20th International Conference on Composite Materials
Copenhagen, 19-24th July 2015

AUTOCLAVE INFUSION OF AEROSPACE RIBS BASED ON PROCESS MONITORING AND CONTROL BY ULTRASOUND SENSORS

N. Liebers[1], M. Buggisch[1], M. Kleineberg[1] and M. Wiedemann[1]

[1]Institute of Composite Structures and Adaptive Systems, German Aerospace Center (DLR)
Lilienthalplatz 7, 38108 Braunschweig, Germany
Email: nico.liebers@dlr.de, web page: http://www.dlr.de/fa/

Keywords: In situ testing, Infusion, Process control, Process monitoring, Ultrasonic

ABSTRACT

In this paper the manufacturing of a series of two wing carbon fiber reinforced ribs by an autoclave based infusion process is presented. The manufacturing concept is based on a low cost male aluminum tool, where the expected spring-in deformation was fed into the tool design. The spring-in angles were predicted by a novel pheno-numerical simulation.

The manufacturing process was monitored by a network of a high number of ultrasound sensors, which were mounted on the bottom tool side and on the vacuum membrane. The sensors are easy to integrate, low cost and do not require direct contact to the part. Due to the sensors all quality relevant parameters of the composite part can be acquired over the whole process. The results of the flow front, laminate thickness and cure monitoring and their use for process control and optimization are presented. The autoclave based infusion the manipulation of flow front and laminate thickness through the setting of pressure, where the process monitoring results are used as input.

1 INTRODUCTION

In order to achieve low part costs in composite production the use of dry non crimped fiber (NCF) textiles with vacuum resin infusion technologies offer high potential, as well as the advantage of a broad choice of materials and high drapability. On the other hand the process control is challenging and hard to automate. A critical manufacturing step is the infusion, which is very sensitive to deviations risking effects like race tracking leading to entrapped air and finally to a scrap part. Also the thickness of the part is variable due to the variable membrane and depending on the infusion parameters, which can result in high thickness and weight tolerances.

Today the typical way of resolving this problem is defining a quite conservative, invariable production corridor which is based on worst case assumptions and indirect production parameters like time, pressure and temperature. These invariable production cycle parameters are often derived from extensive trials and inherit high safety margins, i.e. long tempering cycles in order to secure sufficient cure. A key to overcome these problems is monitoring the quality relevant parameters in situ providing the possibility to feed the gained data back to the process control. Ultrasound is particularly well suited for this task as the waves can propagate through the mould and thus the sensors do not require direct contact with the part. The DLR developed adapted sensors, which are low cost, small, reliable and powerful. Due to their small size and costs they allow installing a mould specific network of a high number of sensors, often even subsequently in existing moulds. [1]

The developed ultrasound sensors and data processing algorithms allow monitoring the most critical parameters during infusion and cure. The flow front can be detected by pulse-echo (only sensors on mould) by analyzing the amplitude of the reflected sound signal. The cure can be monitored by measuring the sound velocity over the part thickness, which is increasing by about 66 % during cure. As the time of flight is also a function of the laminate thickness, the thickness can be derived as well. Therefore the influence of the changing sound velocity has to be compensated by special sensor settings and data processing. While for flow front detection tool-mounted sensors pulse-echo mode is sufficient, for cure and thickness monitoring transmission mode with a sender-receiver-setting is needed. But first successful trials were performed where the time of flight could be provided by pulse-echo.

The current level of technology readiness has been demonstrated in the FP7 Project LOCOMACHS[1], where several pairs of ribs have been produced in an autoclave infusion technology. The ribs were derived from existing ribs of a full size demonstrator wing and when fully developed has the potential to be introduced in production e.g. in processes such as BOMBARDIER Aerospace UK autoclave based RTI (Resin Transfer Injection) process. BOMBARDIER Aerospace UK is one of the partners within the LOCOMACHS project and provides valuable input to bring the presented technology closer to industrial application.

2 ULTRASONIC PROCESS MONITORING

Ultrasound based process monitoring has several significant benefits over other sensor technologies, especially in regards on industrial composite manufacturing. Among other – for industrial manufacturing often less suitable sensors – broadly used process monitoring sensors are dielectric, resistive and ultrasonic sensors. Dielectric and resistive sensors measure the electrical properties of the resin during cure, which is linked to the reaction progression. Their disadvantage is that they require direct contact to the resin, so they leave unwanted mark-ups on the part surface. They are difficult to integrate, as they require threaded holes in the mould which can lead to reduced vacuum integrity. Only the cure state on the surface can be obtained which limits their information content and their electrodes need to be protected against short circuit when they are in contact with carbon fibres. [2–4]

Ultrasonic sensors on the other hand do not need direct contact to the resin as the sound waves can be sent through the mould wall, thus the part surface and mould vacuum tightness are not affected. Furthermore with ultrasound the average of the resin cure progress over the whole part thickness is acquired. The typical application uses the transmission mode, where an ultrasound impulse is generated in a transducer and sent through the mould wall, the part and second mould wall and is detected by the receiver located on the opposing side (left in Figure 1). With progressing cure the longitudinal sound velocity c_l increases due to a growing elastic modulus E or respectively the compression modulus K in case of liquids. The sound velocity value almost doubles during cure which allows a sensitive cure monitoring. [5,6]

The ultrasound transducers conventionally used for composite process monitoring showed an insufficient reliability in practical application due to coupling problems into the mould and are expensive and bulky. The solution to this problem were piezoelectric ceramics directly mounted on the tool are used instead (Figure 1 and Figure 2). In this manner the tool becomes part of the ultrasound transducer and significantly higher signal amplitudes and reliability is achieved. Due to their small size the piezoceramics are easy to integrate while they are less expensive than commonly utilized transducers. These advantages facilitate higher number of sensors and wider application field for process monitoring. This is an important step towards broad industrial application. In addition to the cure progress the resin arrival in liquid moulding processes can be monitored as well as the mould wall temperature and the laminate thickness can be acquired during the running process. [1,7]

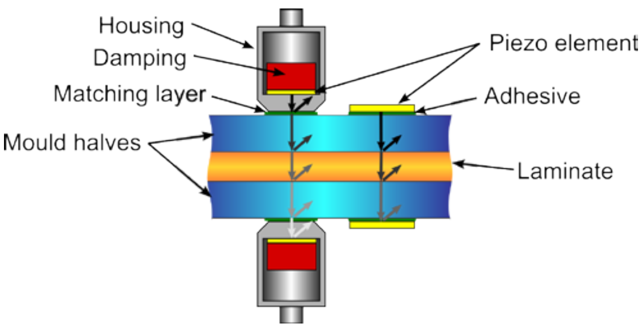

Figure 1: Comparison of conventional and novel

Figure 2: Tool mounted piezoceramics as

[1] www.locomachs.eu

process monitoring sensors composite process monitoring sensors

3 EXPERIMENTAL SETUP AND AUTOCLAVE BASED INFUSION PROCESS

In the FP7 Project LOCOMACHS (**Lo**w **Co**st **M**anufacturing and **A**ssembly of **C**omposite **H**ybrid **S**tructures) manufacturing and assembly processes for next-generation aircrafts are the focus. Within the project one of the demonstrators is the **L**ean **A**ssembly **W**ing **B**ox (LAWiB, Figure 3), which is derived from a former full scale demonstrator wing by BOMBARDIER AEROSPACE. The DLR part is the manufacture of the two composite ribs in the middle, where geometrical accuracy was as important as the laminate quality itself. Therefore a variety of measures have been implemented in order to actively measure and control all quality relevant production parameters. The chosen manufacturing is a combination of resin infusion and autoclave technology offering a wide bandwidth of process parameter variation. The rib design with one integrated rib foot and one integrated rib post leads to a good combination of simplicity and degree of structural integration. The second rib foot and rib post will be installed by bolting during assembly, where tolerances can be compensated.

Tool design for high geometrical precision composite structures is challenging. The combination of different materials, the anisotropy and high-temperature processes lead to process-induced distortions (PID), namely spring-in, warpage and forced-interaction [8]. The PID issues are often reduced by the use of mould materials with low thermal expansion like INVAR or by special designed composite moulds with the same expansion properties as the produced part. Both materials are cost intensive. The chosen mould tool concept is a low cost male, open-mould, aluminum tool, where both ribs are manufactured at the same time and the flange angles of the rib foot and rib post have been designed to compensate Spring-In deformations. The PID of the ribs have been predicted with a novel pheno-numerical simulation approach that has been introduced within the LOCOMACHS project.

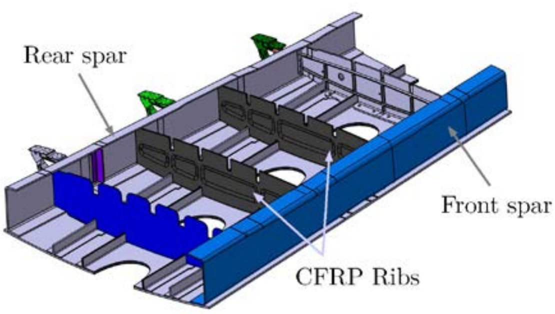

Figure 3: LOCOMACHS Lean Assembly Wing Box (LAWib) demonstrator

Figure 4: Aluminium open mould tool for simultaneous manufacture of the two ribs

For the infusion the “Single Line Injection” (SLI) process [9] in combination with an autoclave was chosen. A scheme of the process principle is given in Figure 5, where the mould with the preform covered and sealed in a vacuum bag is placed inside an autoclave. In the SLI process the same line is used for evacuating the preform and for injecting the resin. The autoclave pressure is fed to the resin pot, which increases the flow rate and extends the maximum flow length due to a higher pressure gradient, while the effective resin pressure must not exceed the autoclave pressure applying on the vacuum bag. The pressure inside the resin pot can be regulated by a valve which provides the possibility to control the flow rate, but also the injected resin volume and thus the laminate thickness. During infusion the maximum resin pressure is used in order to achieve short filling times. Due to the pressure gradient formed during infusion (Figure 6) the laminate thickness is not homogeneous over the flow length [10]. When the resin flow stops, the pressure gradient starts to equilibrate as well as the laminate thickness, as long as the resin gelation is not occurring. Due to the growth of the laminate thickness over the infusion duration, more than the minimum required resin volume was transferred into the preform leading to a low fiber volume fraction. Therefore, when the impregnation is completed – which can be obtained from the ultrasonic flow front monitoring, but also by radar based fill level monitoring of the resin – the resin pressure is decreased to squeeze out the excessive resin and control the laminate thickness to the target value. The input for the laminate thickness is obtained by the ultrasound monitoring system.

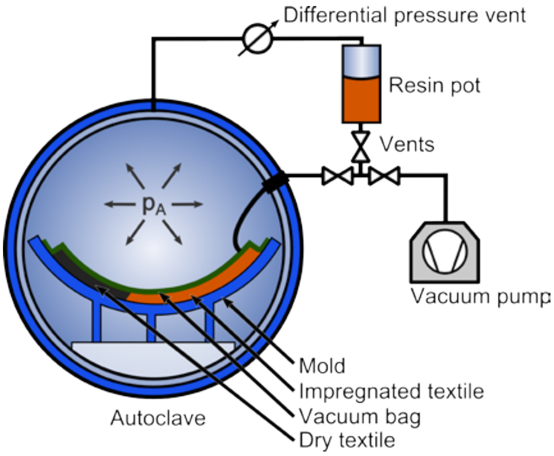

Figure 5: Principle of the autoclave supported SLI process

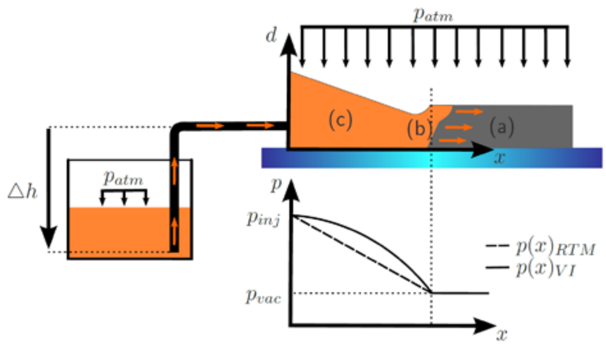

Figure 6: Physics of infusion process [10]

For ultrasonic process monitoring a network of a high number of sensors where installed onto the mould. The number of active sensors was limited to 24 by the number of feed through connections into the autoclave. The sensors were applied with a high temperature adhesive on the bottom side of the mould tool. Only at six sensor locations the through-transmission mode was employed in order to use the rest of the available connections for flow front monitoring by pulse-echo to cover a large area (see Figure 7). Also the focus was put on monitoring one of the ribs more detailed. For the following assembly the flange thicknesses are critical, thus four of the six through-transmission-sensors for thickness monitoring were placed on the flanges and two on the web. The through-transmission locations can be used for resin arrival detection in both through-transmission and pulse-echo.

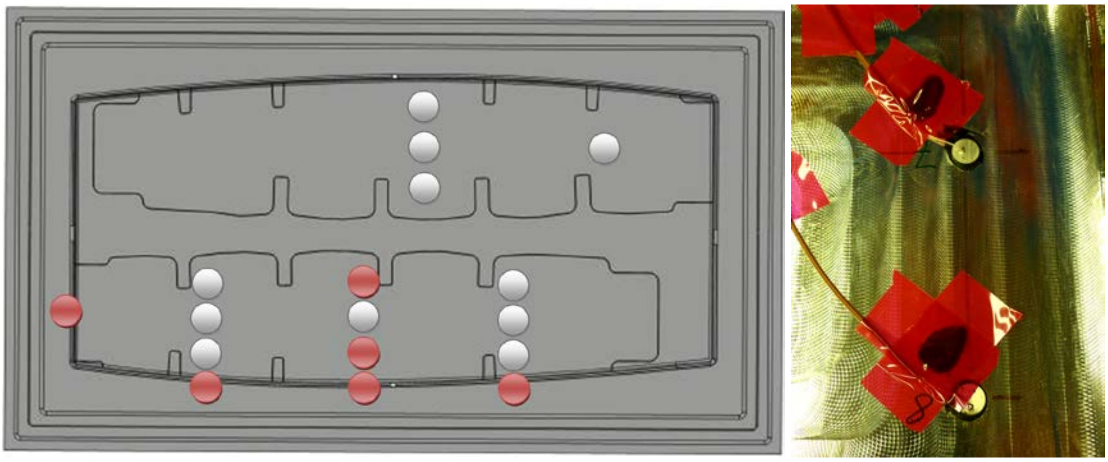

Figure 7: Left: Sensor network, grey: only pulse-echo (sensors on bottom side of tool), red: through-transmission (receiver on vacuum bag side) Right: Sensors mounted on outer tool side

The sensors on the bag side are more challenging to integrate. Two nylon vacuum bags were used, where the six bag side sensors were put on top of the first bag. In order to ensure good acoustic contact a small amount of adhesive was used. With this method a high signal quality was achieved and the data could be used for process monitoring and control. On the other hand as the sensors and the cables were placed between the two vacuum bags, they led to unwanted mark-ups on the part surface. As the surface quality was poor in general, thin aluminium caul plates were used in the following trials. The caul plates were placed on top of the first nylon bag and did not have direct contact to the part. On top of the plates the sensors were installed (Figure 8), which has also the advantage that they can be reused in opposite to when they were glued onto the nylon bag and the preparation time for positioning the sensors was reduced.

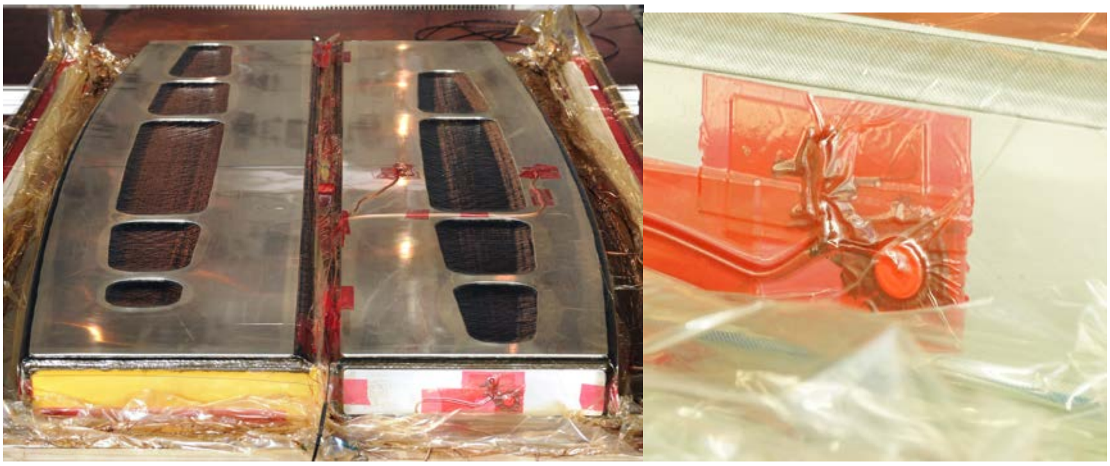

Figure 8: Layup using caul plates with integrated sensors

4 ULTRASOUND SENSOR CONTROLLED INFUSION: FLOW FRONT

For resin arrival detection it is sufficient to use the pulse-echo mode, i.e. one single sensor, which transmits ultrasonic impulses and then detects the arriving echoes. The sound impulse is sent through the mould thickness and when reaching the interface between the mould and laminate a high fraction is reflected. The fraction of the reflected sound pressure depends on the acoustic impedance *Z* of the two materials. The impedance is calculated by the product of density ρ and sound velocity *c*:

$$Z = \rho \cdot c \tag{1}$$

The fraction of the reflected sound pressure is given by the reflection factor *R*:

$$R = \frac{p_r}{p} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{2}$$

Before the resin arrives the second material is air or even vacuum, where R becomes nearly 1.0, leading to a total reflection. When the flow front arrives at the sensor location and impregnates the mould surface *R* drops significantly and thus the amplitude of the echo. In the case of an aluminium tool, the reflection factor will drop from 1.0 to approximately 0.82. For an increased sensitivity the analysis the amplitude drop of an impulse that has been reflected multiple times can be used, where the amplitude drop is multiplied as well.

In Figure 8 the principle of flow front monitoring by pulse-echo, but also through-transmission is shown. With through-transmission only when the laminate is impregnated over the whole thickness at sensor location the transmission of a signal is possible. Therefore for detecting the resin arrival the amplitude of the transmitted signal is used, which is increasing from that point on, while only noise was detected beforehand. The amplitude is rising until the whole cross section is impregnated and possible bubbles have passed. Combining both methods can give information about the shape of the flow front.

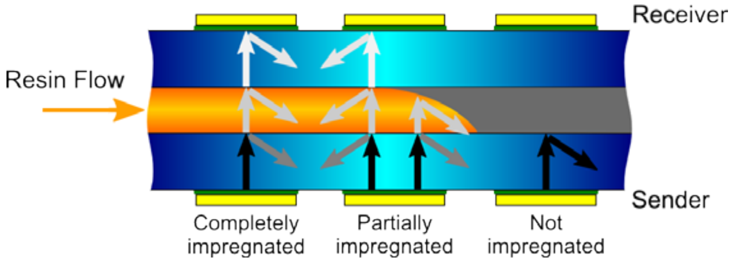

Figure 9: Principle of flow front monitoring by ultrasound

In the case of the ribs the sensors were used to monitor the injection progress in order to evaluate the flow simulation and injection concept, but mainly to take active process control. Due to the information on impregnation progress, the injection parameters could be adapted individually. As the resin flow depends on a broad number of parameters, the impregnation time can vary strongly, but also air can be trapped when enclosed by two joining flow fronts. In the current state of development of the sensors and measurement software the signals are processed online, showing the infusion and cure progress, but the system is not yet connected to the process control. The process control is done manually by the operator based on the sensor information.

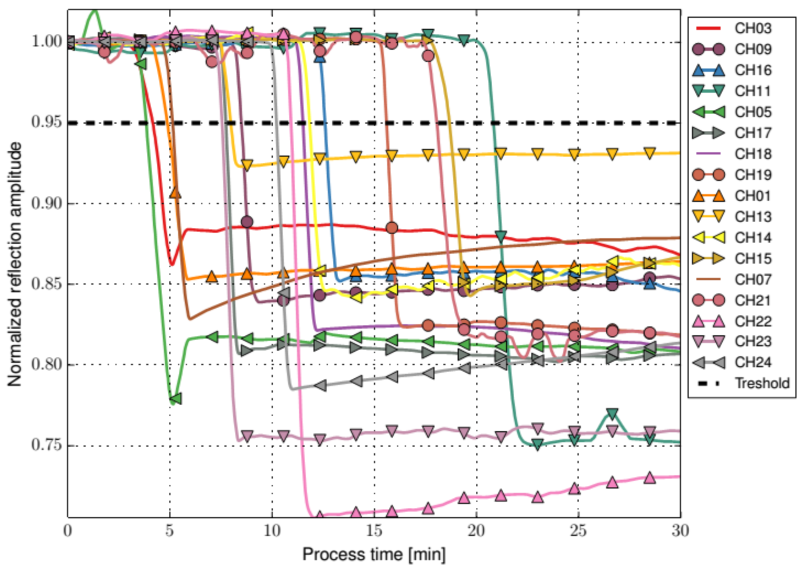

Figure 10: Reflection amplitudes for flow monitoring

One set of the results of the flow front monitoring by pulse-echo amplitude is show in the graph in Figure 11. The amplitude was calibrated and normalized to 1.0 before resin arrival. The amplitude drops significantly on resin arrival which can be used in a robust and reliable way. The amplitude was calculated by Fast Fourier Transformation, which was found to be more stable than taking the signal maximum or energy. To acquire the time of resin arrival a threshold was used. In Figure 10 an overview is given in function of the sensor position of the times after injection start.

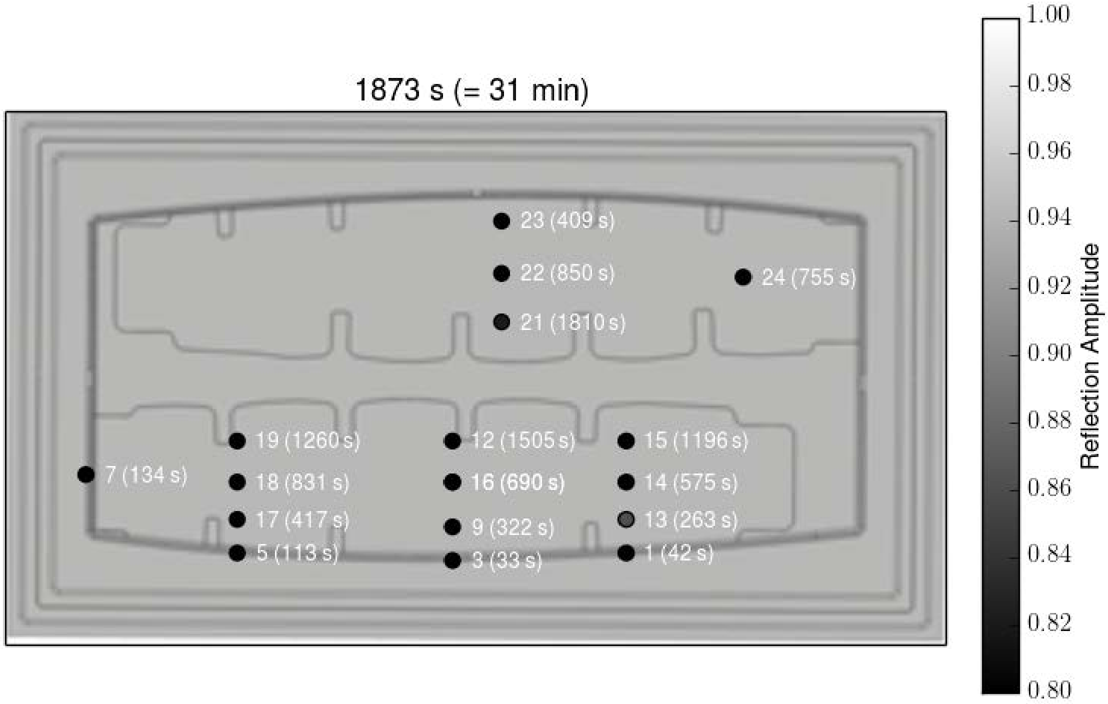

Figure 11: Flow front arrival times detected by pulse-echo ultrasonic sensors

5 ULTRASOUND SENSOR CONTROLLED INFUSION: LAMINATE THICKNESS

As soon as the preform is impregnated by resin at the sensor location, a through-transmission signal can be received. Also, from this point during progression of the flow front, the resin pressure is growing leading to a laminate thickness increase. Especially for structural parts a high fiber volume ratio is demanded to achieve the required mechanical properties. For the ribs a fiber volume fraction of 60 % was targeted. With the autoclave based infusion process the high pressure can be used to remove the excessive resin inside the preform by lowering the resin pot pressure when the impregnation is finished. Therefore a differential pressure $\Delta p = p_{autoclave} - p_{resin}$ of about 0.8 bars was applied. The differential pressure was manually set based on the information of the ultrasonic cure monitoring.

As the time of flight of the ultrasound impulse through the laminate depends on both the sound velocity and the thickness, the laminate thickness can be calculated when the sound velocity is known. For the LOCOMACHS ribs an advantage was the slow cure of the used resin, EPIKOTE 600 [11], thus the sound velocity remains almost constant during the infusion stage. But for most thermosets, including epoxy resins, the sound velocity increase before gelation is very small, as up to this point the resin is in a liquid state [12], which is the definite end point of infusion. In series production, with relative reproducible parameters, calibration curves can be acquired in at least one process and then used as guidelines for the following cycles.

In Figure 12 the results of the six through-transmission sensor locations is shown converted into the laminate thickness. The sensors 1, 3, 5, 7 are located on the flanges, where the resin arrives shortly after infusion start, as they are close to the resin distribution line integrated into the mould. At these locations the thickness is increasing considerably as the flow continues and the pressure equalizes. The sensors 9 and 11 are located farther from the injection line, thus the resin arrives late in the process and the thickness increases less.

When impregnation was finished, differential pressure was applied to reverse the flow direction and remove excessive resin. Then the laminate thickness dropped significantly, but slightly suspended depending on the distance of the sensor location to the injection line, as the pressure gradient alters slowly. The laminate thickness reached an even level at all sensor locations and the estimated end values were close to the measured thickness distribution on the finished part.

The results reveal also the dilemma, that the differential pressure is the only control parameter to set the thickness on a global level, but not the thickness distribution itself. A homogeneous distribution has to be ensured by the preform thickness and the injection strategy together with the global thickness control.

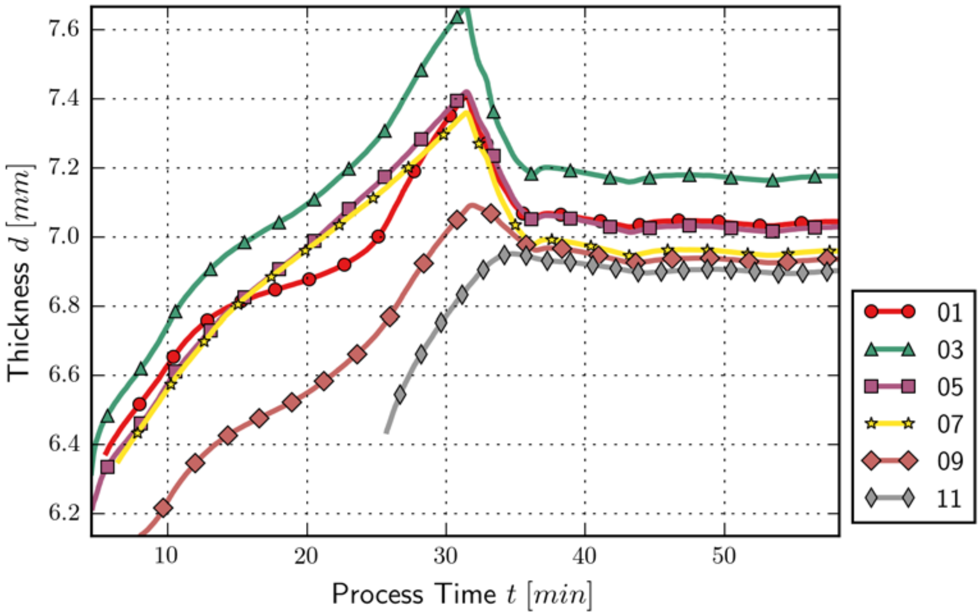

Figure 12: Ultrasonic laminate thickness monitoring

6 ULTRASOUND SENSOR CONTROLLED INFUSION: CURE

After impregnation, removal of excessive resin and thus thickness control the resin line was closed and the temperature was increased from 120 °C to 150 °C. This temperature was held for 30 min for a relatively slow pre-cure in order to reduce residual stress due to the different thermal expansion of fibers and matrix. Finally the temperature was set to 180 °C during two hours after which the cool down began.

In Figure 13 the results of the ultrasonic process monitoring during heat-up from 120 °C and 150 °C and the dwell step are presented. Due to the temperature increase the sound velocity of the resin falls, as the resin softens. The effect reverses when due to the cure the sound velocity rises considerably. At this point gelation is taking place, where the resin transits into a solid form and the elastic modulus increases noticeably. Until this point the resin was able to flow, but with an increasing viscosity. The sound velocity rises then significantly, while the sound attenuation reaches a maximum leading to a temporary signal loss at some sensor locations.

At about 210 minutes process time the sound velocity gradient and thus the cure progress come to a stop followed by the heat-up step to 180 °C. The results of the 180 °C cure step have been left out, as the sound velocity increases only slightly. The results suggest that during this step the cure progress is minor and less important compared to the step before. During cool down, the sound velocity increases further. Due to thermal expansion the contacts between tool and part weakens leading to a cut off of the signal. In this study the cure monitoring results were only used for quality assurance and not fed back into the process design or control.

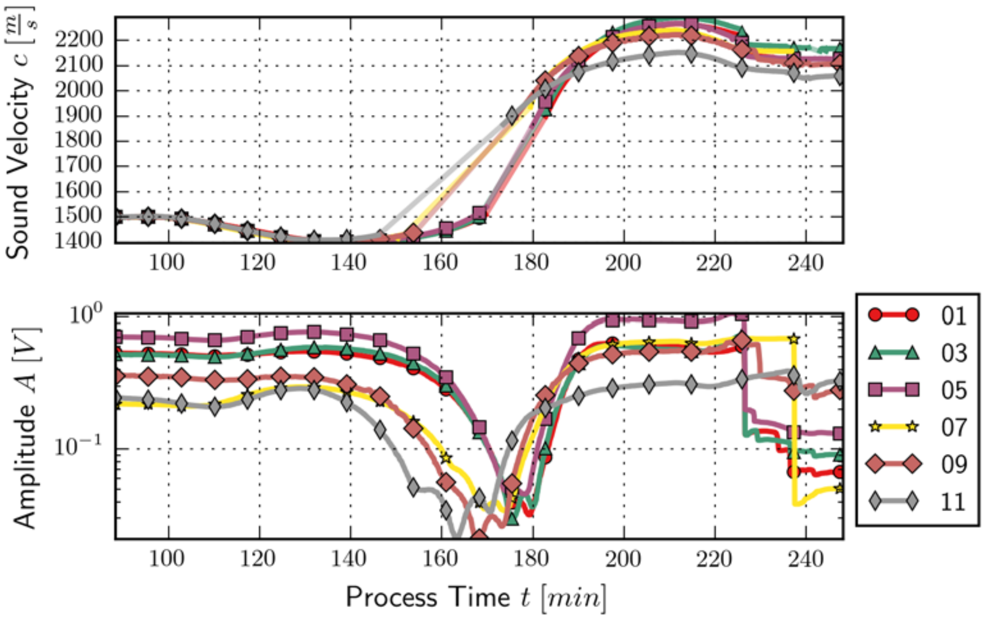

Figure 13: Sound velocity and amplitude development during 150 °C dwell step including heat-up

7 CONCLUSIONS

In this paper the results of the production of four pairs of carbon fiber reinforced plastic ribs for a demonstrator wing in the EU project LOCOMACHS was presented. The ribs and autoclave based infusion process are close to aeronautic industry conditions. A low cost aluminum mal tool was used, where the angles were the spring-in angles were predicted and compensated in the tool design. The autoclave based infusion process has the advantage of reaching high fiber volume fractions, being able to impregnate toughened non crimped fiber textiles and to apply thickness control by differential pressure.

The focus was on the process monitoring with a network with a high number of low cost ultrasound sensors, where the infusion progress, laminate thickness evolution and resin cure was obtained in the running process. The information was used to actively control the process parameters and achieve the required part quality. The novel sensors were presented as well as their integration into the open-mould tool. The results of flow front, laminate thickness and cure monitoring were presented and analyzed in detail.

The study was also a benchmark for the novel ultrasound sensors and the developed chain of data acquisition and analysis software under industrial conditions. The system shows a high maturity and has the potential when fully developed to be integrated into industrial composite manufacturing chains like the resin transfer process of Bombardier Aerospace in Belfast. As the sensors work without contact to the part itself, the threshold for integration into existing processes is low.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement n°314003.

REFERENCES

[1] N. Liebers, *Effective and flexible ultrasound sensors for cure monitoring for industrial composite production*, Deutscher Luft- und Raumfahrtkongress, Berlin, 2012.

[2] M. Kazilas, Cranfield University, *Acquisition and Interpretation of Dielectric Data for Thermoset Cure Monitoring*, Cranfield University, 2003, http://books.google.de/books?id=d1lEywAACAAJ.

[3] N. Pantelelis, E. Bistekos, *Process monitoring and control for the production of CFRP components*, SAMPE, Seattle, USA, 2010, accessed 5 March 2014.

[4] A. McIlhagger, D. Brown, B. Hill, Composites Part A: Applied Science and Manufacturing, *The development of a dielectric system for the on-line cure monitoring of the resin transfer moulding process* 31 (2000) 1373–1381.
[5] J. McHugh, *Ultrasound technique for the dynamic mechanical analysis (DMA) of polymers*, Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin, 2008.
[6] N. Liebers, D. Stefaniak, M. Kleineberg, M. Wiedemann, *SENSOR GUIDED CURE PROCESSES – A STUDY OF PRODUCTIVITY AND QUALITY OPTIMIZATION POTENTIAL*, ICCM, Montreal, Canada, 2013, iccm19.org.
[7] N. Liebers, *In-Situ Laminatdickenmessung während der Infusion und Aushärtung von Faserverbundkunststoffen*, DGZfP-Jahrestagung 2014, Potsdam, 2014.
[8] E. Kappel, D. Stefaniak, G. Fernlund, Composite Structures, *Predicting process-induced distortions in composite manufacturing – A pheno-numerical simulation strategy* 120 (2015) 98–106.
[9] M. Kleineberg, J. Nickel, A. Pabsch, C. Schöppinger, C. Sigle, *Resin injection equipment for production of fiber reinforced plastic products uses a common line instead of separate lines for gas evacuation and resin injection*, 2000.
[10] N.C. Correia, F. Robitaille, A.C. Long, C.D. Rudd, P. Šimáček, S.G. Advani, Composites Part A: Applied Science and Manufacturing, *Analysis of the vacuum infusion moulding process: I. Analytical formulation* 36 (2005) 1645–1656.
[11] MOMENTIVE, *Technical Data Sheet*: EPIKOTE System 600, 2011.
[12] F. Lionetto, A. Maffezzoli, Materials, *Monitoring the Cure State of Thermosetting Resins by Ultrasound* 6 (2013) 3783–3804.