SENSOR AND REAL-TIME-PROCESS-SIMULATION GUIDED AUTOCLAVE PROCESS CONTROL FOR COMPOSITE PRODUCTION

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Abstract

In this paper a new architecture for process control for autoclave composite manufacturing is being presented. Its aim is to match the challenges of high volume production of composite parts for aircrafts, but also for other applications such as wind turbine rotor blades and automotive structure parts.
The process control is based on sensors, process simulation and a learning process database. All this information is gathered in a central communication system, where the data is processed and evaluated and finally decisions are taken if and how the process needs to be influenced. The goal is to ensure the desired quality and prevent scrap parts while reducing process time and resources.
The described modules are still in development, but most of them are mature to be integrated into the process. Currently the modules and the communication center are being put together and the first test runs are in preparation.
An overview is given about especially developed or adapted sensors, gathering important information about the processed part, with the focus on cure monitoring. This paper shows the development of a process simulation able to run in parallel to the real autoclave process in order to support the control decisions. All data of performed processes are saved in a database, where they are analyzed and used as experience for future processes. Finally the most important step is to evaluate the information and to take action in case of a critical process state.

1 Introduction

In the background of energy efficiency by weight reduction composite materials are gaining importance in primary aircraft structures. As carbon fiber reinforced plastics possess extraordinary mechanical properties and low density they are excellently suited for lightweight applications.

These large components like fuselage barrels and wing covers are preferably manufactured in autoclaves to reach the high quality demands. But to be compatible to established production technologies of for example aluminum structures today's autoclave processes are in urgent need for higher productivity and flexibility.

2 State of the art autoclave processes

The main objective of the autoclave process is to cure the thermoset matrix activated and controlled by heat and to set the laminate thickness or respectively the fiber volume content by applying pressure.

The mold tool and the part are heated by air flow through the autoclave which results in relatively slow and partly unpredictable heat transfer. Especially large, heavy tools possess a high thermal mass risking excessive temperature variations. Due to limited information about the heat distribution and or even the cure state during the running process the temperature and

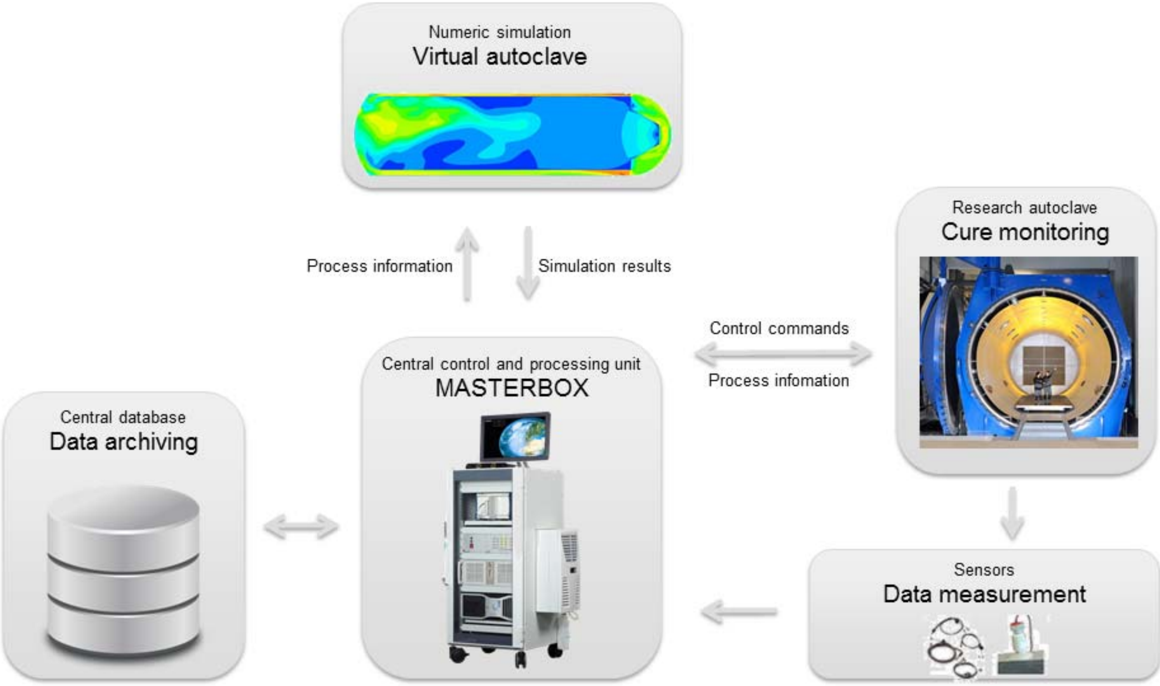

Fig. 1. Communication System for Autoclave Control

pressure cycles are prolonged by high safety margins to ensure a complete cure. This often leads to process durations of 12 hours or more. An incomplete cure would require repair measures or might consequent a scrap part. [3,4,5]

In state of the art composite autoclave manufacturing the process control program strictly follows a given temperature and pressure sequence with no consideration of the actual autoclave status and part condition. The pressure and temperature sequences are often experience-based and need to be adapted for new part designs and material combinations by extensive tests or are prolonged by safety margins.

In the best case temperature monitoring and controlling is realized by thermocouples fixed to the mold tools. Most commonly the hottest spot in the mold is used to control the autoclave air temperature or heat power. Only when the coldest spot reaches the designated minimal cure temperature the process step timer is started. In case of large or several molds at the same time this can result in an enormous lack in cure progress between cold and hot spots.

For more advanced process surveillance video cameras and cure monitoring are already used. But today the cure monitoring is performed outside the autoclave in a furnace simulating the measured autoclave conditions [5,7]. Since the cure progress is very sensitive to the temperature, small differences between the real and the simulated autoclave conditions may lead to inaccurate results.

The gathered information is used for documentation, only the temperature measurements are taken into account for the process control. This means in return that the part quality might be insufficient quality and consequently scrap fault parts are not discovered until demolding and final part inspection. Although there are procedures available to correct process deviations – for example by adding a cooling phase – they cannot be applied correctly as long as there are not enough measures to detect critical situations to define corrective actions and to monitor the response.

3 Sensor and simulation guided processes

Autoclaves are very effective in today's production chain of high performance CFRP components. The operating high pressure ensures a well-defined and homogenous fiber volume fraction and low or negligible porosity. But the influence of the physical and chemical processes in the autoclave on material properties and component geometry can be tremendous. The understanding of these processes and their interdependencies are the prerequisite for a stable and robust autoclave process. With regard to all aspects mentioned before, the high demands of cost efficient and high volume composite production cannot be fulfilled with the state of the art. Improved productivity, substantial cost reduction and continuous quality assurance during the whole curing process in the autoclave require a new control system. This system includes additional sensors, numerical autoclave simulation and a central database. Thermal inertia, exothermal heat and incomplete or inhomogeneous cure are some of the challenges to be solved.

The development of such a control system with objective to manage the information flow leads to the concept of a superordinate control and processing unit. Especially developed for this purpose, the so-called "MASTERBOX" is the core of the new control system. The MASTERBOX performs the acquisition, storage, processing and exchange of all relevant information. In return this information can be used to optimize the polymer reaction by a dynamic autoclave process control to increase the process reliability and to ensure the required part quality.

Figure 1 shows the structure of the developed communication system. The information flow within the system is established by auxiliary tools and is indicated by arrows. The following chapters give a detailed description of the interfaces and subordinated modules.

3.1 Sensors for Process Monitoring

3.1.1 Process Monitoring in Industrial Environment

Sensors play an important role in monitoring and especially controlling the process effectively. Basic concept is to gain information of the part's status directly where possible under the condition not to affect the part quality or necessitate long preparation time. To give an example the temperature and cure monitoring sensors will be connected by the principle of "plug and play", where there are few connectors installed at the tool which can quickly be linked to the installed cables inside the autoclave. The sensors remain permanently installed in the tool and no special effort for preparation is required. Sometimes additional information might be requested coming from sensors placed in the vacuum bagging, for example when the degree of cure of thick laminates or sandwich needs to be obtained. These should be only used when necessary at few critical areas which need monitoring.

In order to further reduce preparation time a quality assurance system for sensors is required. This system consists of semi-automated functional testing and calibration methods.

3.1.2 Sensor Systems: Temperature

For temperature monitoring state of the art thermocouples and resistance thermometers but also thermography cameras are used. The thermocouples and resistance thermometers are mounted on the tool close to the part's surface. The thermography cameras are protected against the harsh autoclave conditions and are placed in such a way, that the part's surface can be monitored. A system is in development to move and tilt the thermography cameras when the autoclave is running. This will give the opportunity to scan the part surface temperature. As result there will be a two-dimensional temperature distribution image.

3.1.3 Sensor Systems: Cure Monitoring

Key parameters in the autoclave process are the degree of cure and the laminate thickness or respectively the fiber volume content which are set and controlled by temperature and pressure sequences. Both values can be measured by ultrasound sensors with the advantage that they do not have to be in direct contact with the part or resin itself as the sound waves can propagate through the tool. Consequently the ultrasound measurements do not affect the part quality or tightness of tool or vacuum bagging (Fig. 2).

The cure monitoring with ultrasound is based on the fact that with progressing cure the resin's speed of sound is increasing [6]. By measuring the sound travel time through the laminate first the laminate thickness can be measured as long as the resin has its lowest and defined viscosity and in the next phase the degree of cure can be derived. Additionally the ultrasound sensors are able to obtain the tool temperature average over the thickness and to detect the arrival of the resin flow front for infusion processes. All in all the ultrasound technology is a powerful method to obtain relevant parameters which enable process control in function of the produced part.

Fig. 2. Cure Monitoring by Ultrasound

With respect to the application in an industrial production environment special ultrasound sensors and methods as well as integration principles were developed. While the method described above (Fig. 2.) needs access from both sides – the tool and vacuum bagging – a method has been developed making use of the fact that at the interface between tool and resin the sound waves are reflected partially and the ratio of the reflected waves is also proportional to the cure progress [8]. By applying this method the sensors only need to be installed at the tool side connected by one single plug. However they only obtain the cure state at the surface which can differ from the one inside the laminate, especially when dealing with thick laminates.

Test runs with ultrasound cure monitoring clearly revealed the necessity to develop improved sensors. The conventional sensors showed instable measurements due to unreliable acoustic coupling. Furthermore they are relatively spacious. New ultrasonic sensors made from thin piezoelectric ceramics are directly applied to the tool for example by an adhesive film [1]. With this method the ultrasound waves are passing a less instable interface that higher ultrasound amplitudes are emitted and received. Consequently the cure monitoring is more reliable and precise. Furthermore the integration of the developed sensors is simple concerning the tool design thus reducing tool cost and making the sensors applicable at much more locations. The sensors themselves are significantly less expensive than the conventional transducers.

Fig. 3. Reflection method with adapted ultrasonic sensors

3.2 Simulation module: Virtual Autoclave

One of the key premises for industrial composite production is to obtain the necessary process stability and to prevent or at least minimize the number of scrap parts. To achieve these, it is not sufficient to monitor the directly measurable parameters during whole autoclave process with sensors. The industry demands for process-related monitoring which is capable to predict any process deviation of all quality relevant parameters at an early stage. Within this system the effects of deviations have to be identified, assessed and used for corrective actions as far as possible.

In order to reliably detect potential deviations, an auxiliary tool is needed that is not only able to enrich the process comprehension by additional parameters, but also is able to make precise predictions about the running autoclave process taking into account the current process conditions. Numerical simulation tools especially optimized for such complex fluid mechanical and thermodynamic processes can meet these challenging requirements. The designed process simulation meeting this purpose is called *Virtual Autoclave* based on the detailed description of the autoclave process in a realistic model.

The enrichment of the existing system with the numerical autoclave simulation, inter alia, has the advantage of extending the data pool with not direct measurable parameters. These parameters can describe aerodynamic, thermal, chemic and mechanical conditions. In this way the comprehension of the autoclave process will be extended, new effects will be identified as well as the strength of their dependencies will be revealed more clearly.

3.2.1 Simulation Modules

The *Virtual Autoclave* is divided in two simulation levels; a sophisticated 3D-CFD-simulation and a 2D real-time simulation (Fig. 3).

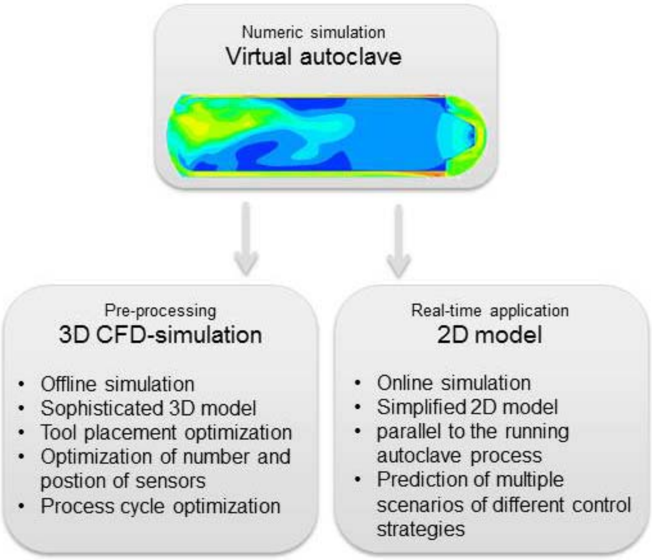

Fig. 3. The two modules of the numerical autoclave simulation

The 3D-CFD-simulation serves as a basis model that describes the entire autoclave process in consideration of the loading condition. As a result, time dependent 3D-distributions of temperature, pressure, flow velocity and the degree of the cure are available. The required calculation times for such sophisticated models are generally significant. In consequence they are not suitable as real-time applications. But they are interesting for accurate prediction and offline optimization of the autoclave process. Furthermore the simulation results supply valuable information about critical areas – for example concerning exothermic reactions or cold spots – so they can be used for the optimal placement of sensors on the part and for the optimal position of the (various) tool(s) inside the autoclave (Fig. 4).

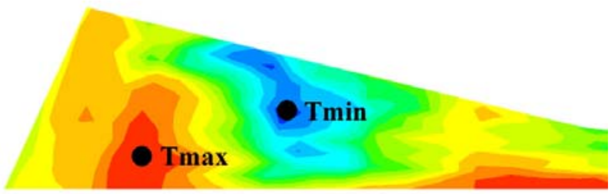

Fig. 4. Optimal placements of the temperature sensors

The second module is a simplified 2D model derived from the sophisticated 3D model. Based on the calculated field functions of the basis simulation, this module of the *Virtual Autoclave* is able to simulate the autoclave process at least in real-time. At the current state of development the simulation speed is 10 times faster than real-time. A compromise between calculation speed and accuracy must be found. Currently tolerances between simulation and measurements of ± 5 % have been defined as acceptable, which will be evaluated and adapted in validation test runs.

3.2.2. Simulation Module for Process Control

The calculation speed of simulation allows a direct intervention in the process procedure of the real autoclave while the *Virtual Autoclave* predicts multiple scenarios for different control strategies parallel to the real autoclave process. This simulation tool opens up new dimensions for process control of inert systems: deviations in the autoclave process like exothermal processes in the thermoset resin can be evaluated before they occur. In such cases, countermeasures can be introduced early before any sensor would recognize a critical situation. In the case where the part cannot be prevented from scrap the process could be terminated and the part removed to save time and to reduce cost.

Furthermore, it is also possible to define *Virtual Sensors* before the simulation starts. This tool is available in both simulation modules. *Virtual Sensors* are nodes in the physical model and allow the monitoring of critical areas at the part or within the autoclave. Simulations can calculate on the one hand data expected from the real sensors for comparison and on the other hand physical information which cannot be measured directly, for example residual stress, chemical shrinkage, three-dimensional temperature and cure degree distributions. The *Virtual Sensors* provide the possibility to compensate malfunctioning real sensors (Fig. 5).

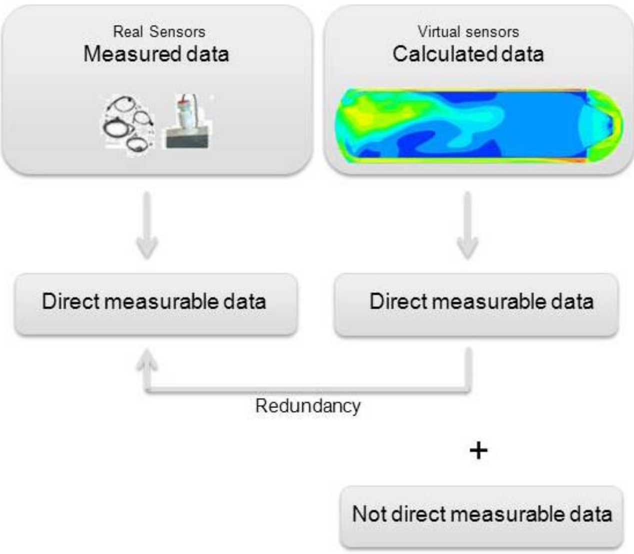

Fig. 5. Comparison of Real and Virtual Sensors

3.3 Central database

The key element of an information system forms a database where all data will be archived. Analysis of the collected data allows to find relations between different parameters in the production process, to detect deviations and to identify defects within the parts in production. In turn this knowledge can be used to improve the information content of the *MASTERBOX*.

While all information in conventional systems is used for post processing, the idea of the described database is that the data is available during the whole process. In this way, the information can be lead back in the running process giving the opportunity to learn from the experience of previous processes.

Further the recording shows what counter-measures lead to which consequences and additionally to adapt and optimize their parameters. This will indicate good or suitable reactions from bad or rather inappropriate reactions. This information can be used in next processes to select the best counter measures in case of process deviations.

3.4. Taking Decisions in the *MASTERBOX*

The developed communication system concept is working with the conventional state of the art PLC (programmable logic controller) which is controlling the temperature and pressure cycle in the autoclave. The *MASTERBOX* intervenes only in the *PLC* if deviations between target value and actual value become too high. These deviations can be detected in the *MASTERBOX* by analyzing and evaluating the information flows within the system. In this case, a decision making process is activated, supported by the database. The objective is making a decision out of an assortment of control strategies to set a new process course. The new process parameters are sent to the PLC where it is included to the original process cycle.

The *MASTERBOX* makes a distinction between sensor-guided and simulation-guided control. While the sensor-guided control is based on direct measured data through real sensors, the simulation-guided control is based on calculated values from the simulation. Both types of control are performed with the support of the database. Through this approach valuable computing time will be saved, because pre-calculated scenarios will not be calculated one more time. The experience and the knowledge of prior processes are passed in the *MASTERBOX* to adjust the optimal reaction for the curing process.

3.4.1 Sensor Guided Processes

The process monitoring sensors, for example for cure monitoring, can be used effectively to control and thus optimize the control sensors. In the conventional processes only indirect quality parameters like temperature are measured and used as control feedback. Although the cure reaction is primarily controlled by temperature, an exact curing by pure temperature control is not possible due to temperature measurement uncertainties. A direct cure control is highly advantageous as it is a direct quality parameter.

Usually the cure is divided into several steps, for example in the first step the resin is cured until gelation at a lower temperature to reduce residual stress. In the next steps the temperature is increased and the cure continued to final cure state (Fig. 6). With a simple temperature control, the process steps have to be sufficient long to reach the designated cure states, usually including high safety margins. When using cure monitoring in the running process the steps can be terminated as the designated cure state is reached and hence at the optimum time.

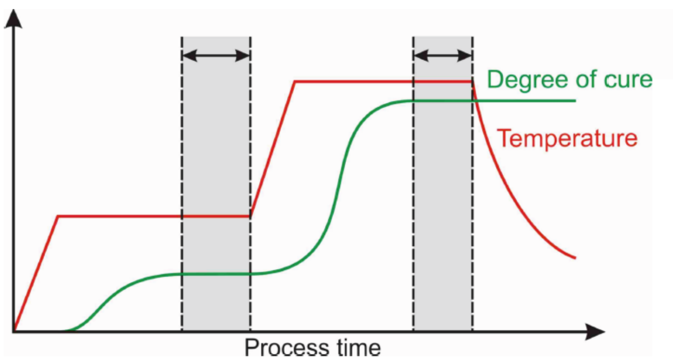

Fig. 6. Safety Margins in Conventional Cure Process

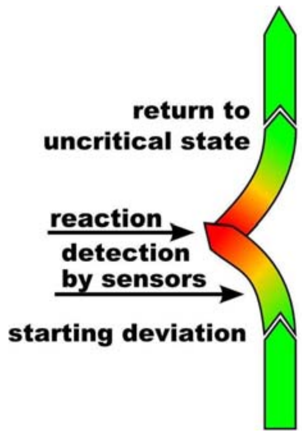

Fig. 7. Principle of Sensor-guided Process

This principle is applicable for other parameters which can be monitored and for which there are measures to be influenced (Fig. 7).

To give another example the laminate thickness can be obtained by ultrasound sensors and being influenced by pressure. As well as cold areas could be heated by additional heat systems.

3.4.2 Simulation-Guided Processes

One phenomenon in the curing process of thermoset resins is the exothermic reaction in which heat is released. Especially in thick laminates the released heat cannot be transferred outside because of the resin's low thermal conductivity. The released heat leads to an acceleration of the reaction and eventually a higher release rate. Finally the effect can cause thermal damage of the part. Due to the high thermal inertia this deviation must be detected and predicted far before occurring. This is not possible by measurements with sensors only (Fig. 7).

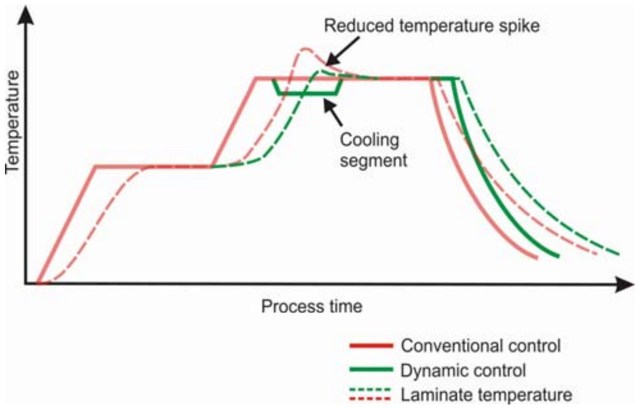

Fig. 7. Exothermic phenomena in conventional and dynamic autoclave control

Therefore the real-time simulation is performed during the running process detecting an overheating prior to arising. As correction measurement an auxiliary cooling phase is added to the process cycle. If applied correctly the maximum temperature of the exothermal heat remains within the limits. With the obtained process information by simulation it is possible to apply the right correction measures and monitors their impact (Fig. 8).

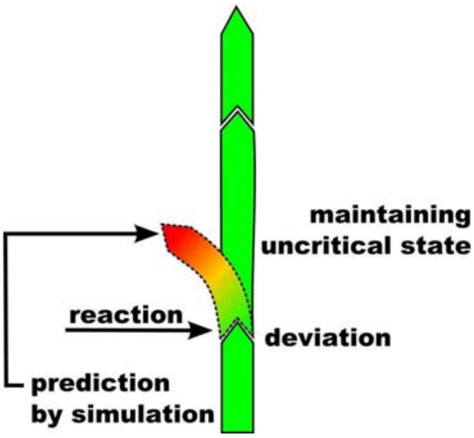

Fig. 8. Principle of real-time-simulation based control

4 Conclusion

We described and evaluated the state of the art composite production autoclave technologies and revealed their drawback of being inefficient and inflexible standing in discrepancy with todays and future demands for composite production.

A control concept addressing these challenges is being presented. It is based on process monitoring, real time process simulation and database connected by a control and communication center, called the *MASTERBOX*. The current state of development and results of these modules were discussed. As innovative sensor systems a thermography camera integrated into the autoclave and cure monitoring by especially adapted ultrasound sensors have been developed. For more advanced process control for systems with high inertia a real time process simulation running parallel to the real autoclave is in development. The data of performed processes is stored in a database and then analyzed for patterns, learn form experience and for optimizing future processes.

5 Outlook

The presented modules will be integrated into the autoclave lab unit and first evaluation tests will be performed. In the first phase the sensors and process simulation will run without any feedback to the autoclave. The acquired data is used for evaluation of each module. Based on the results a database of control strategies and counteractions will be developed as a step towards automatic cure processes which then will be evaluated in the next test phase. Finally the tests will provide a benchmark of the improvement of production duration, part quality and scrap part accomplished by the control system compared to state of the art processes.
But not only production processes of large or high volume parts will profit of the sensor and simulation based control system. As the run up time for designing processes can be reduced drastically the presented control system is also interesting for small volume production or where the process needs to be adapted to new materials or part design. Nevertheless are the developed modules limited to autoclave processes, they can be adapted to all other composite technologies.

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