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P171

Process selection for production scale-up	
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Overview[edit | edit source]

This document provides a summary of recommended factors to consider when selecting a manufacturing process to use for production of industrial grade composite parts. The following composite manufacturing processes are referenced in this document:

- A293
- Hand layup prepreg (Autoclave/Out-of-autoclave) processing
- Vacuum assisted resin transfer moulding (VARTM)/resin infusion (VARI)
- A184
- A298
- Filament winding
- A300

Many different criteria must be considered when selecting an appropriate manufacturing process for a composite component. The relative importance of each will depend upon the functional and other design requirements of the part, which should be used to determine their weighting in the decision making process.

Part geometry considerations[edit | edit source]

Dimensional tolerances[edit | edit source]

Manufacturing process selection has a strong influence on the practical limits of dimensional tolerances that can be achieved. Highly manual layup processes in the production of open-moulded parts yield the least dimensional control and repeatability. The best dimensional tolerances are obtained from processes that use two-sided rigid tooling. Examples include conventional A293 which typically use clamshell metallic (steel or aluminum) moulds.

The most dimensionally accurate composite processes are capable of producing parts with tolerances of 0.005" to 0.010". This is close to those expected of CNC machined metallic parts.

Thickness[edit | edit source]

Any component with a section thickness of 1” or greater can be considered a relatively *thick* composite part. With Vacuum assisted resin transfer moulding (VARTM)/resin infusion (VARI) type processes, as part thickness increases, it becomes increasingly more challenging to achieve complete filling of the mould and good resin wet out. This consideration applies to A184 and other similar manufacturing methods which are based on infusion of liquid resin under relatively low process pressure differentials. When fabricating thicker parts with these processes, special consideration must be given to the choice of material. The use of high permeability fiber mats and low viscosity resins is recommended to facilitate production of thick parts without dry spots or other processing defects.

Size (Surface Area)[edit | edit source]

Resin dryness issues may be experienced with larger parts in general when using two-part thermoset resins in Vacuum assisted resin transfer moulding (VARTM)/resin infusion (VARI) processes or open moulding with hand layup. This is due to the large surface areas to be wet out and the long process times required. Working time for these resins is limited by the fact that the viscosity starts to rise continuously after the individual components are mixed together. Once a certain period of time has passed the resin will become too viscous to work with, eventually gelling. At this point it no longer suitable for hand laminating or to properly flow through the fiber mat in an infusion process. Attempting to continue processing will result in dry spots in the final part. The working time of the resin therefore places a practical limit on the size of parts than can be produced. With Vacuum assisted resin transfer moulding (VARTM)/resin infusion (VARI) processes, wet out problems may be mitigated to some extent by adding additional resin ports so that the resin can more easily reach all areas of the part, or by adding flow media to facilitate better resin distribution over the surface.

Additional considerations related to part size and its impact on tooling and equipment costs are discussed in a next section.

Curvature and Complexity[edit | edit source]

There are varying degrees of conformability and drapability limitations when working with different styles of fabric reinforcements. In order to conform over complex surfaces it may be necessary to dart or splice material at strategic locations. This adds to the number and complexity of process steps involved in composite production, which in turn impacts the overall processing time and cost. See A301.

Complex parts with many small features are generally better suited to processes that use two-sided rigid tooling. Material options for these types of components may be limited to those with non-continuous reinforcements (chopped fibers, particulate) as it may not be possible to conform continuous fibers or fabrics to the desired shape without defects such as wrinkling or fiber fracture.

High pressure processes, for example Resin transfer moulding (RTM) and Compression moulding, are capable of producing tighter corner radii due to the compaction forces provided by the tool/part interaction. Attempting to achieve tight radii with processes that provide insufficient compaction in areas of curvature can lead to defects such as fiber bridging, resin rich pockets, and voids localized to the corner regions.

Ultimately, the limits of achievable radii in a specific part may depend not on process parameters, but material. Since glass and carbon fibers are brittle by nature they will fracture if forced around very small radii (i.e. less than 1/8"). For non-structural parts, this may not be a concern, and it may be acceptable to have some degree of fiber fracture in corner regions as long as all applicable aesthetic and geometric requirements are satisfied.

A consideration specific to filament winding is that this process can only accommodate convex part geometries. It is not possible to produce concave features via winding. This type of feature geometry will lead to fibers bridging over the shape as material is wound around the rotating mandrel.

Pultrusion processes also have unique limitations. These processes can only be used to manufacture parts that are designed with a constant cross-section.

Monolithic Laminate vs. Sandwich Structure[edit | edit source]

All composite processes listed above can be used to fabricate monolithic (solid) laminate parts. In the majority of cases, these processes can also accommodate the inclusion of cores to create sandwich structure components. However, there are limitations on the types of cores than can be used with certain processes.

Structurally weak core materials cannot tolerate high pressure processes such as RTM, autoclave cure, and compression moulding. The core will become crushed if it lacks sufficient compression strength to withstand the processing conditions.

Open cell foam and honeycomb cores are not typically used in liquid resin processes (e.g. RTM, Light RTM, closed cavity bag mouding, open moulding) unless advance preparation steps are carried out to seal off the open cavities. Otherwise, these cores become filled with resin, which adds to the weight of the final part and thus negates the weight savings benefit of a composite design.

See Sandwich Panels for more information on the constituent materials, design, fabrication, and quality control of sandwich panels. The manufacturing processes and common use for honeycomb, wood, and foam core materials are discussed in Cores & inserts.

Mechanical performance considerations[edit | edit source]

The strength and stiffness of composite parts are largely due to the fiber component, with the resin acting as a binder to transfer load between fibers. The fiber volume fraction (amount of fiber versus resin in the part) and fiber orientation (whether or not it is aligned with the direction of applied mechanical stress) are therefore critical to structural performance. Manufacturing process selection can have a significant impact on the achievable limits of fiber content in a part and the amount of precision with which fiber content and orientation can be controlled during fabrication.

Required Fiber Content and Tolerance for Voids[edit | edit source]

High pressure processes including RTM, compression moulding, and autoclave cure are capable of producing higher fiber volumes. This is due to the external compaction pressures that are applied to the part during processing. This compaction facilitates thorough wet out of the fiber with resin and ensures intimate contact between plies if using a layered material. It reduces the chance of forming internal air pockets or voids and squeezes out excess resin from the part.

Prepreg-based processes provide a high degree of control over the fiber volume fraction of manufactured components. Prepregs are intermediate material forms that incorporate both resin and reinforcement into a single product. The resin to fiber content of these materials is usually strictly controlled by the material supplier, and the final fiber volume fraction of fabricated parts is largely influenced by the predetermined ratio in the prepreg going into the process. This makes it more controlled and predictable compared to many other manufacturing methods. In other processes, the fiber and resin are introduced as separate components and combined during the processing to create a composite. Many different factors can influence the outcome of these processes including measurement errors when weighing separate components, amount of excess resin being drawn out of the part through vacuum lines, and resin that becomes captured within flow media and other process consumables.

On the low end, processes such as open moulding may achieve only 20% to 30% fiber volume fraction. On the high end, processes such as high pressure RTM and autoclave cure of prepreg can result in fiber volume fractions of up to 70%.

VARTM type processes may require flow media layers within the reinforcement fiber mats to facilitate good resin distribution. This further reduces the effective reinforcement fiber volume as the flow media are typically materials such as loosely comingled, random oriented, thermoplastic fibers which have low mechanical strength and do not appreciably add to the mechanical performance of the part. Since the flow media layers are designed to be lofty and low density to facilitate resin flow, they become filled with resin and form resin-rich areas in the final part. This can create a preferential location for structural failure initiation and cracking and limit the ultimate observed mechanical performance.

The following table shows the expected range of fiber volume fractions for different composite manufacturing techniques and different fiber architectures (source [1]):

	Fiber volume fraction (%)					
Manufacturing technique	Random mat		Woven roving		Unidirectional and multiaxial	
	Min	Max	Min	Max	Min	Max
Spray-up	10	20	...	...	...	...
Hand lay-up	10	20	25	40	40	50
Vacuum infusion	20	30	40	50	50	65
Resin transfer moulding	20	30	40	50	50	65
Prepreg compression moulding	...	...	40	55	50	70
Filament winding	...	...	...	...	50	70
Pultrusion	20	30	40	55	50	70

Fiber Orientation[edit | edit source]

With filament wound components, it is not possible to place fiber reinforcements along the zero degree or longitudinal direction. This is due to physical limitations imposed by the material lay down process. However, slightly off-axis wraps of fiber may be done.

Fiber format[edit | edit source]

Continuous reinforcements, such as those found in unidirectional and fabric material forms, provide better mechanical properties compared to discontinuous reinforcements, including chopped fibers and particulates. Some processes are limited in the types of materials that can be used. For example, spray up (a form of open moulding) is only used to produce parts with discontinuous reinforcements.

Thermal performance considerations[edit | edit source]

Required Thermal Properties[edit | edit source]

Curing at higher temperatures typically results in better thermal performance for a final processed part. This includes a higher glass transition temperature (Tg) and lower rate of degradation of mechanical properties when exposed to hot environments.

For some processes an even higher post cure temperature may be required to achieve optimal properties. This is performed after initial cure and may be conducted either with the part on the tool or with it removed from the tool and placed in a freestanding condition.

Material Temperature Limitations[edit | edit source]

The cure cycle for a component is typically determined based on resin cure kinetic properties. However, the maximum allowable cure temperature can be limited by other factors. For example, some types of core and fibre materials used in composite fabrication have low melting temperatures and are therefore incompatible with high temperature processing.

Tooling material selection may also limit cure temperature. Certain types of tooling foams as well as wood based (e.g. MDF) tooling can only withstand lower temperature cures without risking degradation or warping.

Production quantities and rates considerations[edit | edit source]

Production volume[edit | edit source]

Some manufacturing processes are preferred for mass production (thousands of parts) while others are better suited to low scale production rates (hundreds or less). The main factors that determine this are the associated cycle times and costs. Although all composite processes can be used to make small quantities of parts, they may not be economically practical for all products. The cost of certain processes may be prohibitive without sufficient production quantities over which to amortize non-recurring expenses such as equipment and tooling.

Cycle Time[edit | edit source]

Processes that lend themselves to high degrees of automation, including RTM, press moulding, and pultrusion, tend to have shorter cycle times compared to highly manual processes, such as open moulding. These automated processes can have per part cycle times of one minute or less. However, the single process step of laying down material over a mould using an involved manual method such as prepreg hand layup or open moulding may take several hours to days. This significantly impacts the number of parts that can be produced in a given time period.

Overall part cycle time is also highly influenced by factors outside of process selection i.e. resin choice as this determines cure time/temperature and cure (crosslinking for thermosets, melt/solidification for thermoplastics) is often the longest step in the composites manufacturing process.

Certain processes allow for processing of parts in batches. With proper mould design several parts can be layed up and cured using a single mould/process cycle. This effectively lowers the cycle time per part where mass production is needed. Pultrusion is unique in that they are continuous production processes. Parts can be continuously processed and cut off at the required length (i.e. window frames, architectural railings). This can be a very rapid method of producing simple geometry parts.

Setup time[edit | edit source]

Aside from cycle time, machine setup time for a process should be considered as it will have an influence on overall production rates. This can be significant for shops requiring frequent change over in the types of parts being produced rather than doing large runs of the same component.

Cost considerations[edit | edit source]

Per part-labour, materials[edit | edit source]

The majority of processes use liquid resin and dry fabrics or rovings as inputs. These are relatively inexpensive material forms. Prepreg used in autoclave processing is more costly as it requires more intensive processing on the part of the material supplier.

Injection moulding and RTM have a low cost per part for mass production as they are highly automated. The incremental cost per part for labour and materials is low. If tooling and equipment is amortized over a large number of parts then it can be very cost effective.

Pultrusion, being automated continuous processes, is also inexpensive on a per parts basis.

Open moulding, manual prepreg layup, disposable bag infusion are labour intensive. Lots of hands on work is required to lay up the materials in the mould and for other setup tasks such as vacuum bagging or placement of flow media. This raises the per part cost. These types of processes require a skilled workforce and sizable investment in training to produce high quality parts.

Tooling[edit | edit source]

Generally with composites a custom tool is required for each unique part geometry.

The cost of tooling depends on several factors. This includes complexity of part geometry, material (MDF, foam, composite, metal, etc.) and the tolerance on surface accuracy.

Robust tooling required for autoclave, RTM and injection moulding processes is generally expensive. This can make it impractical for larger parts. These types of tools can range in cost from a few $1000 for smaller parts to $100,000+ for larger components.

Lower cost tooling can be used for open moulding, Light RTM and disposable bag infusion. Composite, MDF or foam tools can be used depending on the number of process cycles it needs to withstand (prototype or low volume production vs. high volume tooling). This option can practically accommodate larger components.

Capital equipment[edit | edit source]

RTM, injection moulding, and autoclave cure have high initial start up costs for companies due to the large investment in capital equipment. High pressure presses used in RTM, autoclaves used in some prepreg processes, are expensive. The size of available equipment can limit part size.

Aside from capital cost, operating cost can be significant for autoclaves due to the consumption of energy and need for supply of an inert gas such as nitrogen for pressurization.

Very little capital is required for open moulding and it can be done with simple hand tools and trained labour. Disposable bag infusion and Light RTM have moderate requirements.

Consumables[edit | edit source]

Autoclave cure uses vacuum bagging materials (breather, release film, outer bag, edge dams) that are typically disposed of after each cure cycle. Disposable bag infusion also has a high amount of disposable consumables including outer bag, flow media, resin channels, etc. which are used to create a vacuum cavity and facilitate resin flow. The disposable nature of these process materials generates large amounts of waste and increases the per part production costs. Reusable bag moulding results in less waste than disposable bag infusion; with proper care a silicone bag can typically be used for hundreds of parts before needing replacement.

Surface finish considerations[edit | edit source]

Aesthetics[edit | edit source]

Processes that use rigid tooling (metal, composite) in contact with the part surface during cure produce a smooth surface and aesthetic finish. RTM, compression moulding, injection moulding, and Light RTM use 2-sided rigid tooling and produce parts with 2 “good” surfaces. Often these parts require no extra finishing after demoulding. Other processes such as wet layup, closed cavity bag moulding, or VARTM use a rigid tool on one side and semi-rigid or flexible covering opposite (thin fibreglass countermould or reusable silicone bag or disposable polymer bag). These processes produce parts with one aesthetic surface (A-side) and one rough (B-side) surface. The B-side of parts made with reusable bag moulding are smoother than those made with disposable bag infusion (there is no leftover flashing from pleats and wrinkles) and requires less post processing. The worst surface finish is on the back side or B-side of open moulded parts as there is no control on the appearance or geometry.

Surface coatings (Gelcoats) that improve surface appearance and/or chemical resistance can be applied in mould in some processes (RTM and Light RTM) and cured with the part. This reduces the manufacturing process steps otherwise required to prepare the surface (sanding or grit blasting) and apply the coating as separate steps after cure.

Mating Conditions[edit | edit source]

Part surfaces cured on rigid tooling are more smooth and flat and have better geometric tolerances, making them better suited to mating with connecting parts. Often these can proceed to assembly stages with few or no additional process steps for prepare them. B-side surfaces that will later be bonded may require significant machining/sanding to bring them into dimension tolerance for thickness, flatness, etc. Cauls/pressure pads may be used to improve B-side surface smoothness in some processes with only one-side rigid tooling. For example they can be placed between the bag and part in vacuum bagged autoclave cure parts.

For parts that contain multiple mating surfaces, i.e. interface to multiple other components in an assembly, 2-sided tooling is best to control tolerances and ensure proper fit up with other components. 2-sided tooling is recommended if opposite surfaces are required to be highly parallel.

Quality considerations[edit | edit source]

Quality Control Requirements[edit | edit source]

Quality control requirements vary by industry and part type. Aerospace, structural components (wind blades, vehicle frame) and aesthetic components (vehicle interior panels) have more rigorous requirements compared to non-structural parts without critical aesthetic requirements.

Repeatability[edit | edit source]

Highly automated processes, i.e., RTM and injection moulding, are the most repeatable.

Achieving high quality and repeatability in processes with lots of manual steps requires highly trained fabrication personnel. In manual processes, ply positioning, wet-out, and consolidation are completely dependent on operator skill.

2-sided rigid tooling yields parts with more consistent thicknesses than open moulding or flexible B-side covers.

Worker Safety and Environmental Considerations[edit | edit source]

Ergonomics[edit | edit source]

Size and weight of tooling may require special handling equipment. Tooling for autoclave based processes and RTM tends to be heavier as it must be built more robust to withstand high processing pressures. Heavy steel or invar autoclave tools are common. Composite or foam tools are lighter and easier to handle but less durable.

Manual processing of large parts, as in open moulding or setup for vacuum bag infusion may require workers to physically reach all area to lay down materials, or apply compaction to ensure resin wet-out. This can be challenging and require special platforms to be built to allow access to difficult to reach areas if the tool cannot support directly standing on it.

Chemical Exposure / Emissions[edit | edit source]

Low viscosity is preferred in many manufacturing processes to increase working time, resin flow, etc. This is typically achieved by using PE and VE resins with a high styrene content. The styrene acts as a solvent to keep viscosity low but is highly volatile and will evaporate into the atmosphere during processing and cure. In high enough concentrations these emissions can pose health and environmental concerns.

Closed moulding processes reduce worker exposure to airborne volatiles emitted during processing. Consideration is required for sufficient air extraction to limit the airborne styrene levels in open moulding processes using PE and VE resins. If exposure cannot be reduced to acceptable levels with general environmental controls, individual PPE may be required to protect workers. Always need to be cognizant of local health & safety and environmental regulations and follow appropriate measures when working with chemicals including resins.

Supply Chain and Lead Time Considerations[edit | edit source]

Tooling[edit | edit source]

Design and manufacture of tooling can take several weeks to months. Longer lead times are associated with complex metallic tools.

Material[edit | edit source]

Processes that use specialized materials can be significantly impacted by material supply issues. There may be a limited number of suppliers producing materials, and they may only be produced at specific intervals to meet demand, limiting availability. An example of this is the prepreg materials used in autoclave processing. These materials can have lead times of several months. However, common styles of dry fibreglass fabrics which are used in many processes including open moulding Light RTM and others are available on a continuous “off-the-shelf” basis from several sources.

Conclusion and Further Information[edit | edit source]

The selection of a manufacturing process for composite scale-up involves a careful consideration of various factors. Part geometry, dimensional tolerances, thickness, size, curvature, and complexity all should be considered to determine the most suitable manufacturing method. Mechanical performance, fiber content and orientation, along with thermal and aesthetic considerations, also contribute to the decision-making process. In addition, production quantities and rates, setup time, and cost considerations, including labor, materials, tooling, and equipment, significantly impact the choice of manufacturing process. Quality control requirements, repeatability, worker safety, and environmental considerations add additional layers to the decision-making process. Finally, the supply chain and lead time considerations for tooling and materials should not be overlooked. Given that a substantial portion of scale-up decisions and associated costs are made in the early stages of design and prototyping, a thorough assessment of these factors is crucial to guarantee the effective and streamlined production of composite components.

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References

1. ↑ [Ref] Hoebergen, Arlen; Holmberg, J Anders (2001). *Vacuum infusion*. Vol 21.

About

Help

Engineered materials (designed to have specific properties) made from two or more constituent materials with different physical or chemical properties. The constituents remain separate and distinct on a macroscopic level within the finished structure.

For polymer matrix composites (PMCs), resin refers to the matrix; the continuous material phase that binds the reinforcement together, maintains shape, and transfers load. Resins are divided into two main groups: thermosets and thermoplastics.

Permeability refers to the resistance to fluid flow through a porous material.

- Resin flow through fibre
- Gas flow through prepreg

In composites processing, viscosity is an indicator of how easily the resin matrix will mix with the reinforcement and how well it will stay in place during processing. The lower the viscosity, the more easily resin flows. Resin viscosity ranges considerably across chemistries and formulations.

By scientific definition, viscosity is a measure of a material's resistance to deformation. For liquids, it is in response to imposed shear stresses.

Thermosets are a class of polymer that undergo polymerization and crosslinking during curing with the aid of a hardening agent and heating or promoter. Initially they behave like a viscous fluid. During curing, they change from viscous fluid to rubbery gel (viscoelastic material) and finally glassy solid.

If heated after curing, initially they become soft and rubbery at high temperatures. If further heated, they do not melt but decompose (burn)

Comes in two parts: part A (resin) and B (hardener). When mixed, curing reaction starts and is not reversible.

Examples include epoxy or polyester.

A single unit of fibre reinforcement that cannot be separated further without breaking it. It often has a circular cross section that is formed by the dies used to create it or its precursor material. Many filaments are manufactured in parallel to produce a strand or tow. The number of filaments in a strand or tow is often references by how many thousands of filaments comprise the tow. e.g. an 18k tow is made up of ~18000 filaments.

Resin transfer moulding (RTM) involves loading a preform into a two (or more) piece, matched tool, closing it, and injecting resin under pressure (~15-100 psi, or ~1-7 bar).

Well suited to small to medium sized parts, limited to large sizes due to injection pressure loads and tool cost.

The individual materials that combine to form the composite material. The constituent materials are separate and distinct on a macroscopic level.

Volume fraction of either matrix or fibres with respect to total composite volume (matrix + fibre).

Pre-impregnated (prepreg) material refers to fibre that is already combined with resin. It is the most common material form used in aerospace.

During prepreg production, (e.g. fibres are run through a resin bath), prepreg is heated and partially cured to B Stage (< 5 % degree of cure). Thermoset prepregs (e.g. epoxy prepreg) have to be kept in a freezer at around -20 °C. At room temperature, the epoxy starts to cure.

Vacuum assisted resin transfer moulding (VARTM) - also known as vacuum assisted resin infusion (VARI), vacuum infusion process (VIP) or often just resin infusion. VARTM is a liquid composite moulding (LCM) closed mould process with a single side tool and vacuum bag where the resin is drawn through the preform using vacuum.

A class of polymer, some common examples include polypropylene and polyethylene.

They soften and melt upon heating (i.e. potentially recyclable), high viscosity when melted, therefore difficult to saturate fibres. Usually needs a lot of pressure and heat to process.

The glass transition temperature (T_g) is the temperature region where the polymer transitions from a hard, glassy material to a soft, rubbery material. It is one of the most important properties of any amorphous polymer.