LIQUID COMPOSITE MOULDING TECHNOLOGIES FOR SPACE APPLICATIONS

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OVERVIEW

Presently, with the usage of fibre-reinforced materials in aerospace, the use of preimpregnated fabrics - so called ‘prepregs’ – is on the rise. Preimpregnated fibre materials have the advantage that fibre angles can be very well adjusted thus allowing a good prediction of the structural strength. However, the drapability of the material strongly decreases due to preimpregnating and it cannot compete with untreated fibre semi-finished material. Consequently, if combined manufacturing of highly complex composite components is desired, injection technologies have to be used. An example is the DP-RTM (Differential Pressure Resin Transfer Moulding) method developed by the German Aerospace Center (DLR). This procedure allows the manufacture of high-duty fibre composites with outstanding mechanical as well as geometrical features, which are highly economical, since the costs of semi-finished material are significantly lower than those of the prepreg material. Apart from the laminate quality, attention must be paid on reducing the manufacturing preparation, the manufacturing steps and material costs so that it is also suitable for prototype or small-scale manufacturing.

1. MANUFACTURING OF COMPOSITES [1]

With the exception of filament winding structures, high-quality, continuous fibre-reinforced components are currently industrially manufactured following the prepreg method. However, due to rising production costs, research on the so-called Liquid Composite Moulding (LCM) method has been intensified since this method promises a significant reduction in manufacturing costs.

The production process is divided into the following sections:

1.1. Manufacturing Tools

These tools for the manufacture of a composite structure form a crucial factor for a reproducible production run. The investment costs depend primarily on design, size and complexity of the components. Above this dimensional accuracy and the serviceable life-span of a unit are further essential cost factors.

Principally, there are integral-milled metal tools and tools made from composites materials.

1.1.1. Integral Milled Metallic Tools

The advantage of integral-milled metal tools is their relative short term production process, being constructed directly from solid block material. The basis for the tool is mainly derived from a 3D CAD model, provided by the CATIA design software, which is used directly for the production of the milling program. Therefore complex 2D design models can be avoided. A further advantage is the high service life of metallic tools (more than 1,000 mouldings possible) and the possibility of repair by welding or soldering. A disadvantage is the high thermal capacity of metal tools. In order to heat up the composite structure, the manufacturing tools must be warmed as well, thus slowing down the heating process in general and requiring a greater amount of energy. Options include various materials, the most common ones discussed here briefly.

Aluminium:

Benefits are given by the simple and fast milling process. The high thermal expansion coefficient ($\alpha=23.8*10^{-6}\ K^{-1}$) is unfavourable compared to the coefficients of expansion of carbon fibre structures (approx. $\alpha=1*10^{-6}\ K^{-1}$). Results can include blocking and deformation of the carbon fibre structure in the mould.

Stainless steel:

The machinability is clearly more difficult than with aluminium. Likewise though, the manufacturing tool management is prone to difficulty since the density of high grade steel is approx. three times higher than with aluminium. The advantage of stainless steel tools is in the higher achievable surface quality. The resulting surfaces quality exceeds that of aluminium significantly. Moreover stainless steel tools can be used very well for RTM processes as well as for press moulding, due to their beneficial material properties.

Invar (Ni36):

Invar is an iron nickel alloy, which is characterised by a thermal expansion coefficient of approx. $\alpha=1*10^{-6}\ K^{-1}$ similar to carbon fibre structures. So, despite high thermal gradients, distortions are excluded, which otherwise might have negative effects on the part. The surface quality of the component is comparable with those manufactured in stainless steel tools. The disadvantage of invar, however, is the high price of the material.

1.1.2. Composite Materials With Carbon Fibre Reinforcement

The advantage of tools from carbon fibre composites compared to metallic tools is for once in the smaller thermal capacity. Hence shorter heating up and cooling down times in shorter autoclave cycles can be achieved. Likewise the tool treatment is simpler due to decreased density. Furthermore the thermal expansion coefficient, which is required for the production of the component, and the accompanying low costs make composite materials more efficient than pure metal tools.

Compared to metallic tools, composite materials, however, have the disadvantage of a reduced durabiltiy (300-600 mouldings), as with increasing age embrittlement appears and the wear increases with the increasing number of demoulding procedures. Repair of composite materials is more complex, since an absolute vacuum tightness is a prerequisite for excellent quality.

1.2. Manufacturing Preparations

First of all, the fibre semi-finished material is cut out on a computer numeric controlled rotary fabric cutter according to the given geometry. With the assistance of the CATIA ‘Composite Part Design’ tool, the flat pattern geometry can be generated. The control software of the cutter computes the optimal pattern from the different layers and positions in order to avoid possible waste of material. After this layout has been fabricated, the layers are draped into the tool in the desired orientation. This step can aided by a laser beam. The laser data may be derived from the CAD data generated before. Thus the exact positioning is ensured and the error rate is lowered, since the adjustment and positioning of all individual layers are clearly projected by the laser. The following steps are depending on the different manufacturing processes and hence are separately examined.

1.2.1. The Prepreg Autoclave Technology [2]

At present, the prepreg autoclave method is primarily being used for the manufacture of high quality composite components since it provides a very high and reproducible component quality, while requiring a moderate investment of tools. The high component quality is attained by compacting the prepregs (resin impregnated, continuous fibre products), in the autoclave. Simple tools are required because only single-sided supporting tools are needed, which have a flexible vacuum cover. However, prepregs are costly due to their specialised manufacturing process. In addition the lay-up process with prepreg is more complicated than with dry fibre material.

1.2.2. The Resin Transfer Moulding Method [2]

The Resin-Transfer-Moulding method was established in the past few years as an alternative to the Prepreg Autoclave technology. With this method, a cost-effective and non-impregnated fibre preform is placed in a massive mould, to which a low-viscous resin system is injected under pressure. Here the considerably lower costs of the semi-finished products are advantageous, when the manufactured quantity warrants the enormous investment costs for the vacuum-tight, temperature adjustable, pressure loaded, and often very complex and heavy moulds. Since a compacting of the laminate which is even and expandable in all directions is not possible in massive RTM moulds, a reduction in the quality of the laminate and fibre content must be expected.

1.2.3. LCM / SCRIMP Technology

A subtype of the LCM (Liquid Composite Moulding) technology is the SCRIMP method. In the SCRIMP (Seeman Composites Resin Infusion Moulding Process) method a flow aid is applied to the dry fibre perform that enables a quick distribution of the resin over the part’s surface during infiltration. As opposed to RTM methods, the infusion and curing process take place at ambient pressure. In contrast to classical LCM methods, the infiltration of the resin takes place perpendicular to the flat fibre reinforcement. Normally, a single-sided mould is further used here, which is sealed with a vacuum bag. Because of the low fibre compacting as well as uncontrolled resin distribution, the quality of the laminate is usually considerably lower than with the Prepreg Autoclave method.

1.3. The Autoclave Procedure

Inside the autoclave the heated resin system is injected via a resin infusion line at autoclave pressure into the component. Hereby the volumetric current of the resin and based upon this the impregnation status of the component is measured. For tools with a flexible, transparent vacuum bag, a camera is installed for further inspection, which provides information on the flow process of the resin. If the volumetric current at a certain adjusted differential pressure (FIG 1) is terminated and absorption is finished, the cross-linking of the polymer is activated by increase of temperature. After the given curing time specified by the manufacturer the component can be cooled down and be demoulded.

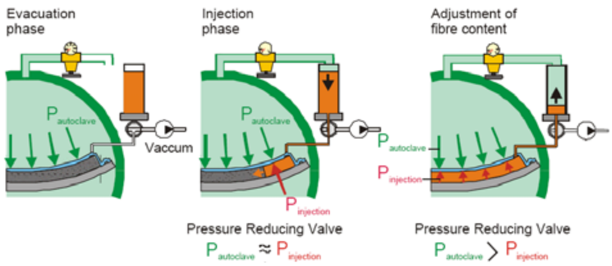

FIG 1. Adjustment of fibre volume content

1.3.1. The Differential Pressure Resin Transfer Moulding Method [3]

Via the DP-RTM procedure the dry synthetic material is inserted into an injection mould with the contours of the later component. Unlike the conventional RTM procedure, it works without the solid and pressure resistant moulds, as the closing pressure is not applied mechanically by the tools, but by the differential pressure of an autoclave. Thus the tool can be supported by a simple metal construction, since it is loaded only by the dead weight of the component inside in contrast to the common RTM-procedure. Subsequently, the lay-up is vacuum-tightly locked by a flexible upper shell. The most simple could be a vacuum-foil.

The set-up of mould and fibre lay-up has a resin injection conduit besides a vacuum conduit, where a permanent negative pressure is exerted over. Reaching the desired temperature in the autoclave, the resin is injected into the component via the infusion line. Due to the permanent negative pressure over the vacuum conduit, also resin systems, which tend to outgassing during the injection process, can be used. Thus there is no risk of solvent evaporation into the component or weakening of the structure itself. After the component has been filled with the resin, the vacuum conduit is closed, and the pressure on the resin conduit is generally decreased below the autoclave pressure. Consequently, the fibre volume content of the component is controlled via the pressure differential between autoclave and resin line (FIG 1).

1.3.2. The SLI Procedure [3]

The SLI procedure is an optimised version of the DP-RTM-procedure and is suitable for prototype and small-scale manufacturing up to approx. 500 items. The additional vacuum conduit, which exerts a permanent negative pressure, is replaced by a cavity in the structure. The resulting advantage: the flow process of the resin in the component occurs as precisely as planned, and therefore there is no exhaustion of resin through the vacuum conduit. Moreover the efforts are minimised as only one conduit has to be attached to the component.

2. APPLICATION OF THE LCM TECHNOLOGY

During the past ten years more than 5,000 parts have been successfully manufactured with the LCM Technology. Most of the structural parts were designed as highly integrated monolithic or sandwich structures. In case of the sandwich structures, Rohacell PMI foams showed the best structural performance and can be worked in 180°C production processes after being appropriately tempered. The high degree of compressive strength of medium weight PMI foams makes it possible to apply autoclave cycles with more than 0.5 MPas at temperatures of 180°C, meaning they are suitable for standard prepreg and SLI production cycles [4].

2.1. The OOV-Project (On-Orbit Verification Deployment Experiment)

Within the “Solar Sail” project the DLR Institute of Composite Structures and Adaptive Systems was responsible for the manufacturing of the boom structure now used for the On-Orbit Verification Deployment Experiment. The boom structure had extreme weight critical requirements, meaning that only the finest prepreg available was able to meet the demands. For the processing of this special prepreg a thermal expansion compatible tool had to be applied. The tools required for the manufacture of the big and extremely lightweight booms consist of several single parts, which are attached and aligned on a steel frame. Hence 14 m long components can be assembled.

In order to reduce the tooling costs, a CFRP tool manufactured using the SLI Technology was chosen, because the void free laminate quality ensured sufficient gas tightness and a smooth surface without any additional surface treatment.

2.2. Nose Landing Gear Door For The Fairchild Dornier 728 [3]

Based upon the experiences in manufacturing the „Solar Sail deployment module“ for ESA ESTEC and various Class III Fairings for the Fairchild Dornier Do 328 Jet, INVENT was able to assert itself against established international suppliers with the Nose Landing Gear Doors and the RAT (Ram Air Turbine) Door for Fairchild Dornier’s Do 728 regional jet. Right from the start the production of the very first component set confirmed that using a fibre semi-finished product with draping properties and a precisely prefabricated foam core with locally adapted densities is successful regarding production times and the costs of the semi-finished products. In case of the Nose Landing Gear Door and the RAT Door, the applied Rohacell PMI foam core is designed as a structural sandwich element and also as an effective manufacturing aid. In case of the Fairchild 728 the decision to use foam cores instead of honeycomb cores for this application was a sole customer requirement by a major airline. The contribution of the DLR Institute of Composite Structures and Adaptive Systems within the Fairchild 728 Project was the development of an effective tooling strategy where several components were simultaneously infiltrated.

2.3. Frame Structure

Within the FFS research program at the DLR Institute of Composite Structures and Adaptive Systems, a manufacturing concept for a double curved framework was developed. The frame structure is a connecting element for the fixation of a pressure membrane. For cost reduction, not only a manufacturing concept had to be developed, but tools to produce two symmetrical structures in one go. As the geometry of a double curved surface could not be realised with prepregs, a special mould was developed and optimised for the LCM technology.

With satin weave the complex geometry can be draped rather well. As a suitable manufacturing technology the SLI procedure was chosen since the flow front of the resin can be determined by integrated cavities. FIG 2 shows the dry synthetic fibre material in a metallic tool. The resin injection starts from the centre and ideally impregnates the lay-up according to the symmetrical arrangement.

FIG 3 shows the netshape components.

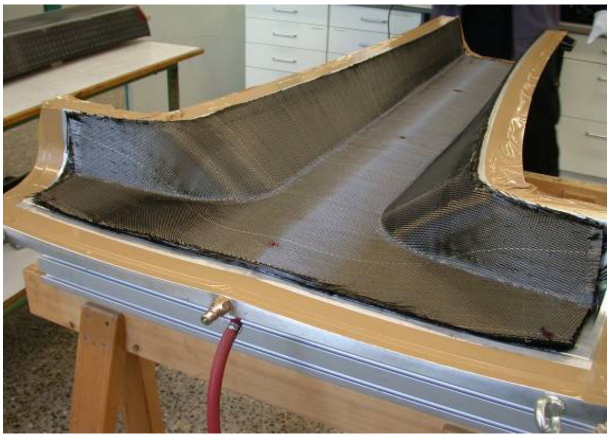

FIG 2. Complete lay-up with dry fibre preforms

FIG 3. Complex geometrical structure

2.4. Leading Edge

FIG 4 shows a front edge demonstrator with foam core. The demonstrator component represents a leading edge of an engine intake, manufactured with SLI. Here the unilaterally curved geometry, which shows a very strong curvature at the front edge, posed a great challenge for processing. In addition, material thickness at interior and exterior sides is irregular, hence synthetic material within defined ranges of the component ends. The material used for the demonstrator is a glass fabric with quasi-isotropic orientation. The dark areas on the outer side, which can be recognized in the picture, are polymeric inlays, which may not change their position during production. For the construction of the prototypes Rohacell foam was used, which was first stretched and then milled according to the outer contour. Afterwards, the core was wrapped in fibre preforms and surrounded with a u-shaped fibre preform. The lower web was formed by a further u-shaped preform. The body was inserted into the mould and consolidated via the SLI procedure. The final step included the exact trimming of the extruded profile on both front sides according to the prerequisetes.

FIG 4. Leading Edge

2.5. Holder

A further prototype, constructed by DLR, is a holder. The component (FIG 5) represents a curved outer contour with an integrated cover. The cover was manufactured along the same work procedure as the frame structure, therefore possesses an absolute form and appropriate fitting accuracy. The application possibilities for such a structure are enormous. Systems underneath such a closure head could be easily serviced without losing the aerodynamic properties of the surface.

FIG 5. Holder (front side)

FIG 6. Holder (back side)

3. ADVANTAGES OF THE LCM TECHNOLOGY IN RELATION TO THE PREPREG TECHNOLOGY

In the past prepreg materials were the first choice for highly-stressed composite structures because of the fibre orientation, the structures made like this achieved very good mechanical properties. The disadvantage of preimpregnated semi-finished material concerns the bad flexibility of the material. The drapability is significantly reduced by the introduced matrix material and therefore cannot be used for the production of complex geometries. However, untreated fibre synthetic material can be very flexibly arranged using special weaving patterns and so double-curved components can be manufactured. With an improved combination of materials (fibre and resin) nowadays, material properties are reached via the LCM technology, which exceed those of prepreg materials.

3.1. Cost Advantage

While analysing manufacturing methods, costs are of great importance. Especially the costs of constructing prototypes or individual manufacture are usually rather complex to predict. Experience and management play a special role, particularly for composite structures. The analysis of several manufacturing methods must be case-related and is discussed here via the example of a small-series component.

	cost driver	ratio	complexity
1.	mould	4%	Write off (5J)
2.	fibre and resin	26%	Semi-finished material
3.	ply cutting	5%	Personal, Cutter write off
4.	lay-up and mould sealing	29%	Personal, expendable
5.	process attendance	6%	Personal, Autoklavcosts
6.	demoulding/ cleaning	15%	Personal, CNC-cost
7.	quality control	8%	Personal
8.	project management	7%	Personal

TAB 1. Relative production costs for SLI-procedures

The allocation of expenditure shows that during the composite material production with SLI technology, costs of personnel resources represent the largest proportion. In particular, the process sections ‘draping and sealing’ allocate nearly 30% of the production costs.

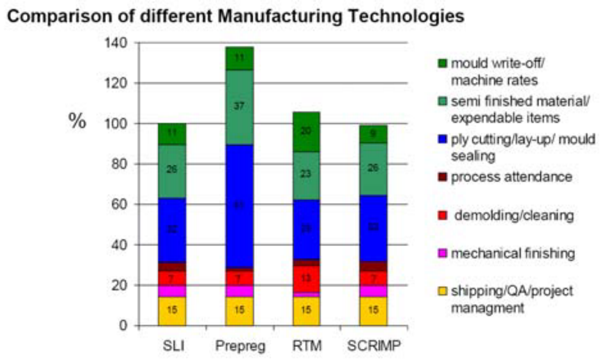

FIG 7. Cost Analysis of different composite manufacturing technologies

Comparing various production forms for composite structures components [FIG 7], it becomes obvious that the SLI technology and SCRIMP obtain the best cost advantage. The cost factor for ply cutting, lay-up and mould sealing with prepreg amounts to about twice as high as for LCM technologies. Next large cost difference is between semi-finished material and the expandable items, the prepreg processing exceeding the LCM technology by approx. 50 percent.

3.2. Material Properties

The comparison of various samples produced with LCM technology and two UD-Prepreg materials (FIG 8) illustrates that wet-technology-manufactured samples can reach the material properties of UD-Prepreg.

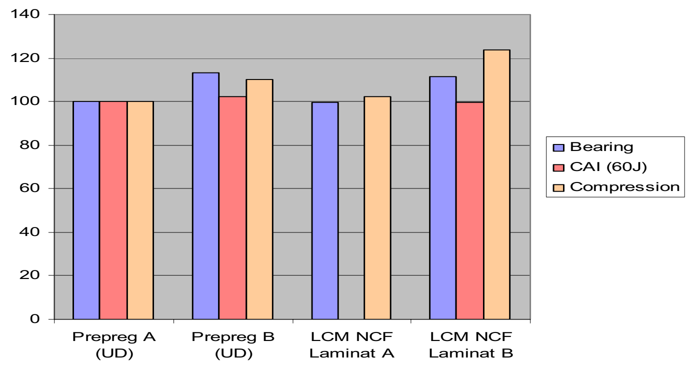

FIG 8. Compares strength coefficients

The samples were manufactured with a material thickness of 4 mm and examined according to AITM conditions. The figure shows that NCF laminates achieved equal or better values than Prepreg A in comparison at the bearing test; Prepreg B exceeded those values even. The comparison of the Compression After Impact (CAI) properties (LCM NCF laminate A was not tested) displayed that the values of the NCF material manufactured in LCM are only slightly lower than the prepreg properties. For the final comparison, the compression, the NFC laminate B rises clearly over all other samples.

4. CONCLUSION

It is not mystifying that particularly for aerospace, structures have to be very lightweight in order to minimise the costs caused by high weight - thus the preferences of the composite materials applications over metallic structures. Composite materials exhibit a higher lightweight construction potential in fibre direction than metals. The second important point is the firmness of the materials used. Pre-impregnated semi-finished materials have the advantage of very good fibre orientations in components produced while increasing manufacture expenditure, but the disadvantage due to the impregnation, which decreases the drapability strongly. Thus simple curved components, up to a certain bending radii can be easily manufactured, but if the radii extend largely the Prepreg is not an option unlike the LCM technology. Likewise the use of Prepreg should be avoided when producing double curved surfaces, since the geometry can be draped only roughly or not at all. With suitable choices of dry fibre semi finished material such surfaces can be draped nevertheless.

A further benefit of using LCM technology is the possibility of the high-integral manufacturing. Savings in costs and weight are possible, since apart from the minimisation by individual components, e.g. the number of bolted joints can be reduced. Especially when constructing space structures, attention needs to focus on the favourable allocation of the strongly limited volume. The dimensions are usually limited; hence it is efficient to integrate mounting areas in order to achieve maximal utility. A further starting point is the integration of components in necessary structures. Antennas can be integrated into the outer skin without additionally mounting plates, allowing one component to fulfil several tasks.

New material mating and improved production methods help already today that with planar components, the material properties are comparably with UD-Prepreg-samples or even further improved by NCF samples (manufactured in LCM technology).

5. REFERENCES

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