hexcel M56 (Source: Hexcel)

6. FUTURE SCOPE IN OOA MANUFACTURING

For the performance of aerospace composites, the fibre volume and void content fraction are important. Autoclave processing is the main method qualified for Tier 1 aerospace component manufacturing. But they are expensive to operate and they limit the component size. We cannot make any adjustments in its process like in tooling configuration or vacuum bagging. Slower cycle times, as well as labour intensity, limit the production volume greatly. There are many more practical barriers in the future. The available autoclave capacity could be out spaced due to the projected growth of aerospace composites. A large number of autoclaves cannot be run to cope up with aerospace components manufacturing. Aerospace companies have not bothered about the cost of running autoclaves in past times, but as autoclave use expands into other parts of an aircraft such as primary structures, the cost of operating them will become an influential factor for aerospace companies. Additional pressure is required in the traditional prepreg process to produce composite laminate with desired ply orientation and lesser void content. But VBO prepregs have an improved resin matrix system which facilitates better flow characteristics, due to which void content will be less in the resulting laminates. VIP (Vacuum infusion processing) is advancing in the composites world and had been qualified globally for high-performance aerospace manufacturing [63].

We can consolidate the fibre pack in the VIP process before the introduction of the liquid resin. This is the fundamental advantage of the VIP process. After the de-bulking of dry laminates and evacuation of the atmospheric gas from the tool cavity, micro voids can be reduced greatly in the composite. We can produce a laminate with acceptable void content for high-performance applications by enabling an atmospheric-pressure vacuum bag. This process is known as dry-fibre pre-consolidation. OOA processing reduces both tooling costs and expenses for autoclave processing. Further, we can tune up processes for specific applications according to our requirement. The performance/cost ratio is required for sustainable growth within the industry and it is moving forward.

The importance of OOA processing:

- VIP is used for high-end aerospace structural applications to those manufacturers who cannot afford autoclave curing.
- VBO processing can be done by a number of moulders and can be used extensively even in the aerospace industry.
- It allows the use of composites for various applications.

Ultimately, OOA methods help the aerospace industry by implementing faster and cost-effective methods. There will be no shortage of customers for composite aerospace products if the price is right. This can be achieved by advancing OOA processing.

7. CONCLUSIONS

This review briefly presents the fabrication techniques for advanced composites using non-autoclave techniques. A new oven cure vacuum bag OOA process was reviewed for the manufacturing of aerospace composites. VBO prepregs and LCM processes allow the manufacture of autoclave-quality parts using the VBO process and convection oven curing. Special types of prepregs are being used so that void-free composite laminate can be fabricated. High-performance carbon composite laminates were manufactured using these non-autoclave techniques. Convection oven curing techniques can be used to produce parts that reduce operating costs drastically when compared to those produced using the autoclave techniques. From this review, we can say that non-autoclave techniques can be very promising in fabricating aerospace components that have qualities comparable to autoclave manufactured components. The OOA process can be expanded in several ways in the future to manufacture complex parts which result in cost reductions.

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