Theoretical and experimental validation of critical properties of composite processes

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Introduction

During the manufacturing of CFRP components one of the most critical process steps is the vacuum bagging. In this process several layers of material are draped separately over complex part shapes. The specific properties of each material are needed for the process (i.e. breathing capability, release property, air tightness) and result into a complex overall behaviour with respect to the process curve.
The aim of the study is to analyze the thermal behavior of a given vacuum bagging (either conventional one made from several layers or a new generation of bagging materials) with respect to heat transfer through conduction and radiation mainly. A COMSOL model has been set-up and tested with the capability to include different relevant bagging materials.

Experimental Set-up

The new bagging material exists only out of one layer compared to standard vacuum bagging set-ups out of three or more layers. The necessary properties will be included in one foil, which can be shaped to the needed geometry. The idea is to identify the specific thermal behavior of the materials with an IR emitter and to validate them using a simulation model in parallel. A comparison of different bagging materials can be done with respect to their thermal behavior.
For the basic model without the bagging material an aluminium plate (2000 mm x 500 mm x 8 mm) with a moving IR emitter is used. The emitter is moving with a constant distance and velocity to the substrate surface.

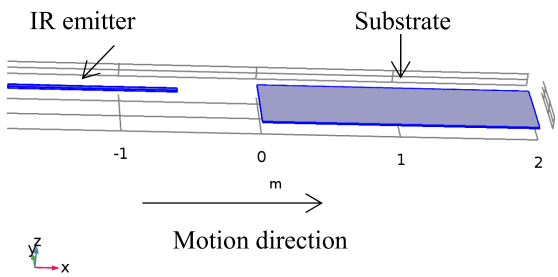

Figure 1: Experimental set-up in Comsol

The IR emitter is used in a preheated stage to achieve a reproducible result for the convection and up to twelve thermocouples are used to detect the resulting heat at the surface of the substrate. The thermocouples are positioned under 90° and 60° angle to the emitter and probes are positioned at the same coordinates in the COMSOL model. The geometry of the IR emitter is approximated out of two tubes with a glass surface and a reflector on the upper surface.

Use of Simulation

For the simulation different modules from COMSOL were used to simulate the same boundary conditions as in reality. To simulate the movement of the IR emitter, the module 'Solid Mechanics' from the physics interface is used with a prescribed velocity of 45 mm/s.
The heat transfer is composed out of the three different mechanisms thermal conduction, convection and radiation and is included in the model with the module Heat Transfer with Surface-to-Surface Radiation.

$$\dot{Q} = \dot{Q}_{cond} + \dot{Q}_{conv} + \dot{Q}_{rad}$$

The calculation and description of the thermal conduction can be obtained by the Fourier approach:

$$\dot{q}_{cond}'' = \frac{\dot{Q}}{A} = -\lambda * \frac{\Delta T}{\Delta z}$$

$$\dot{Q} = -\lambda * A * \frac{\Delta T}{\Delta z}$$

While $\dot{q}_{cond}''$ is the vector of the heat flux density, $\dot{Q}$ is the heat flux with the specific thermal conductivity λ and A the area where the heat flows through with a thickness Δz and the temperature difference through the material. These parameters are included in the module 'Heat transfer in Solids'.
The transport phenomenon of convection is described by the law of Newton:

$$\dot{q}_{conv}'' = \alpha * (T_{air} - T_{sub})$$

While $\dot{q}_{conv}''$ is the vector of the heat flux density for the convection, α is the heat transfer coefficient of the material and the temperature difference between the air and the substrate. The heat flux is included as an external forced convection with a velocity of 2.2 m/s in the model.
The thermal radiation from the IR emitter is described by the Stefan-Boltzmann Law and the resulting heat flux density:

$$\dot{E} = \varepsilon * A * \sigma * T_s^4$$

$$\dot{q}_{rad}'' = \varepsilon * \sigma * (T_{s,1}^4 - T_{s,2}^4)$$

Herein $\dot{E}$ is the emission of a real emitter, ε the emission coefficient, ΔT the temperature difference of the IR emitter and the substrate and σ the Stefan-Boltzmann constant of $5.67 * 10^{-8}\ W/m^2K^4$. The surface of the IR emitter is defined with an emission coefficient ε of 0.95 and a temperature T_s of 1200°C.
For the calculation of the heat transfer the material parameter are needed and for the aluminium substarte the parameters from the material database are used (Aluminium 6063-T83):

Table 1: Material properties aluminium substrate

Name	Value	Unit
Heat capacity at constant pressure	900	J/(kg·K)
Density	2700	kg/m³
Thermal conductivity	201	W/(m·K)
Surface emissivity	0.8	1

For the additional bagging material following values have been defined:

Table 2: Material properties bagging substrate

Name	Value	Unit
Heat capacity at constant pressure	CPWerte(T)	J/(kg·K)
Density	1.258	g/cm³
Thermal conductivity	0.35	W/(m·K)
Surface emissivity	0.85	1

The material density was meassured as well as the heat capacity at constant pressure dependent on the temperature.

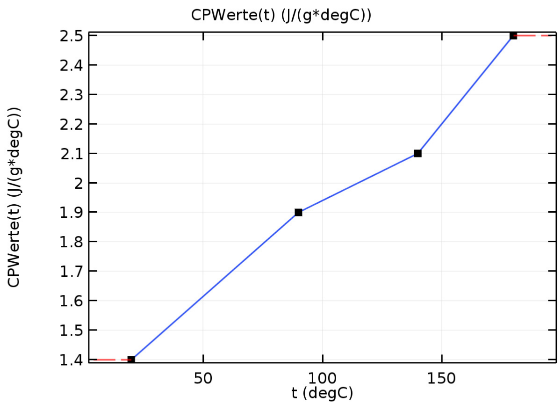

Figure 2: Measured heat capacity dependent on the temperature

The new bagging material is placed as a thin layer on the surface of the aluminium plate within the heat transfer modul asuming a perfect connection of the surface between aluminium substrate and bagging material. The material thickness is defined with 0.5 mm and thermal conductivity and surface emissivity are expected values from the literature. The model is calculating only with the primary radiation and no extra reflection surfaces are used.

Experimental Results and Results from Simulation

In a first step, a test only with the aluminium plate and without the bagging material has been done, followed by a comparison with the results from COMSOL.

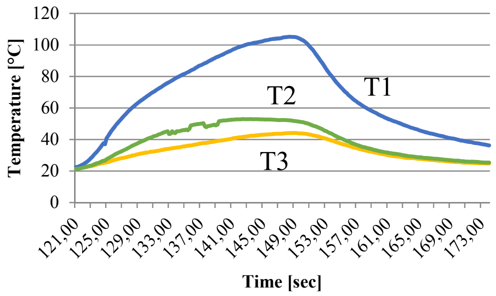

Figure 3: Measured temperature on aluminium plate

The three thermocouples on the surface are located under 90° (T1 blue) and 60° (T2 green and T3 yellow) angle to the IR emitter. The one directly located under the emitter is increasing up to 105°C and the other two are significantly lower between 42°C and 50°C. In comparison to that, the probes of the simulation are showing a lower increase only up to 42°C.

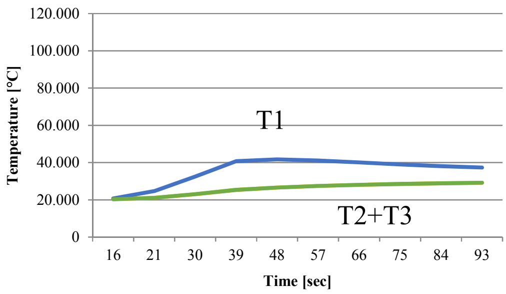

Figure 4: Simulated temperature profile

The values of the simulated temperature curves are lower than the measured ones as well as the gradient of the cooling.
The same test has been done with the surface covered by a bagging material under vacuum for the trial and the integration of the thin layer in the simulation.

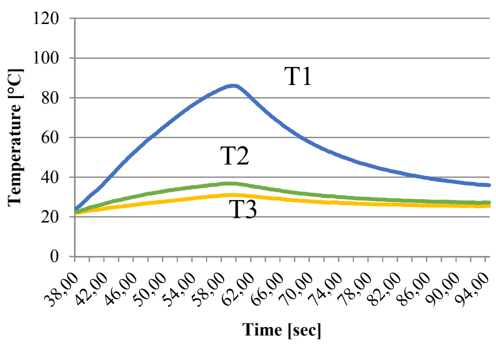

Figure 5: Measured temperature with bagging material

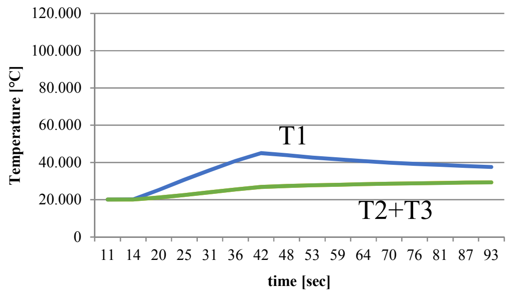

Figure 6: Simulated temperature profile with bagging material

The same behaviour as in the first test can be seen like lower maximum temperatures and cooling rates in the simulation compared to the trial results. The width of the heat allocation underneath the IR emitter can be seen in the figure below.

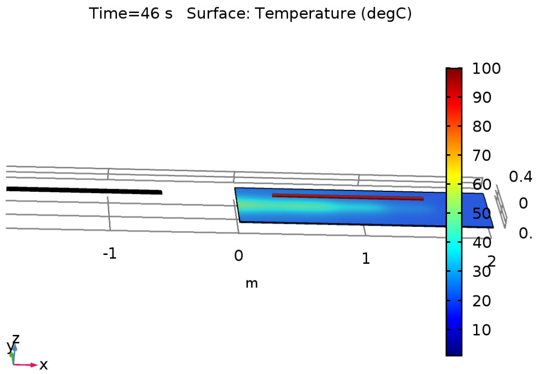

Figure 7: Heat allocation of IR emitter on surface

Conclusion and way forward

Current results show that the model assumptions are not sufficient to accurately predict the temperature evolution over time. The higher cooling rate at the surface for the trial could be caused by the convective part of the cooling fan from the IR emitter. The fan has an inflow velocity perpendicular to the substrate surface of ~ 2,217 m/s. As a next step the convection through the cooling fan will be implemented as well as slight adaptations on the thermal properties. The simulation of the fan and the adaptation of the material emission coefficients within the model will change the peak temperatures.

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