Cost Effective CFRP-Fuselage Manufacturing with Liquid Resin Infusion (LRI) – Technologies

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1 SUMMARY

A cost-optimised production method for high-quality fibre composite components developed at the DLR Institute of Structural Mechanics is presented here. The approach of the so-called Single Line Injection (SLI) method is to combine elements of established production methods with the goal of cost effectiveness at the best possible quality. The object of this presentation is the technological background, the essential steps of the production process and the experiences made during manufacture of large foam core sandwich Panels for the HGF fuselage demonstrator manufactured in SLI Technology.

2 THE POTENTIAL OF COMPOSITE MATERIALS

Because of their many applications in aerospace, fibre composite materials are also being used in other industrial branches and, as a result, their significance is steadily increasing.

![Fig. 1: Specific fibre Young's modulus and specific fibre tensile strength [ref. 1]](attachment:fig1.png)

This development is primarily due to the outstanding lightweight construction potential of the fibre composite materials which is based on the high specific stiffness and strength of the reinforcement fibres. In addition, further advantages for concrete applications such as uncritical fatigue behaviour, designable material properties, high resistance to corrosion and aggressive chemicals, free shape design, very good internal damping properties, or low thermal conduction can play decisive roles as well.

3 MANUFACTURING OF COMPOSITES

With the exception of filament winding structures, high-quality, continuous fibre-reinforced components are currently being industrially manufactured with the prepreg method. However, due to rising production costs,
research on the so-called liquid resin infusion method (LRI) has intensified lately since this method promises a significant reduction in manufacturing cost.

![Composite Manufacturing Technologies](image)

**Fig. 2: Composite Manufacturing Technologies**

### 3.1 The Prepreg Autoclave Technology [ref. 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 and curing the prepregs (resin impregnated, continuous fibre products), in the autoclave under specified conditions. 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 preparation process. In addition the lay-up process with prepreg is more complicated than with dry fibre material because the applied resin film is already activated and therefore difficult to handle.

### 3.2 The Resin-Transfer-Moulding Method [ref. 2]

The Resin-Transfer-Moulding (RTM) method has become established in the past few years as an alternative to the Prepreg Autoclave technology. In this method, a cost-effective, non-impregnated fibre preform is placed in a massive mould to which a low-viscous resin system is injected under pressure. The considerably lower costs of the semi-finished products are advantageous here 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 in all directions is not possible in massive RTM moulds, a reduction in the quality of the laminate and fibre content must be expected.

### 3.3 LRI / SCRIMP Technology

A promising subtype of the LRI (Liquid Resin Infusion) technology is the SCRIMP method. In the SCRIMP (Seeman Composites Resin Infusion Moulding Process) method a flow aid is applied to the dry fibre preform that enables a quick distribution of the resin over the parts surface during infiltration. As opposed to RTM and autoclave methods, the infusion and curing process take place at ambient pressure. In contrast to classical LRI
methods, the infiltration of the resin takes place perpendicular to the flat fibre reinforcement. Normally, a single-sided mould is also 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.

4 THE SINGLE LINE INJECTION (SLI) METHOD [ref. 3]

Since the quality and economical manufacture of fibre composite components play decisive roles in their successful introduction into the market, a manufacturing process was developed at the Institute of Structural Mechanics with the goal of producing high-quality fibre composite components with the best possible laminate and surface quality in a cost-optimised production process. The process was to be optimised for the production of small series and prototype components with a quantity of up to about 500 pieces per year since a great market potential is developing in the areas of aircraft, railway, and vehicle prototype construction.

4.1 The Principle of the SLI Method

The approach for the development of the SLI method essentially is to combine the advantages of the raw material of the liquid resin technology with the laminate quality of the Prepreg autoclave technology. The advantage of this method in comparison to the LRI method is that the resin is injected under pressure and that the laminate can be compacted by the autoclave pressure. The name of the method is an indication that the evacuation of the fibre preform as well as the injection of the resin system is carried out with the same resin transfer line. This resin transfer line can be arranged on the fibre preform in any arrangement to shorten the flow path and, with that, the injection time.

With the SLI method, it is possible to combine cost-effective and dry semi-finished fibre products such as fabrics, weaves, and warp knitted fabrics with the optimal matrix resin for each application. In addition to the standard epoxy resins, vinyl ester resins, polyisocyanurats (Blendur), heat-resistant resins such as bismalimide, cyanate ester and even phenolic resins can be processed. The excellent and void-free laminate quality achieved by the autoclave process leads to a superb component quality which almost reaches the status of a Class A surface.

4.2 Variation of the Fibre Volume Content

An additional characteristic of the SLI method is the possibility to directly influence the fibre content by means of the process parameters. This is possible because the flexible side of the mould enables the autoclave pressure...
to be in equilibrium with the inner resin pressure of the component and the restoring force of the fibre material. If the autoclave pressure is adjusted to be the same as the inner resin pressure, the fibre preform can relax in the thickness direction and can support the impregnation due to greater permeability. If the fibre preform is completely impregnated, the autoclave pressing on the fibre material can be selectively increased by reducing the injection pressure until the desired fibre volume content of typically 60% is reached.

**Fig. 4: Pressure distribution during injection and adjustment phase**

5  THE SANDWICH PRINCIPLE

The basic prerequisite for high-performance structural component parts as used in aerospace applications is light-weight design wherever possible. An essential component of these light-weight structures are load-bearing and buckling optimised shell elements. The classical method to obtain improved buckling properties is using monolithic stringers, although sandwich structures have also proven their worth in a number of fields. The performance of a sandwich structure depends primarily upon the efficiency of surface skins and the distance between them. A great distance between the surface skins produces a correspondingly great geometrical moment of inertia, thus leading to high bending stiffness. Since this arrangement subjects the core of the sandwich to a relatively small amount of stress, it can be reduced in weight significantly. Extremely thin-walled sandwich structures present the problem of how force is introduced and the sandwich structure’s sensitivity towards all kind of impact loads. This means that a minimum wall thickness is required for the surface skins to be able to ensure that it is adequate to the purpose. Beyond this, experiences in the use of sandwich structures in series applications show that it is necessary to take the entire life cycle into consideration when assessing the economic viability of sandwich components.

5.1  CORE MATERIALS

While the most important thing with the surface skins is stiffness and strength, the major factor with the core is keeping the mass down to a minimum. The core stress results from having to keep the surface skins at a distance to one another and providing buckling stability to the skins. This means that the core is primarily stressed from shear and sometimes compression. Honeycomb core materials made of aluminium or Nomex have the greatest potential for performance with regard to weight because they have an amazing compression modulus with minimum material use. Honeycomb core materials have established themselves firmly in aerospace applications and are generally used in combination with prepreg products. Some typical structural components are leading edges on the wing and empennage, landing gear doors and other access doors and all kind of fairings. In spite of the excellent potential for performance of honeycomb core sandwich structures, there is increasing demand among airlines for alternatives because of the high maintenance costs caused by
honeycomb cores in various applications. The reason for these higher maintenance costs is related to the fact that honeycomb cores may fill up with water under certain circumstances, for instance if the surface skins are porous. The water in the full honeycomb cells freezes and expands at low temperatures, which in terms damages adjacent honeycomb cells.

For maintenance activities that means that the honeycomb core components have to be inspected more frequently because they sometimes carry very significant amounts of water. The costs of servicing and repairing these components can diminish the positive aspects of the low structural weight to the extent that a heavier foam-core construction can be more economical over the component's total life cycle. A comparison shows the benefits and shortcomings of the various core materials.

5.1.1 Aluminium honeycomb:
Aluminium honeycomb cores have excellent compression stiffness with regard to weight because it can be manufactured with extremely thin walls. However, these thin walls may also lead to local buckling in the honeycomb surfaces especially with large honeycombs. Beyond this, the combination of aluminium and carbon fibres can produce contact corrosion if both elements are not electrically insulated. Honeycomb corrosion is a serious problem because inspecting the inside of a honeycomb component involves enormous expenditures. However, tapping the surface skins provides initial indications of the condition of a honeycomb core-sandwich component. Since metallic honeycombs satisfy the strict gas exhalation requirements of space applications, they are used more frequently. Of course, aluminium honeycomb’s FST (Fire Smoke Toxicity) properties are a positive characteristic.
5.1.2 Nomex honeycomb:
Nomex honeycomb cores consist of aramid “paper” impregnated with phenolic resin and can be found in a wide variety of applications. There is less of a problem with local cell buckling than with aluminium honeycomb because of the greater wall thickness. Furthermore, there is also no problem with contact corrosion because nomex honeycomb does not conduct electricity. However, a negative characteristic of aramide semifinished products is the fact that they are not resistant to UV light, although this is not a problem with honeycomb cores in lightproof casing. It also has positive FST characteristics because of its phenolic resin sealing.

5.1.3 PMI foams:
PMI (Poly(methacrylimide)) foams are also used extensively in aviation because they 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 suited to standard prepreg production cycles. The PMI foams approved for aviation have a very even distribution of closed-celled pores with their size remaining extensively constant. Its moisture absorption can be as much as 9% with unsealed foams, which is very detrimental. Moisture can produce great problems notably in production when the foam cores are not sufficiently dried. When working resins containing isocyanate (such as Blendur) moisture may even lead to matrix decomposition. If PMI foam cores are used in combination with Liquid Resin Infusion technologies the outside of the foam core is sealed with a thin resin film that effectively stops the water adsorption. The FST characteristics of PMI foams are fairly acceptable.

5.1.4 PVC foams:
The main feature of PVC (polyvinyl chloride) foams is the fact that they are comparably inexpensive. They are mostly used in aviation for building small aircraft where production strategies are mainly without autoclaves at process temperatures below 140°C. Gas exhalation should also be observed with PVC foams used in RTM Processes, because it may lead to porosities in the laminate of the surface skins. The fact that it has low moisture absorption and the great impact strength of untempered PVC foams have a positive effect.
6 ADVANCED FOAM CORE CONCEPTS

Since 1995 the DLR Institute of Structural Mechanics is investigating new manufacturing concepts using optimised fibre products in combination with LRI technologies. Within these activities a number of demonstrator components have been manufactured using a variety of different densities of ROHACELL® PMI foam cores. The primary goal of increasing the performance of foam core components was improving shear strength and increasing the quality of the core-skin interface.

Improved Shear Strength

Increasing shear strength is one possibility for extending the range of applications of foam sandwich components to components with the highest loads. Since a high-quality PMI foam core can only be improved in its performance by increasing its density, it was essential to find a way to combine foam cores with a fibre reinforcement. A structurally very successful method is integrating thrust webs under 45° whose dimension can be adapted to the expected stress [ref. 5]. The resulting foam blocks can be wrapped with the required fibre semifinished products (fabrics, warp knitted fabrics, etc.) or other semifinished products can be used such as braided tubes. An UD fabric product developed by “von Bauer” is especially adequate to this purpose because it makes it possible to handle the sandwich preform excellently with the aid of an expandable Lycra weft thread worked in.

Interface Optimisation

An excellent interface between foam core and skin is also of significant benefit to impact and crash critical applications. A possible approach is to use fibre reinforcements in z-direction to optimise the interface behaviour between the surface skins and the foam core. An elegant method for accomplishing a z-directional fibre reinforcement is the single-sided stitching technique where loops of stitching thread are inserted through the surface skin and into the foam core using a flexible single-side stitching head [ref. 4]. After infiltrating the component during the autoclave process, the thread loops are impregnated and after that consolidated in the curing process.

Fig. 7: A Sewed Sandwich / A Single-Side Stitching Head (KSL, Lorsch)

It makes sense to bring in the thread loops with the aid of the single-side stitching technique because this makes it possible to penetrate the surface layers with the aid of highly optimised needles without harming the
material to much. The flexibility of the single-side stitching head also makes it possible to stitch complex shaped surfaces without any problems.

7 MANUFACTURING EXPERIENCES

Since the decision to manufacture a full size demonstrator was made within the running Project there was a limited time for designing, manufacturing and assembling the demonstrator structure. Further more it was important to show, that the manufacturing concept is suited for series production and has significant potential for automation.

Fig. 8: upper side panel with integrated frames and stringers on its steel sheet manufacturing tool

7.1 The Moulds [ref. 3]

The moulds have proven to be decisive for a reproducible production process. The investment costs for these moulds primarily depend on type, size, and complexity of the component to be manufactured. In addition, criteria such as dimension accuracy and service life are essential cost factors. A variety of tooling concepts like composite tools or nickel galvano tools e.g. can be used for Liquid Resin Infusion Technologies. However for the single part manufacturing of the large fuselage panels welded stainless steel tools showed the best design to cost relationship. The advantage of this approach is, that the tool can be made out of simple, laser cut, curved steel sheets providing acceptable thermal expansion and tooling costs.

7.2 Production Preparation

In a first manufacturing step, the required flat patterns are cut out on a Gerber CNC wheel cutter. Then the aerodynamic cover sheets are laid down onto the manufacturing tool. In the next step, PMI foam blocks are equipped with unidirectional fibre reinforcements and wrapped with braided tubes to build up preformed core modules that can be placed side by side on the aerodynamic cover sheet to form the stringers. To get the required accuracy for the stringer position only the first an the last core module is fixed to the mould. The inner modules are able to float between the two fixed end modules. After that several layers of warp knitted fabric are laid down to build up the load bearing skin. In case of the upper side panel the preformed frames were also part of the perform. The significantly bigger floor panel frames had to be manufactured separately to stay within the tooling costs limits and to reduce the manufacturing risk.

After the performing step, the whole perform set-up was covered with two vacuum bags sealed to the edges of the mould. The preform set up was then evacuated in order to remove all disturbing gaseous elements from the production set up and also to check its vacuum tightness. The second vacuum bag is recommended with costly
productions since this guarantees an almost 100% safe process. A great advantage compared to the prepreg technology is the fact that the prepared production set up can be stored at ambient temperature without risk since it does not contain time-critical components such as active resin. This eases the situation with the autoclave and thus enables an optimal utilisation of the available autoclave capacity.

7.3 The Autoclave Process
When the tool has been heated up to the appropriate Injection temperature and the autoclave pressure has been adjusted the injection process can be initiated. During the infiltration the measurement of the resin flow provides information about the impregnation process and the point in time when the injection pressure must be reduced to set the desired fibre volume content. When the resin flow stops after adjustment of the differential pressure, the impregnation process is over and the fibre content has been set. The temperature of the component has then been raised to the curing temperature of 120°C to cure the polymer. At last the component was removed after a curing period of about 90 min. (at 120°C) when it has cooled off.

7.3 The Mechanical Finishing Process
The finishing process is carried out in a 5-axis CNC machining centre. A saw blade set with diamonds has proven to be the best tool since it achieves the best productivity. The CNC machining centre has to be specially equipped for the processing of carbon fibre reinforced plastics since electrically conducted abrasive dust makes special protective measures necessary.

8 CONCLUSION
Based on the manufacture of the fuselage sandwich panels, it was possible to show that the Single Line Injection (SLI) production method is an excellent and safe method for economical production of complex components at the highest quality. Furthermore the application of foam sandwich modules showed an excellent potential for a significant reduction of manufacturing costs. The fact that all the parts that have been manufactured in Single Line Injection Technology met all design requirements at the very first trial is a good indication for the reliability of the process. Even though Blendur has been identified within the HGF project to be best suited to meet the structural performance and FST demands there is still no satisfying solution for the resin problem when all aeronautical aspects are taken into account.
REFERENCES


