Simulation-based optimization of the manufacturing process for a composite marine propeller

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In the article a manufacturing process used in the maritime industry will be treated. At the Voith Turbo Advanced Propeller Technologies GmbH & Co KG in Rostock thick-walled propeller blades, composed of CFRP and GFRP composite material, are produced in a compression molding process. The objective target is the investigation and description of measures to increase the component productivity and quality. For this prediction and visualization of the processes (flow-, pressure-, temperature- and degree of cure fields) applicable simulation models can be applied successfully. For the simulation models CFRP and GFRP material models are required. The development and validation of these material models by the help of experiments and simulations is described at the beginning of the article. After that these material models will be integrated and used in simulation models for the real compression molding process of the thick-walled propeller blade. It will be shown how the compression molding process can be influenced in a positive way by an optimization of the cooling equipment and the process control.

Introduction

The increasing application of CFRP and GFRP components in structural elements requires economically improved production processes for composite parts which fulfil highest productivity and quality requirements. The development of such production processes can not be based on a “trial-and-error” method due to the considerable costs of the CFRP and GFRP components and of the necessary tools. Modern simulation techniques which take into consideration the physical and chemical effects of the production process can be applied for a reliable prediction and optimisation of composite part manufacturing processes.

Composite materials are used for the propeller blades of Voith Contur Propellers and Voith Inline Thrusters. With these materials, the mass of the blades decreases and the vibration and damping characteristics greatly improves, compared to conventional bronze blades. Furthermore, the hydroelastic properties can be exploited to improve the efficiency in several load cases.

In the following chapters, the development and application of suitable simulation tools for the optimisation of the manufacturing process for a composite marine propeller is presented. The advantages of the application of these tools are discussed.

Abbildung 1: Marine propulsors with composite blades: Voith Contour Propeller (left) and Voith Inline Thruster (right)

The marine propeller is manufactured in a compression molding process. The advantage of the compression molding is the high geometrical precision and reproducibility of the composite part ([1], [2]). Additionally it is possible to avoid undesirably inclusions of air or foreign substances in the matrix material. During the manufacturing process the excessive epoxy resin is pressed through the prepregs out of the tool, so that a uniform resin distribution without inclusions is guaranteed.

Development of sophisticated simulation tools for process simulation

Identification of the CFRP and GFRP material behavior

For the propeller blade manufacturing no composite shells will be used. The whole volume consists of composite material. The part thickness of a propeller blade can be greater than 100mm. The exothermic heat increases with the composite part thickness and the maximal part temperature by equal cooling conditions, too. An exact knowledge of the exothermic processes and the effect of the temperature and degree of cure fields is especially important for a high part thickness. Too high maximal part temperatures respectively temperature- and degree of cure differences can cause a material damage (delamination) or a part deformation.

To simulate the mentioned phenomenon's correctly the knowledge of special composite material parameters is necessary. These are basically the thermal properties, released chemical heat and reaction kinetics of the temperature-dependent polymerisation.

The knowledge of the basic CFRP and GFRP material laws allows the simulation of the time-dependent heat transfer inside the tool and part structure. Essential simulation results are the time-dependent temperature and degree of cure distributions of the curing part.

The polymerisation reaction rate is described by the following equation:

$$\frac{d\alpha}{dt} = A\cdot(1-\alpha)^n\cdot\alpha^m\cdot e^{\left(\frac{-Ea}{Rm\cdot T}\right)}$$

α: Degree of cure,

A: Factor,

Ea: Activation energy,

Rm: molar gas constant,

T: Temperature,

n,m: Exponents.

The reaction rate $d\alpha/dt$ is integrated in a source term for the energy equation and also describes the time-dependent reaction progress.

The described material parameters were identified by the help of experiments and simulations (s. Figure 1 - Figure 3). The time-dependent temperature curves (s. Figure 2 and Figure 3) show the self-heating behavior of the curing plates. Due to the relative high plate thickness of 116 mm the exothermic heat causes a temperature rise to maximal 55℃ (GFRP) and 50℃ (CFRP) after approximately 8 hours process time. For the CFRP plate the maximum temperature is approximately 5K lower, because the carbon fibers can transport the reaction heat over the aluminum tool to the environment better due to its higher heat conductivity in axial fiber direction. After approximately 23 hours the tool is heated by water flowing through channels inside the tool. In this post-curing interval the part reaches over 95% degree of cure (s. time-dependent degree of cure curves in Figure 2 and Figure 3).

Figure 1: Documentation of the performed compression molding experiments for the identification of the CFRP and GFRP material behaviour

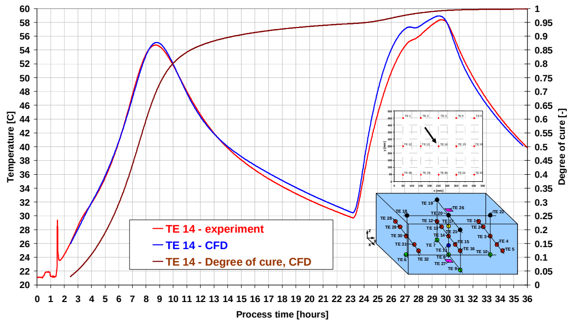

Figure 2: Comparison of the time-dependent measured (experiment) and simulated (CFD) temperature in the plate centre for the GFRP plate (0.5m x 0.5m x 0.116m)

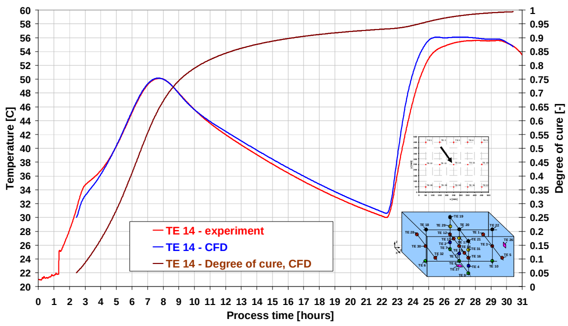

Figure 3: Comparison of the time-dependent measured (experiment) and simulated (CFD) temperature in the plate centre for the CFRP plate (0.5m x 0.5m x 0.116m)

Propeller blade model

The developed geometry and layer structure of the propeller blade model is shown in Figure 4. To reduce the material costs the inner volume is filled with GFRP (s. green layer in Figure 4). The propeller blade inside the form is presented in Figure 5. The previous developed CFRP and GFRP material parameters were integrated into the propeller blade model.

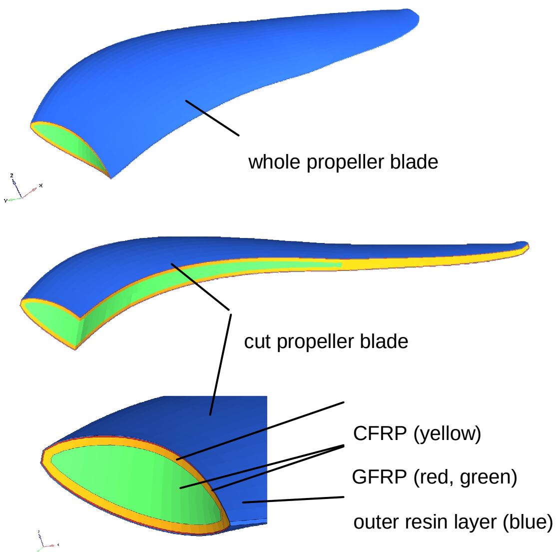

Figure 4: Propeller blade model with layer structure

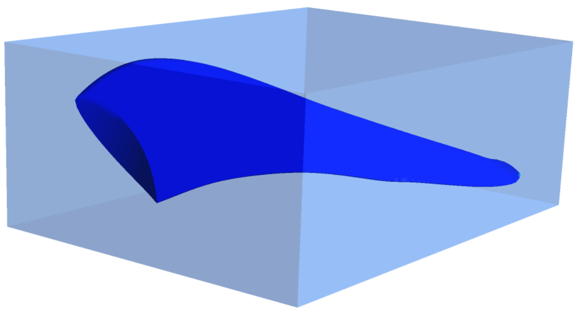
Figure 5: Propeller blade inside a form sand tool

Simulation of the standard compression molding process

Simulated time-dependent maximal temperature and degree of cure curves are shown in Figure 6 and Figure 7. The laying process of the propeller blade inside the open form needs approximately 3 hours. Then the form is closed and for the standard compression molding process no active convective water cooling is used. Starting at a process time of 18 hours the form is heated by a convective water flow through channels inside the form.

The maximum temperature inside the inner GFRP volume by self-heating is 70℃ after 8 hours process time (s. also). After the maximum heat release the part temperature decreases. To increase the degree of cure, especially at the part surface region with a relatively low temperature, the blade is heated actively by a water flow with a temperature of 50℃. After this 3 hours heating interval it is possible for an additional post curing to add an interval with 70℃ water temperature.

Due to the accruing temperature differences there are also induced degree of cure differences between the part centre and the surface with a maximum of 68.5% after 9.48 hours process time (s. Figure 7).

To reduce residual stresses and thereby to improve the part quality the compression molding process of the propeller blade can be optimised by an additional cooling equipment in the blade centre and also by changing the water temperature cycle.

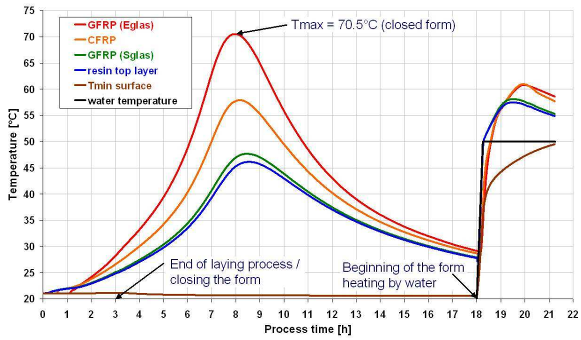

Figure 6: Standard compression molding process - maximal time-dependent temperature curves

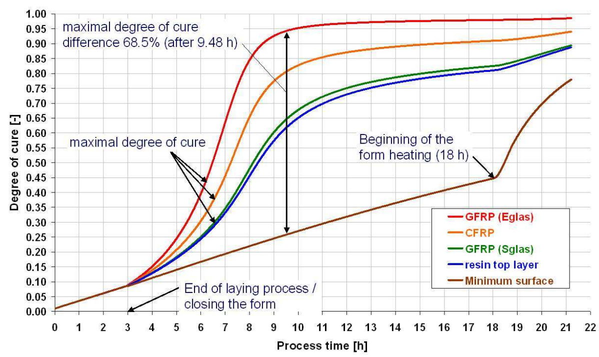

Figure 7: Standard compression molding process - maximal time-dependent degree of cure curves

Simulation of improved compression molding processes

To improve the thermal boundary conditions two models with an additional inner cooling area were generated (s. Figure 8 and Figure 9). The larger inner cooling area is an idealized case and the smaller inner cooling area is a more realistic case with an simplified model of one inner cooling tube.

In the simulations two different water temperature cycles were used:

* cycle 1:

< 3h-7h: 20℃,

< 7.125h-11.125h:35℃,

< 11.25h-14h: 50℃.

* cycle 2:

< 3h-11h: 20℃,

< 11.125h-18.125h:35℃,

< 18.25h-24h: 50℃.

After the end of the laying process and closing the form at 3 hours process time the active water cooling starts with the mentioned temperature cycles.

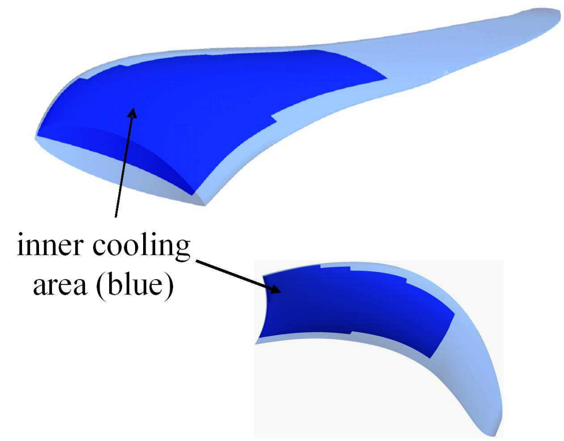

Figure 8: Compression molding process with improved thermal boundary conditions - propeller blade model with the larger additional inner cooling area (blue)

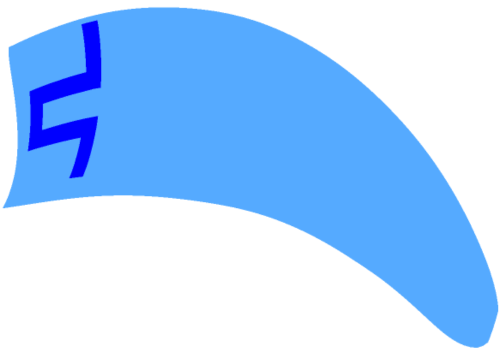

Figure 9: Compression molding process with improved thermal boundary conditions - propeller blade model with the smaller additional inner cooling area (blue)

For the larger cooling area (cycle 1, see Figure 10 and Figure 11) the inner convective water cooling reduces the composite process temperatures and degree of cure differences. In the 35℃ water temperature interval (7h - 11h) the maximal composite temperature reaches 47℃. The maximal degree of cure difference after 11h: is 16.1%. Compared to the standard cycle this difference decreases from 68.5% to 16.1% degree of cure or relatively by -76.5%. Therefore, due to the improved thermal boundary conditions, an increased part quality can be expected.

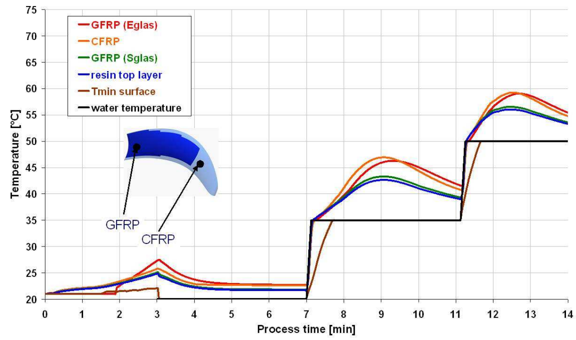

Figure 10: Compression molding process with improved thermal boundary conditions (larger inner cooling area, water temperature cycle 1) - maximal time-dependent temperature curves

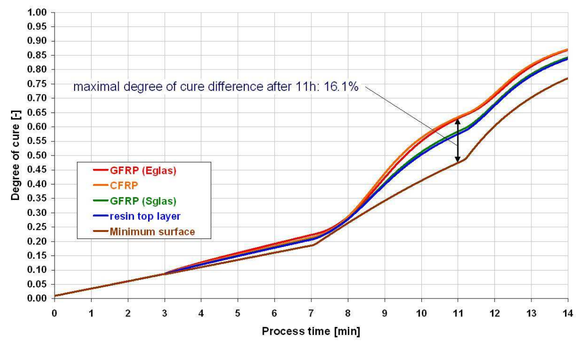

Figure 11: Compression molding process with improved thermal boundary conditions (larger inner cooling area, water temperature cycle 1) - maximal time-dependent degree of cure curves

For the smaller cooling area (cycle 1, see Figure 12 and Figure 13) the inner convective water cooling doesn't reduce the composite process temperatures. In the 35℃ water temperature interval (7h - 11h) the maximal composite temperature reaches 77.5℃ in the composite centre. The maximal degree of cure difference after 11.1h: is 47.5%. Compared to the standard cycle this difference decreases from 68.5% to 47.5% degree of cure or relatively by -30.7%.

To improve the process with the smaller inner cooling area the 20℃ water temperature cycle can be extended up to e.g. 4h. The results in

Figure 14 and Figure 15 show the corresponding improvement. In the 35℃ water temperature interval (11h - 18h) the maximum composite temperature reaches 52.1℃ in the composite centre. The maximum degree of cure difference after 11.1h: is 28.1%. Compared to the standard cycle this difference decreases from 68.5% to 28.1% degree of cure or relatively by -59%.

To be able to compare the four treated cases of the compression molding process in Figure 16 and Figure 17 temperature and degree of cure distributions inside the propeller blade are shown additionally.

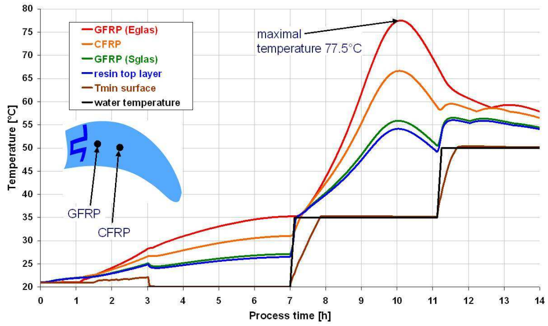

Figure 12: Compression muolding process with improved thermal boundary conditions (smaller inner cooling area, water temperature cycle 1) - maximal time-dependent temperature curves

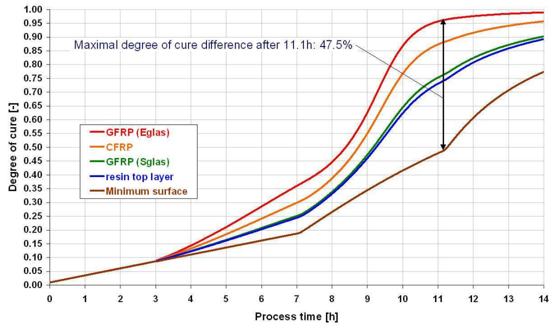

Figure 13: Compression molding process with improved thermal boundary conditions (smaller inner cooling area, water temperature cycle 1) - maximal time-dependent degree of cure curves

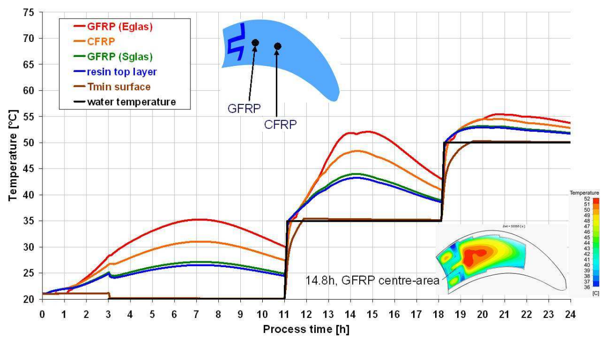

Figure 14: Compression molding process with improved thermal boundary conditions (smaller inner cooling area, water temperature cycle 2) - maximal time-dependent temperature curves

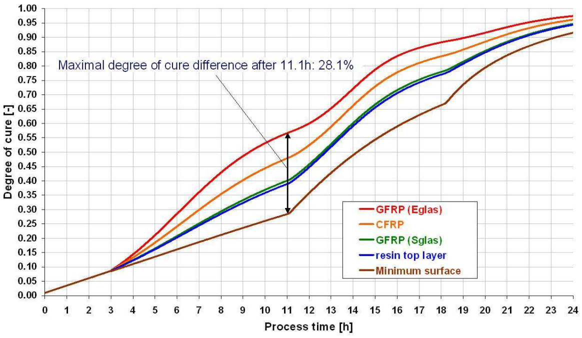

Figure 15: Compression molding process with improved thermal boundary conditions (smaller inner cooling area, water temperature cycle 2) - maximal time-dependent degree of cure curves

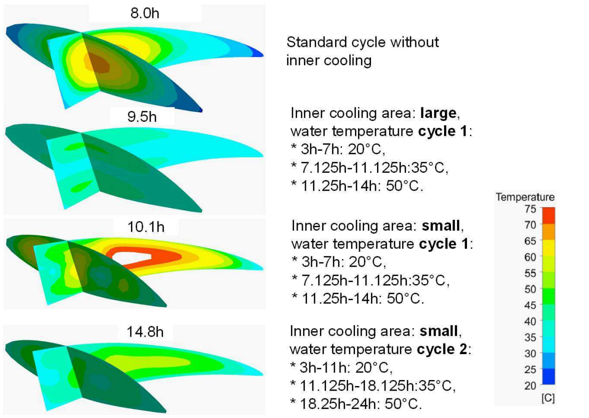

Figure 16: Comparison of results - Temperature distribution inside the propeller blade at the process time with the maximal part self-heating temperature

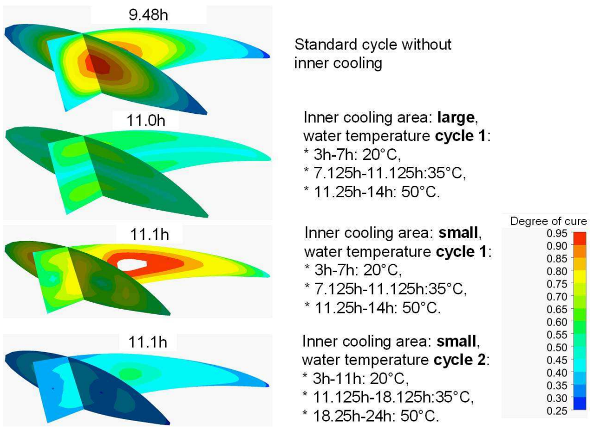

Figure 17: Comparison of results - Degree of cure distribution inside the propeller blade at the process time with the maximal degree of cure difference

Summary

In a first step CFRP and GFRP material parameters were identified by described experiments and simulations. The developed CFRP and GFRP material parameters were integrated into generated simulation tools for the compression molding process of the propeller blade.

The simulation results show that with a cooling equipment in the thick-walled propeller blade centre the maximal composite temperatures and degree of cure differences can be decreased compared to a standard process without an inner cooling area (see Figure 18 and Figure 19). Therefore the part quality of the compression molding process can be improved by the help of an additional inner cooling equipment. The extend of the inner cooling area determines the efficiency of the improvement measure. By using a relatively large inner cooling area the maximal degree of cure difference of the part can be reduced from 68.5% (standard cycle) to 16.1%. For a smaller inner cooling area it is also possible to get a significant process improvement. In an example with an extended 20℃ water temperature interval of about 4 hours the maximal degree of cure difference of the part can be reduced from 68.5% (standard cycle) to 28.1%.

The simulation tools are able to analyze different thermal boundary conditions and water temperature cycles with the possibility to give defined advices for the optimisation of the compression molding process of a maritime propeller blade.

Aside from the compression molding process it is also possible to manufacture a propeller blade in a RTM process. For the RTM process development and optimisation also relevant simulation tools can be generated and used.

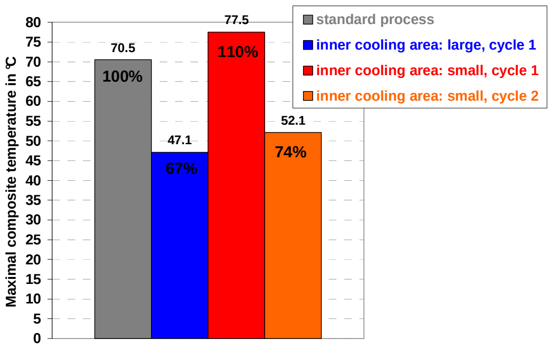

Figure 18: Comparison of different simulated cases - maximal composite temperature

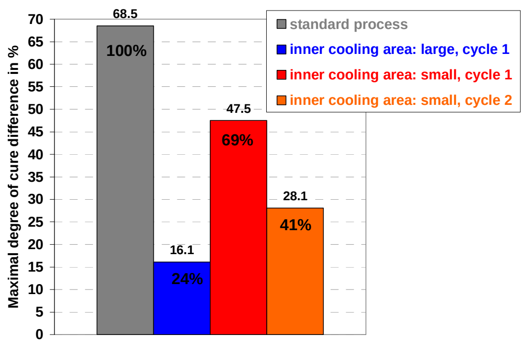

Figure 19: Comparison of different simulated cases - maximal degree of cure difference

References

[1] P.R. Fabri: CFK-fan-blades, Faserverbundwerkstoffe im Triebwerksbau, mobiles 34

[2] United States Patent, Patent Number 5,843,354, 1.12.1998: Method for compression molding a fan blade