INFUSION TECHNOLOGY FOR AUTOMATED PRODCUTION OF HIGH-PERFORMANCE CFRP-PARTS

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Abstract

An infusion technology is presented in this paper that enables an almost fully automated and controllable infusion process with as little technical effort as possible. This technology is supplemented with an optical surveillance and documentation of the injection procedure in the processing tool.

1 Introduction

Various technologies are available for the manufacture of composite fibre components. Two are available for high-performance components: the prepreg technology and the RTM and LRI technologies.

The manufacturer of the semi-finished products already combines the semi-finished product, i.e. the fibre plies, with the matrix (primarily epoxy resin) when making prepreg components. In the LRI process, this combination takes place directly during the so-called 'infusion process' of the component manufacture. A preform is made up of dry, storable fibre plies into which the fluid resin is piped with the aid of an infusion machine during the infusion process.

Different technologies can be used for the infusion process to optimize the component quality. One of these technologies is the Single Line Injection (SLI) process that was developed and patented at DLR. The optimal fibre volume content can be determined in this process by increasing the ambient pressure within the autoclave. This method is described in more detail in Chapter 1.1.

The Institute of Composite Structures and Adaptive Systems (former Institute of Structural Mechanics) has been working on the conception and implementation of composite fibre components and the development of LRI and RTM facilities for about a decade.

The development of the SLI and DP-RTM manufacturing processes created the need for an infusion machine that would provide an optimal way of applying these processes. DLR specified the first ones for partners in the industry (Airbus, Fairchild Dornier) and, together with a manufacturer of the machine, developed and put it into operation. Chapter 2 provides an overview of the infusion machines that were designed and built by DLR.

These infusion machines were thoroughly analyzed and documented in the project presented in this paper. As a result, it was determined that, for further optimization, the infusion machine cannot be regarded individually but as a part of the overall system. The overall system consists of the infusion machine, the autoclave, a replaceable processing tool and a process monitoring and documentation unit.

A typical component was selected for optimization for which only some of the high requirements could be met in the past. These were CFRP laminate plates for the manufacture of test samples for material analysis and qualifications. The aspect of tool optimization is presented in detail in Chapter 3.3

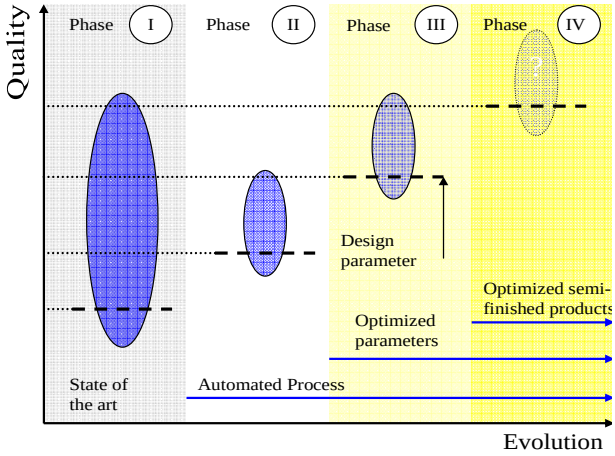

Fig. 1. Development of the component quality

As can be seen in Fig. 1, a considerable amount of variation in the component quality and therefore in the attainable parameters (Phase I) must be expected with the manual infusion technology used today. The automation and optimization of the entire process makes it possible to improve the reproducibility of the quality as well as the operating efficiency. The setup time and rejection rate are reduced at the same time (Fig. 1, Phase II).

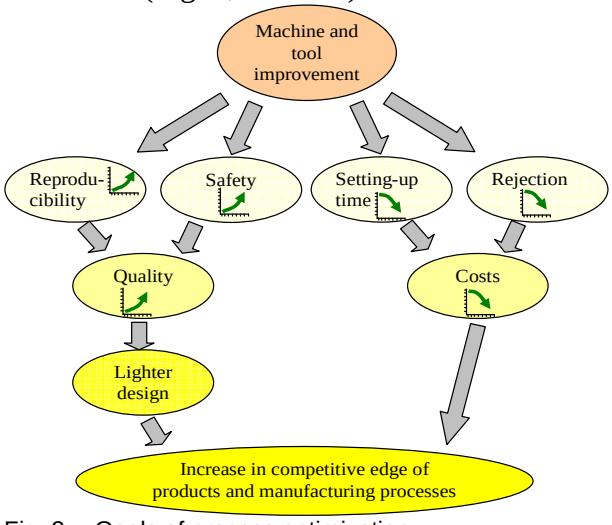

Fig. 2. Goals of process optimization

The quality of the components increase and the running costs are simultaneously reduced as a result. A further increase in the component quality can be achieved by optimizing the parameters (Phase III). The reproducibility necessary for the parameter studies can only be attained by automation. A digital online monitoring system combined with a camera is being used for the first time with the new generation of infusion machines for the surveillance and analysis of all relevant process parameters (Chapter 3.4).

The improved quality and low amount of parameter variation makes it possible to take better advantage of the material's potential during construction and design, as shown in Fig. 1 (Phase II). As a result, there is a considerable increase in the competitive edge on the product level as well as on the manufacturing level due to reduced costs. A further increase in the design parameters (Phase IV) could be attained in the future by improving the semi-finished materials that are used.

As a result, the requirements for current and future commercial aircrafts regarding weight reduction to increase economic efficiency and ecological compatibility can be met.

The machines and systems presented in this paper are set up and tested with an industry partner (automotive company) and also at the institute.

1.1 The Principle of the SLI Process

Due to costly and complex qualification procedures, the introduction of new manufacturing technologies in the field of aerospace only makes sense for technologies that have a very high application potential. The reduction of manufacturing costs in civil aircraft construction is playing a growing role when judging this potential since international competition has greatly increased.

A very promising approach to meet these new challenges is the *Single Line Injection* (SLI) technology that was developed and patented by DLR (WO 30/30823), in which the cost-effective and yet high-performance, semi-finished fibres are processed in autoclaves to composite fibre components of particularly high quality.

The main approach of the SLI process development is combining the advantages of the raw material costs of the wet technology (low-viscosity resin/dry, semi-finished fibres), which is very successfully used in, e.g., the manufacture of boats, with the laminate

qualities of the prepreg technology (semi-finished fibre materials) from the field of aerospace.

For small series production, it is necessary to keep the investment costs in tools small by applying a simple design. This is particularly important in the manufacture of large-surface components that usually have only one functional surface with high surface requirements. Applications for these types of components are e.g. the bodies of boats as well as wing and fuselage skin panels in the field of aerospace.

The main difference between the SLI method and those used for lower-quality applications is that the fibre material is compacted during injection and curing. The processing takes place in an autoclave, which is commonly used for prepreg processing. The name 'Single Line Injection' indicates that, in contrast to all other methods, the evacuation of the fibre-setup and the later resin infusion process are applied through the same line.

This combined injection / evacuation line can be arranged on the fibre preform in any manner in order to shorten the flow line and therefore the injection times. A cost-effective, semi-finished fibre product such as fabric, braids and non-crimped fabrics can be combined with the matrix resin that is appropriate for each application.

In addition to the standard epoxy resins, polyester resins, vinyl ester resins and polyisocyanurates (e.g. Blendur), high-temperature resins such as BMIs, cyanatester and even phenolic resins can be processed. The excellent, void-free laminate quality achieved with the autoclave process leads to excellent component surfaces.

Variation of the Fibre Volume Content

An additional characteristic of the SLI process is the possibility of directly controlling the fibre volume content via the process parameters. This is possible since the autoclave pressure exerted to the flexible part of the tool is in equilibrium with resin pressure in the component and the spring back forces of the fibre material (Fig. 3). If the pressure in the autoclave is compensated with the same amount of resin pressure, the fibre material can relax in thickness direction and support the impregnation process due to the increased permeability.

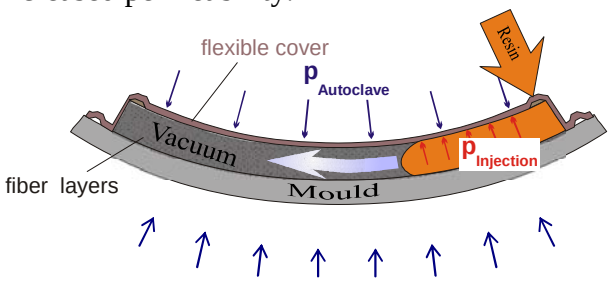

Fig. 3. Pressure distribution of the infusion

Once the component is thoroughly impregnated, the compaction of the fibre material can be directly increased by lowering the resin pressure until the desired fibre volume content has been reached. In contrast to all other manufacturing processes and independent of the applied semi-finished fibre product, an ideal fibre volume content of 60% can be reproducibly achieved for high-performance components using the SLI process.

2 Status of the Infusion Technology

The most important levels of infusion machines are described in the next chapter along with each of their innovations:

A simple test installation for the process development of the SLI technology was created at DLR in 1998. This system was developed for universal test operations.

After the tests, a mobile infusion machine was developed with an autonomous programmable controller (PLC). This machine had already been used at Airbus Stade for the manufacture of test structures. A characteristic of this machine was that it was only designed for one application scenario (resin system, resin mass and packaging). An autonomous machine control and a reusable and cleanable line and valve system were realized.

After test operation, an enlarged infusion machine for Airbus, optimized for series operation, was developed. The infusion machine

was combined with a PC for the first time to control and record the parameters.

In a further evolution step in 2003, DLR set up a universal infusion machine with a complete, PC-based process monitoring. The control of the infusion machine was combined with the autoclave control so that the entire system could be controlled in a partially automated manner. All resin lines were designed as a one-way system, similar to the first machine.

1998 **„Injection test installation“**
- manual operation
- universal test operation
- very simple sensors, e.g. with swimmers

1999 **„First industrial test machine“**
- control optimization via autonomous PLC
- mobile infusion machine
- reusable, cleanable lines and valves

2001 **„Industrial machine for series operation“**
- PC & PLC for machine control
- carousel for filling of large amounts
- determination of resin amount via scales

2003 **„Experimental machine“**
- integration of the autoclave control
- partially stationary machine
- one-way lines with manual squeeze valves

2005 **„Automation“**
- complete automation of the process
- autoclave mounted
- one-way system with automated valves

TAB 1. Chronology of the SLI machines

New generations of machines (Tab 1, 2005 “Automation”) are the last evolution step. Their main characteristic is an extremely high degree of automation. This machine and its boundary conditions are described in detail in the next chapter.

3 Technical Implementation

As described in Chapter 1, it is necessary to analyze the entire process chain of the component manufacture in the LRI technology in order to optimize the general manufacturing process. The process chain is shown in Fig. 4.

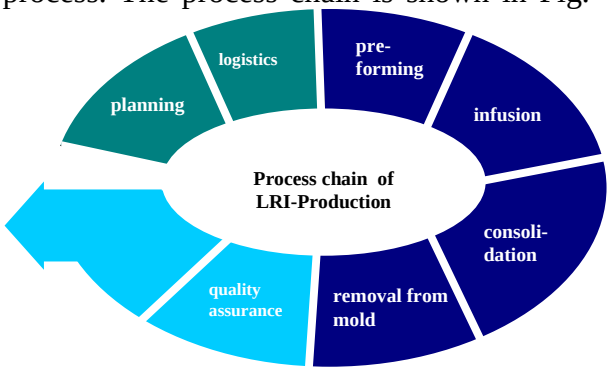

Fig. 4. Process chain

The production process must be planned before the actual manufacture starts. This includes the logistics of the semi-finished materials.

The next step is the preparation of the semi-finished materials for processing. This includes the cutting of plies and laying them down (‘preforming’) in the mould. This mould is an essential factor for the quality of the components. Innovations and further developments in this area are presented in Chapter 3.3. The infusion setup with the appropriate pouring lines and cavities is completed after preforming.

The infiltration of the dry fibre material with the resin system and its consolidation in the autoclave takes place in the next step of the process. The resin is kept ready for the infusion in the infusion machine under a defined pressure and at a defined temperature. The process control in this step is of particular importance for the quality of the manufacturing process and therefore also for the manufactured composite parts. The machine technology is the key part of this report and is analyzed and specified in more detail in the following chapters.

After demoulding a quality check is carried out. Any errors that occur in the previous steps are identified and noted in the process documentation.

The most important design drivers of the latest generation of machines are presented in the following chapters. The fundamentally different machine concepts and their advantages as well as deficits are described in this paper.

3.1 Lessons Learned

The different design concepts for infusion machines are discussed in the following. The paper focuses on the central properties of the machines such as their capability for series production and automation. The results presented here are the basis for the specifications of the latest generation of machines (Tab 1, 2005).

3.1.1 Series Operation Versus Test Production

One of the basic design drivers of the infusion machine is the planned production rate:

An infusion machine designed for series production is expected to be particularly optimized for one resin system and one component size. The process should be automated with the highest degree of reproducibility and system stability. A test machine, i.e. an infusion machine for the manufacture of prototypes or small series, requires a maximum degree of flexibility with regard to resin system, component size (processible amounts of resin), process sequence and expandability.

Here it becomes evident that the planned application conditions have to be known in detail to avoid a conflict of goals. A series infusion machine would reduce the flexibility of a test operation while a flexible layout does not offer the performance required for a series application.

In order to avoid this, the newly developed machines were modularly assembled with standardized interfaces. The functionality can be easily expanded by swapping some of the modules.

After analysis of components manufactured over the past years, the typical amount of resin was below 5 kg. If this amount proves to be ineffective in the future, the machine can be enlarged or reduced by replacing one of the modules, e.g. the resin supply unit.

3.1.2 Complexity

A high degree of universality is always required for a test machine. However, this requirement inevitably increases the complexity and therefore the likeliness of failure.

For this reason, an analysis must be made in advance of which functions and properties are actually necessary. In addition to the technical motivation of creating a "slim" machine that is fail-proof and easy to operate, it is necessary to also consider the economic aspects. Not only the cost of additional and perhaps necessary components but also the considerably increased effort to integrate them raises the price.

3.1.3 One-Way Versus Multi-Way Systems

Elementary parts of resin infusion machines are components such as resin containers, valves and lines that come into contact with resin during each process. These components are particularly examined for their reusability and recyclability within the machine concept.

The completely different concepts are evaluated with regard to environmental protection, operator safety, quality assurance and economic efficiency. Present machines were examined for the analysis of the multi-way and one-way systems:

All lines, containers and valves of the multi-way system machines were cleaned with a solvent (acetone) after the process or in regular cycles. Most of the solvent is collected and purified after the cleaning process.

Copper pipes and flexible tubes are used for resin lines in one-way system machines in addition to the standard tin or plastic cans as resin containers. The resin in the system is cured after the infusion by increasing the temperature. The lines are disposed or recycled together with the cured resin remains.

When performing an evaluation, it is important that not only individual components are evaluated but also the entire system and therefore all steps that go along with it. For example, the lines of the multi-way system can be reused but this requires large amounts of solvents that can only partially be recovered.

As a result, the one-way system, which is based on recyclable copper pipes, obtains an at least equivalent ecological efficiency. The advantages of the one-way system become evident once the system stability and operational safety are also taken into account: Analysis of the machines has shown that, even after several cleaning cycles, a 100% cleaning is not possible. Resin remains that had loosened during subsequent infusions caused component errors and therefore malfunction.

If the necessary manual effort and labour costs are taken into consideration in addition to the material costs, the one-way system machines come off much better, also from an economic point of view since the cleansing process is completely eliminated.

The resin lines as well as the number of components that come into contact with the resin should be kept to a minimum as far as possible in order to maximize the economic efficiency.

The length of the resin lines are reduced by locating the new machines directly at the autoclave or oven. This also considerably reduces the long, unheated flow path that is critical to the process.

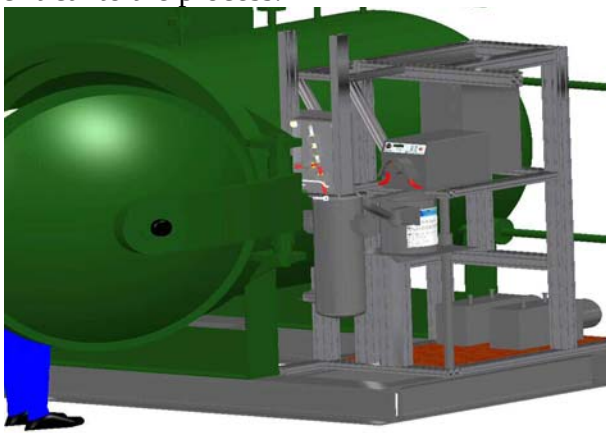

Fig. 5. Infusion machine with one-way system

A tube with a T-piece and several tube squeeze valves are used instead of the complex multi-way valves. With these valves, only the inserted tube is contaminated with resin so that the mechanical components neither have to be replaced nor cleaned.

3.1.4 Manual Operation Versus Automation

Generally speaking, complexity and investment costs increase with automation. However, machines that are primarily operated manually require a greater number of personnel. In the mid and long term, labour costs will surpass the purchasing costs of an automated machine.

In addition, the desired quality and reproducibility of composite fibre components can only be improved by automation and optimization of the process chain.

The infusion machine presented here was specified to run automatically during the entire process after being manually activated. The entire process can be programmed and controlled with simple ‘recipes’.

A manual operation of all control cycles is additionally realized with the software.

3.1.5 Mobile Versus Stationary Operation

The type of system integration (autoclave + infusion machine + mould) depends on the required mobility of the machine. The control of the entire stationary machine's system can be concentrated in one unit whereas, in a mobile machine, an additional control is necessary that interacts with the entire system.

One advantage of the mobile infusion machine is that it can be replaced with another machine of the same type if standard interfaces are used. However, this only works as long as all machines are equipped with ‘identical interfaces’, which limits the flexibility and cuts down on the innovation potential.

Directly mounted machines can ideally be integrated into the entire system, which, in turn, enables very short resin lines with homogenous heating. This provides a number of advantages for the test operation and particularly in the series operation.

3.2 Newly Developed Infusion Machines

The analysis of existing machines (‘Lessons Learned’) made it clear that these machines can only be optimized at a considerable expense.

Therefore, the decision was made to develop a completely new generation of infusion machines. The cooperation with a partner in the industry made it possible to theoretically and practically realize this goal within a very short time. The particular features of this new machine generation are described in the following.

3.2.1 Full Integration into the Whole System

An important aspect of the new machine philosophy is the integration of the individual components (infusion machine + autoclave + mould) into the entire system.

For the first time, the autoclaves were particularly specified and set up for the infusion machine. This way the individual infusion machines could be permanently installed and integrated into the individual autoclaves. As described in the next chapter, this results in a number of advantages regarding the thermal and line management. In order to fully integrate the control of the infusion machine, the modern autoclave control was upgraded instead of using an independent second control. This now makes it possible to operate all process-relevant parameters with a single control.

3.2.2 Optimum Line Management

The specification of new autoclaves in parallel to the development of infusion machines made it possible to coordinate the individual systems with one another for the first time.

Fig. 6. Valve plate with tube squeeze valve

The ideal positioning of additional flanges on the autoclaves makes it possible to directly attach the infusion machine without requiring long connecting tubes as was the case in the past. The lines outside of the autoclave are reduced to a minimum and consist of a T-piece and tube squeeze valves. The lines are controlled over an integrated heating system at a predetermined temperature to prevent the resin from cooling down. This enables a considerable reduction in the resin flow resistance.

The change from manual tube clamping pliers to pneumatic tube squeeze valves considerably increases the operating comfort and safety while simultaneously decreasing the error rate. These components enable an automation of the entire process.

3.2.3 Fault-Tolerant Design

It is particularly important in an experimental operation with often changing personnel to design the machine in such a manner that individual errors do not endanger the system or those working on it.

Most mistakes are already eliminated in the machine concept with the standardization of all upgrading components. For example, the riser with the necessary tubes and T-piece can be preassembled and mounted beforehand.

"Critical areas" where, for example, material faults in the tube would have severe consequences, are secured with a protection cover and gas discharge safety valves. The high degree of automation helps eliminate many operating errors.

The comprehensive safety concept is topped off by additional sensors and valves with which errors are not only directly detected but where counter measures automatically take place such as blocking off defective lines. In addition to this ‘software backup’, all aggregates and sensors are secured with mechanical resin traps, and ‘opener valves’.

3.3 Process-Optimized Moulds

Processing moulds or hand lay-up equipment are essential links in the process chain of the LRI technology.
A process-optimized, mould is described in the following that is used for the quality-assured and efficient implementation of professional test specimen programs.

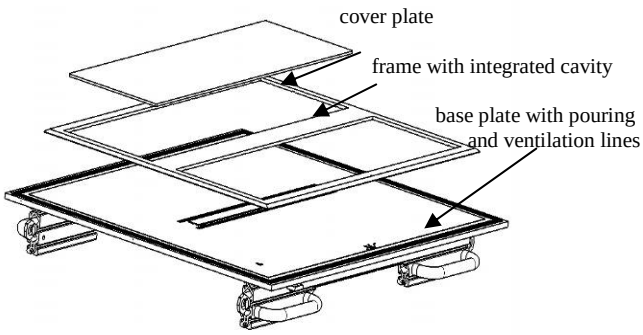

Fig. 7. Tool for the manufacture of test plates

This tool was used to test and run in the infusion machines.

The manufacturing technology of the components by means of fluid resin infusion brings a variety of problems with it. In addition to operation errors in the infusion machine technology, a large part of these problems can be traced back to the tool conception design.

Several examples of innovations and further development in the area of tool design are shown in the following.

3.3.1 Standardization

Qualification programs are greatly facilitated by standardization of the entire manufacturing process. The previously mentioned ‘test plate tool’ was designed to obtain a constant component geometry, and a greatly simplified planning is a particular advantage. The material ply cut and work preparation time are reduced during the cutting and layout process by preassembling the semi-finished fibres.

The process of marking the sawing lines afterwards is eliminated by integrated and castable markings on the mould surface. The component is labelled (project, component no., manufacturer, etc.) using integrateable labels on the component surface.

3.3.2 Integrated Infusion Management

The problem of component reproducibility mostly lies in the manual preforming and installation of flexible pouring lines that are positioned ‘instinctively’. The solution for this problem is integrated, precisely marked pouring lines and predetermined cavities over the tool geometry. In addition, the exact position is also given for the lay-down position of the individual plies with the tool geometry of the multi-part tool. This way, possible variables that lead to variations in quality are strongly limited.

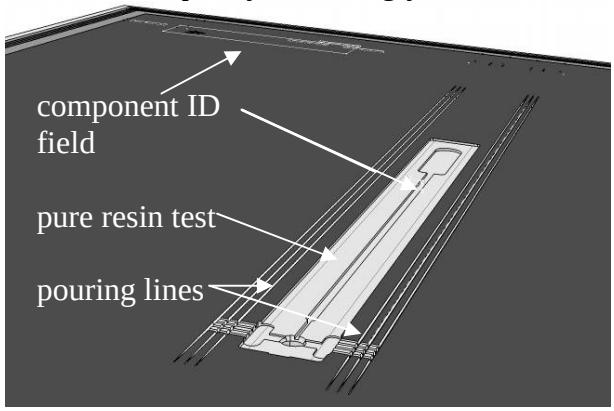

Fig. 8. Features of the tool

Due to the multi-part set up of the mould, the infusion line casts can be easily removed and separated at a pre-determined breaking point when the component is removed from the mould. The change from undefined, flexible pouring lines and cavities to those that are integrated in the mould makes it possible to precisely calculate the exact amount of required resin and thus reduce waste in the form of spare amounts.

3.3.3 Vacuum Technology

The question of how vacuum-tight the mould is presents a main safety aspect for the infusion process during all LRI processes. In this process, the second half of the mould is a film. State of the art is installation of this film with wrinkles. This endangers the compactness of the setup during thermal stress in the autoclave.

Wrinkling is avoided by integrated injection and suction lines, particular tool geometry in the border areas (sealing surface) and integrated ventilation channels. A simple

'levelled sealing' can lead to considerable safety, time and therefore also cost advantages.

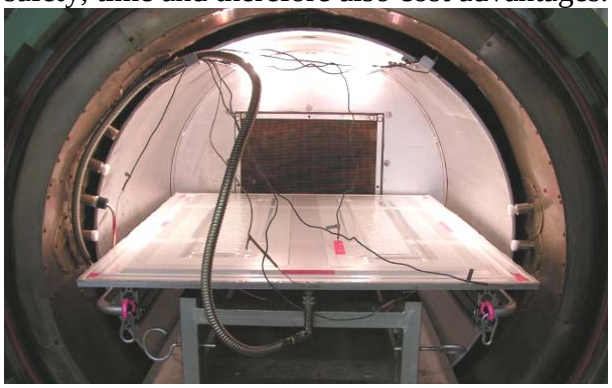

Fig. 9. Tool setup for infusion in the autoclave

The handling of the vacuum technology is improved by the use of standardized quick couplers and ergonomically designed handles on the transportation frames.

3.4 Online Monitoring

Online monitoring of the entire process chain is a further, innovative element of the new infusion system. All parameters such as pressure, differential pressure, temperatures in all relevant areas, vacuum and resin amount as well as resin mass flow are digitally recorded.
The monitoring and recording of all parameters is for the purpose of quality assurance and is therefore an elementary part of every qualification program. These recordings are also used for other components and projects to identify errors that took place during production and to eliminate them in the future. In this machine concept, a modern, industrial PC takes on the task of not only controlling the parameters but automatically storing them with the measurements and displaying them online.

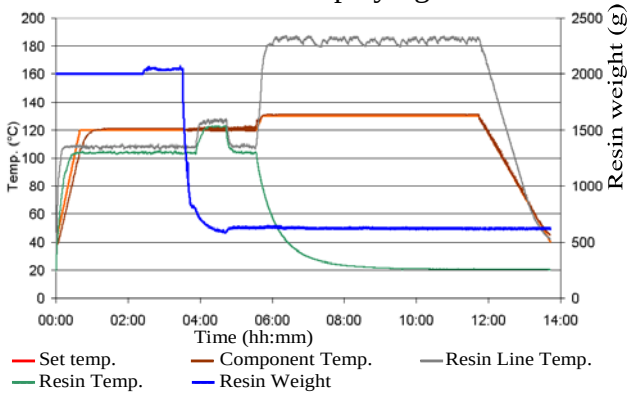

Fig. 10. Documentation of the process parameters

The result of this recording is displayed as a graphic ('Life-Data-Sheet') in every manual that goes with the component (Fig. 10).

The recording of the measurement values is supplemented with the integration of a camera system to depict the component surface on the inside of the autoclave. This makes it possible to study the material behaviour also inside the autoclave. This way the flow behaviour of the resin during infusion can be studied at different geometries and with different materials. It is then also possible to improve the pouring concepts and cavities. The result is a considerable improvement in quality and productivity.

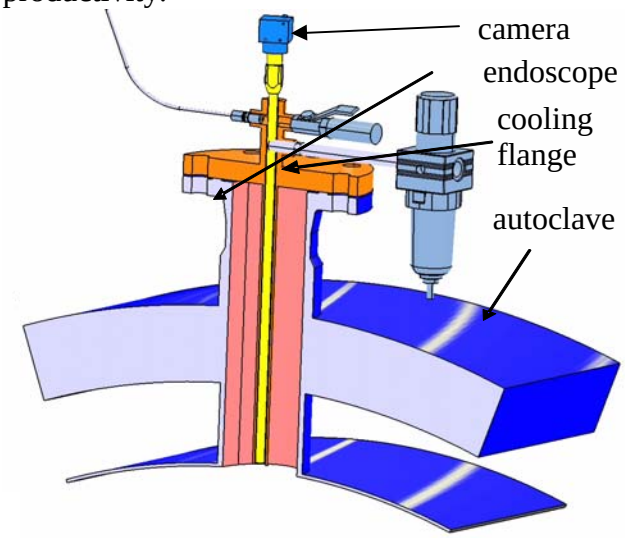

Fig. 11. Autoclave camera

The same principles that were portrayed in 'Lessons Learned' were also applied to this system. Therefore, the system is also modularly built. The industrial camera, for example, can be replaced with a high-resolution, digital camera for special experiments throughout the standardized interfaces.
The control of the required optical cooling is automated with the system controller.

4 Conclusions / Prospects

The development of the latest generation of infusion machines has shown that it is wise to closely analyze state-of-the-art as well as 'older' machines to not only learn from their weaknesses but also from their advantages.
The advantages as well as new insights were combined and integrated in the new infusion machines.

The newly developed infusion machine has already been built several times. This is a clear indication that the strategy has proven to be successful. This new generation of infusion machines has the potential of being established as state of the art.

Analysis of the LRI process chain lead to a number of optimizations, new concepts and detailed solutions that are collectively displayed in the form of a resin infusion machine in connection with a process-optimized processing tool. Tests on the entire system were completed now and, after smaller reworking measures, show the following process improvements:

- Quality improvement due to reproducible and precise laying down of the fibre material
- Cost savings by means of efficient and more simple preforming and infusion processes
- High degree of work and process safety as well as reproducibility due to automation
- Standardized quality assurance methods
- Large parts of the process chain were automated and simplified with the new machine and tool generation presented here.

The development goal of maximizing the reproducibility (Fig. 1, Phase II), as stated in the introduction, was therefore achieved.

In addition, these new developments create a platform for parameter studies, test programs for material optimization and component manufacture. The performance and competitive edge of the technology can be further increased by varying the parameters (Fig. 1, Phase III).

The optimized handling and consistent application of one-way systems enables the application of fast-curing, high-performance resins (Phase IV), like polyurethane, for the first time. New applications previously deemed unthinkable are now feasible and affordable.