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Designing of the Heating Process for Fiber-Reinforced Thermoplastics with Middle-Wave Infrared Radiators

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Abstract**—**Manufacturing components of fiber-reinforced thermoplastics requires three steps: heating the matrix, forming and consolidation of the composite and terminal cooling the matrix. For the heating process a pre-determined temperature distribution through the layers and the thickness of the pre-consolidated sheets is recommended to enable forming mechanism. Thus, a design for the heating process for forming composites with thermoplastic matrices is necessary. To obtain a constant temperature through thickness and width of the sheet, the heating process was analyzed by the help of the finite element method. The simulation models were validated by experiments with resistance thermometers as well as with an infrared camera. Based on the finite element simulation, heating methods for infrared radiators have been developed. Using the numeric simulation many iteration loops are required to determine the process parameters. Hence, the initiation of a model for calculating relevant process parameters started applying regression functions.

Keywords**—**Fiber-reinforced thermoplastics, heating strategies, middle-wave infrared radiator.

I. Introduction

FOR fiber-reinforced constructions and components there is an increasing use of semi-finished products in form of sheets with thermoplastic matrix systems to realize small production cycle times. Generally, the manufacturing of components of fiber-reinforced thermoplastics requires three steps: heating the matrix, forming and consolidation of the composite and terminal cooling of the matrix. For the heating process a pre-determined temperature distribution through the layers and the thickness of the semi-finished product is recommended to enable necessary forming mechanism [1], [2] like transverse and shear flow of fibers or inter-ply slip and rotation. Furthermore, experiments on forming processes demonstrate positive and negative spring-in of the formed geometry, shown in Fig. 1. To determine decisive parameters for the spring-in a die bending tool has been designed. The forming temperature, radii and the consolidation time have been analyzed. Finally, the forming temperature is one of the most important factors for the contour accuracy. A controlled heating process has to be guaranteed by a continuous temperature measurement. Different methods are suitable for heating fiber-reinforced thermoplastics like hot-chamber ovens, contact or radiant heaters. Infrared radiators are an effective solution for serial productions. However, an economically measurement of the temperature is only possible at the surface and insufficient to obtain information about the temperature distribution of the center layers-especially heating sheets of large wall thicknesses. Thus, a design for the heating process for forming composites with thermoplastic matrices is necessary.

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Fig. 1 Spring-in effects of formed fiber-reinforced thermoplastics according to the process temperature

II. Proceeding

First of all, two series of experiments were carried out to determine the temperature distribution while heating the composite specimen by middle-wave infrared radiators. Infrared pyrometers measured the temperature on the top and the bottom surface during the whole process. The specimens with a length of x = 300.0 mm and a width of y = 100.0 mm for the first experiment were manufactured of completely consolidated sheets of glass fibers embedded in polyamide 6.6 with a thickness of z = 1.5 mm. The fibers were woven to twill and stacked up to three plies. The fiber volume content was 45%. The dimensions and technical data of the experimental set-up are shown in Fig. 2. At the end of the first experimental series the surface temperature distribution was recorded using an infrared camera.

In the second experiment, resistance thermometers were inserted between the fabric layers and on the surface of the composite specimens with a thickness of z = 3.0 mm and a diameter of d = 93.0 mm in order to measure the change in temperature in the sheet. The experimental set-up was similar to the first one. Only the reflecting sheets were replaced by a wire grid to minimize heat conduction. After reaching the defined temperature on the surface the specimens were transferred to an aluminum tool. The transfer took t_{Trans} = 12.0 s while the specimens cooled down by convection. Following, two finite element simulation models were generated with the software ABAQUS to analyze the temperature distribution through thickness and width of the fiber-reinforced thermoplastic. A validated model reduces the number of experiments for further material set-ups.

Model I serves the determination of the heating curve of the radiators, the inspection of the implemented material properties, interactions and thermal behavior and is validated by infrared pictures of the first experimental series, which were also used to research the lateral temperature distribution on the surface of the sheet. The model considers the three types of heat transfer: convection, conduction and radiation. The implemented material properties and model parameters are shown in Table I. Mesh Elements of the type heat transfer, a linear geometric order and an implicit solver were used for the numerical calculation.

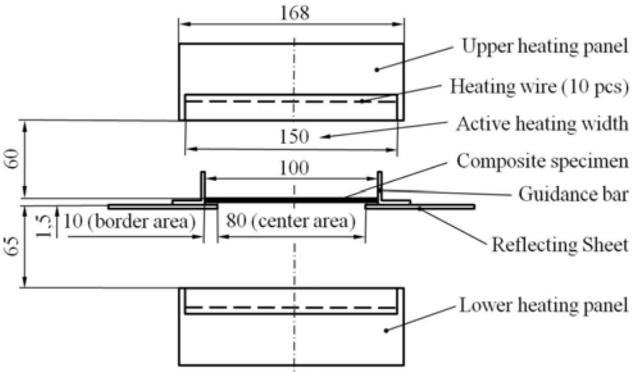

Fig. 2 Experimental set-up

TABLE I
INITIAL PROPERTIES AND PARAMETERS OF THE FINITE ELEMENT MODEL

Symbol	Quantity	Reflecting sheet	Heating panel	Composite
ρ	Density [kg/dm³]	2.70	7.85	1.80
c_p	specific heat [J/(gK)]	850.00	500.00	2300.00
λ	Conductivity [W/mK]	236.00	42.00	0.33
T_0	initial temperature [°C]	20	20	25
T_a	ambient temperature [°C]	20		
α	heat coefficient [W/(m²K)]	5.00		
ε	emissivity [-]	0.97		
f_v	view factor [-]	0.30		
σ_{Bolz}	Stefan-Bolzman-constant [W/(m²K⁴)]	5.667 x 10^8		

Model II is utilized to research the temperature distribution through the wall thickness and to obtain information about the influence of process parameters, such as ambient temperature T_a, heat coefficient α and radiator distance d_R. Model II is based on the results of the first simulation model and uses identical properties and parameters. Model II is validated by the second experiment. Thus, heat transfer by conduction to the reflecting sheets did not take place. Subsequently, heating strategies were developed realizing homogeneous temperature distributions based on the finite element simulation. To simplifying future heating jobs and to support the adjustment of process parameters regression functions had been derived from the simulation for the chosen composite material.

III. RESULTS

A. Surface Analysis

The first experiment and simulation focus on determination of the temperature and amplitude for the radiators and the temperature distribution on the top and the bottom surface of the thermoplastic composite sheet. Thus, the longitudinal change in temperature for L1, L2, L3 and the transverse change in temperature for T1, T2, T3 as shown in Fig. 3 of the recorded infrared pictures were compared to identical node lines of the modeled composite sheet for the validation.

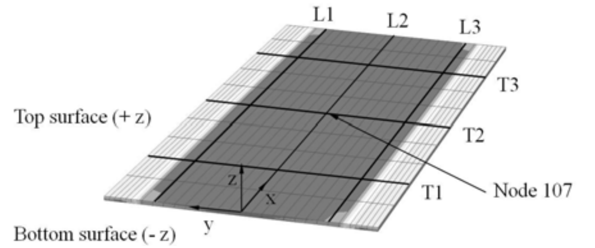

Fig. 3 Longitudinal and transverse node lines for validation of the lateral temperature distribution

The increase in temperature measured by infrared pyrometers was compared with node 107 on the top surface and node 552 on the bottom surface. 80% of the energy is available after *6 s* according to the manufacturer of the middle-wave radiators. Thus, several amplitudes for the specification of the heating curve for the radiators had been designed (see Fig. 4).

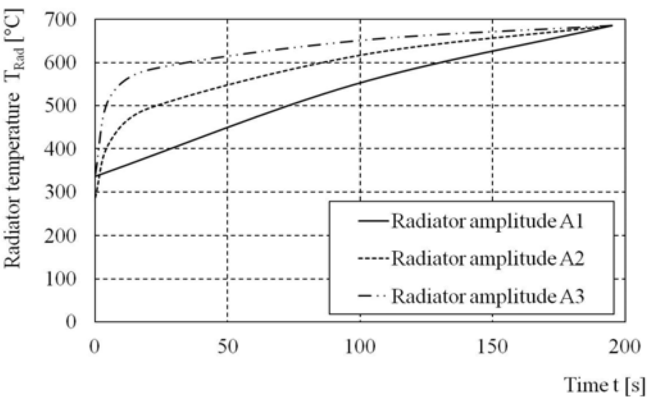

Fig. 4 Radiator amplitudes

Regarding the change in temperature of node 107 and 552 amplitude A3 reproduces the experimental results closest. But quantitative variations appeared. The constant specific heat of the composite was substituted by thermal-coupled data. According to [3] the data were calculated using equation (1) based on the mass fraction of the fibers ψ_{fiber} and the matrix ψ_{matrix} as well as the specific heats of fibers $c_{p,fiber}$ and matrix $c_{p,matrix}$.

$$c_p(T) = \psi_{fiber} \cdot c_{p,fiber}(T) + \psi_{matrix} \cdot c_{p,matrix}(T) \qquad (1)$$

As in [4], the specific heat of glass fibers is constant at $c_{p,fiber}$ = 0.825 J/(gK) up to a temperature of T = 400 °C for the type E-glass and independent of the architecture of the fabric [5]. Data for the thermal-coupled specific heat of polyamide 6.6 $c_{p,matrix}$ were taken from [6] and fragmentary linearized. Finally, the implementation of the thermal-coupled specific heat is essential for the simulation of composite heating processes, shown in Fig. 5 using radiator amplitude A3.

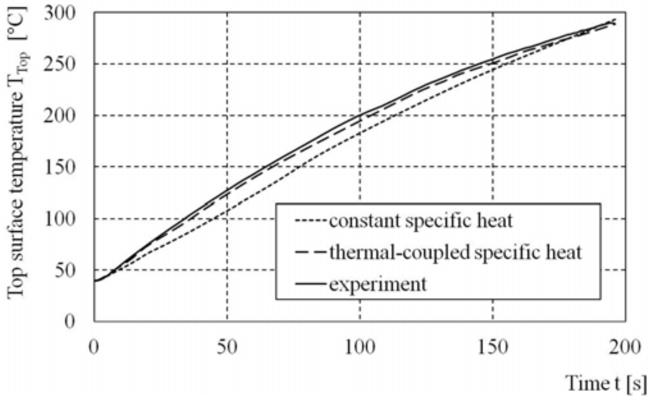

Fig. 5 Temperature curve of the composite sheet with constant and thermal-coupled specific heat in comparison to experimental results

The lateral temperature distribution was analyzed after adjusting the parameters for the radiator and substituting the constant with the thermal-coupled specific heat. The simulated temperature distribution of the composite nearly fits the measurement in the completely heated region, called center area. The regions covered by the reflecting sheets (border area) exhibit lower temperatures than in the experiments. Getting information about relevant model parameters to increase heat transfer by conduction in the border areas, a sensitivity analysis was carried out. The analyzed parameters and their ranges are shown in Table II.

TABLE II
PARAMETERS AND RANGES FOR THE SENSITIVITY ANALYSIS OF MODEL I

Symbol	Quantity	Range
T_a	ambient temperature [K]	20–100
α	heat coefficient [W/(m²K)]	3.00–15.00
e	Element size [mm]	1.0 0–10.00
$T_{0,RS}$	Initial temperature of the reflecting sheet [K]	20–100
f_v	view factor [-]	0.10–0.50

The results of the sensitivity analysis are separately normalized, to increase the assessment of the influence of parameters regarding border and center area (see Fig. 6). The element size e and the initial temperature of the reflecting sheets $T_{0,RS}$ are significant to improve Model I in the border area. Due to the center area the view factor f_v, the heat coefficient α and the ambient temperature T_a are the major factors. To simulate lateral temperature distribution Model I was verified using the analyzed parameters. Fig. 7 visualizes the iterative improvement of the model. At last the maximum deviation for the border and center area was 9.4 % and 3.9 %, respectively.

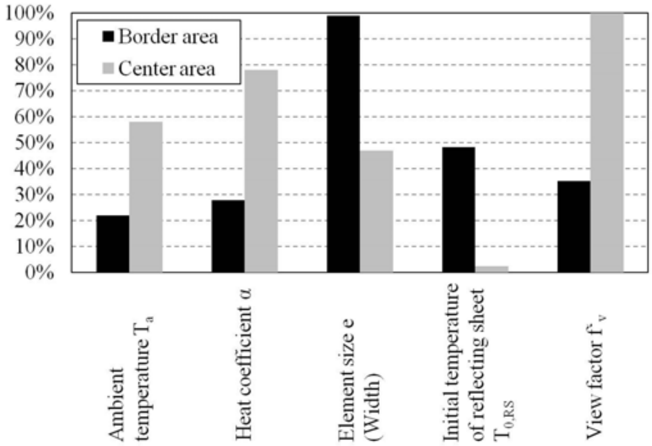

Fig. 6 Normalized parameters to determine the influence on the modeled heating process

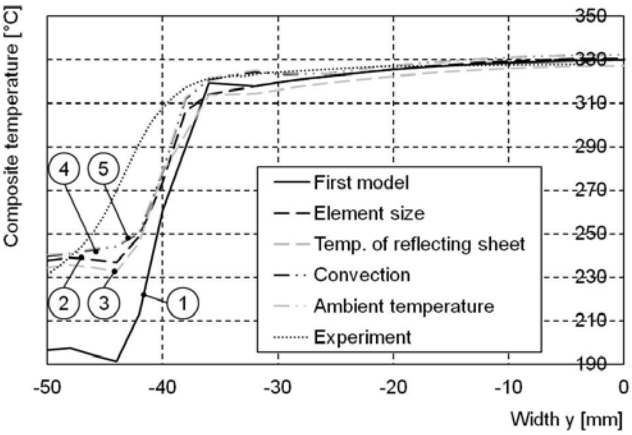

Fig. 7 Steps of improvement from first to verified model

B. Thickness Analysis

To analyze the influence of the composites wall thickness and several process parameters a second simulation model was generated. In contrast to Model I the second model included also cooling by convection while transferring the composite sheet to the tool. To validate Model II several nodes on the surface (*Top 1*, *Top 2*, *Bottom 1* and *Bottom 2*) and center layer (*Center 1* and *Center 2*) were compared with the experimental results, shown in Fig. 8.

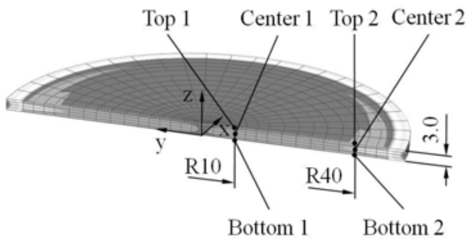

Fig. 8 Nodes for validation on top and bottom surface and the center layer of the modeled specimen

The experimental determination of the heat coefficient α as the major factor for convection was not possible. Thus, the implemented heat coefficient was varied in iterative loops between $\alpha = 10$ W/(m²K) to $\alpha = 30$ W/(m²K). Finally, a heat coefficient of $\alpha = 30$ W/(m²K) fits for both temperature curves of the experiment surface and the center layer.

The radiator distance d_R, the ambient temperature T_a, the wall thickness z and the heat coefficient α were varied in ranges, listed in Table III, in order to determine their influence on the temperature distribution through the composite sheet during the heating process and the transfer.

TABLE III
PARAMETERS AND RANGES FOR THE SENSITIVITY ANALYSIS OF MODEL II

Symbol	Quantity	Range
s	wall thickness [mm]	0.50 – 3.00
d_R	radiator distance [mm]	20.00 – 140.00
T_a	ambient temperature [°C]	20 – 100
α	heat coefficient [W/(m²K)]	5.00 – 30.00

To exclude the influence of the specimens geometry on the temperature distribution the change in temperature for nodes of a round sheet with a diameter of d = 93 mm, shown in Fig. 8, were compared with the temperature distribution of a squared sheet. For this sensitivity analysis an identical feed size was used.. The total variation of temperature through width and thickness of the sheets was lower than 1 °C. The influences of the wall thickness s and the radiator distance d_R are displayed in Fig. 9 and Fig. 10.

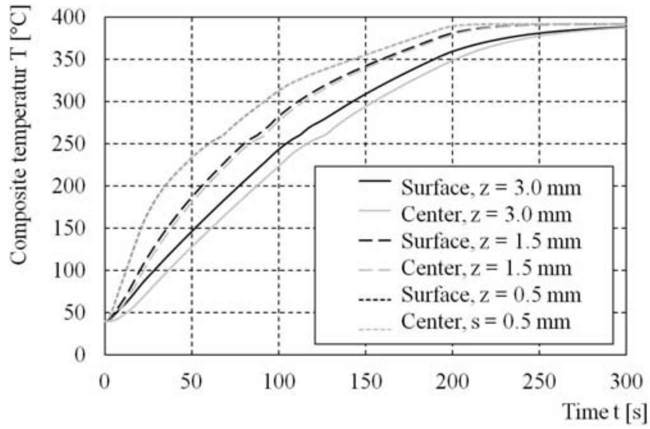

Fig. 9 Influence of the wall thickness z using a radiator distance of d_R = 20.0 mm

Both parameters visualize an increase in time to reach the forming temperature of T_{Form} = 250 °C. Furthermore, thin sheets could be heated nearly homogeneous while the temperature of the center layer lags the surface temperature for major wall thicknesses, significantly. However, the lag in temperature decreases by major radiator distances. The maximum composite temperature is adjustable using a specific radiator distance d_R. For a forming temperature of T_{Form} = 250 °C the radiator distance has to be adjusted at d_R = 115 mm. Beyond that, the influence of the ambient temperature T_a and the heat coefficient α on the cooling had been analyzed while transferring the composite sheet. The ambient temperature T_a has a minor effect on the cooling. The total variation of the temperature distribution is less than ΔT = 2 °C (see Fig. 11). Varying the heat coefficient α in the mentioned range the temperature distribution is less than ΔT = 3 °C, but requires an increase in transfer time of Δt = 5 s, shown in Fig. 12.

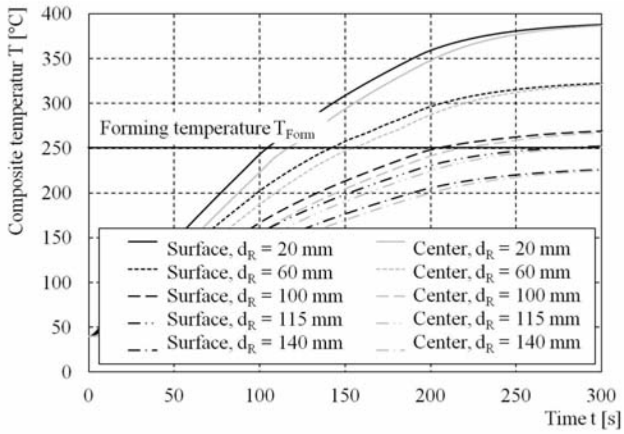

Fig. 10 Influence of the radiator distance d_R for a wall thickness of z = 3.0 mm

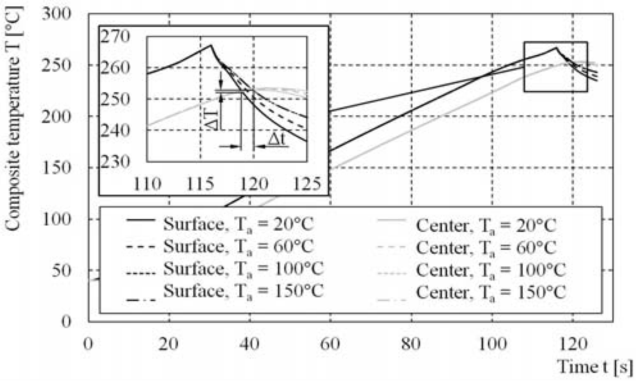

Fig. 11 Influence of the ambient temperature T_a while cooling

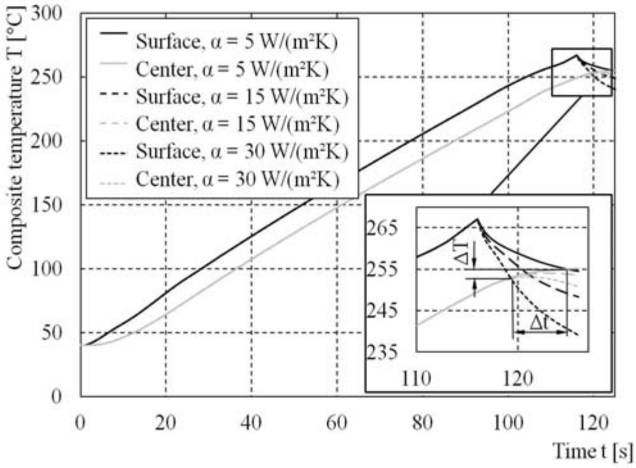

Fig. 12 Influence of the heat coefficient α while cooling

C. Heating Strategies

To heat up reinforced thermoplastics, three heating strategies have been developed. The first heating strategy is called *immediate transfer (HS1)*. The transfer of the sheet is carried out directly after achieving the forming temperature T_{Form}. The second method named *intersecting temperatures (HS2)* uses the effect of surface cooling after finishing the heating process while the temperature of the center layer T_C is still increasing by heat transfer. The forming temperature is reached as soon as the temperatures of top and middle layers intersect each other. Using the third heating strategy *radiator distance (HS3)* the forming temperature T_{Form} of the thermoplastic sheet is realized by adjusting the radiator distance d_R. The three heating strategies are visualized in Fig. 13.

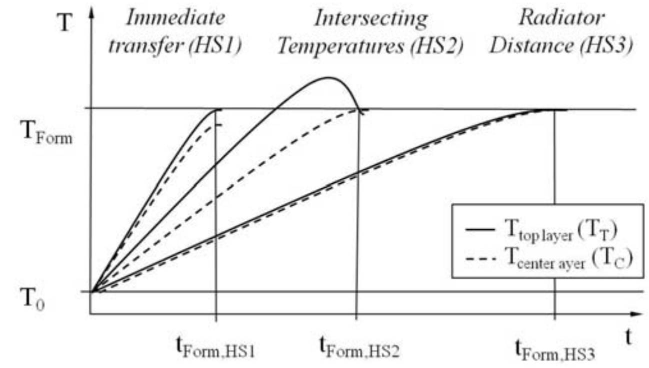

Fig. 13 Heating strategies

Following, the heating strategies are analyzed regarding the temperature distribution through wall thickness z and width y for a forming temperature of T_{Form} = 250 °C. Using *HS1* only thin sheets up to wall thicknesses of z = 0.5 mm can be heated homogeneous. According a wall thickness of z = 1.5 mm similar results for the temperatures of the nodes *Top 1* and *Top 2* as well as for the nodes *Bottom 1* and *Bottom 2* were read out. However, the temperature distribution through the wall thickness achieves a difference of more than ΔT = 5 °C. A Further increase of the wall thickness effects both an increase in temperature variation through thickness and width, represented in Fig. 14.

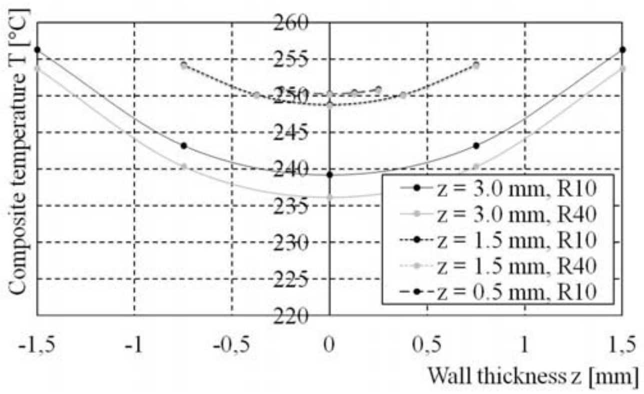

Fig. 14 Temperature distribution through composite sheets using *HS1*

The maximum variation in temperature for a wall thickness of z = 3.0 mm through the width and thickness of the specimen is approximately ΔT = 20 °C.

Heating composites with *HS2* the global temperature variation of every analyzed thickness decreases and becomes more homogeneous. The graphs shown in Fig.15 demonstrate a decrease in temperature for top and bottom surface caused by surface cooling while the center layer is influenced by heat transfer through conduction.

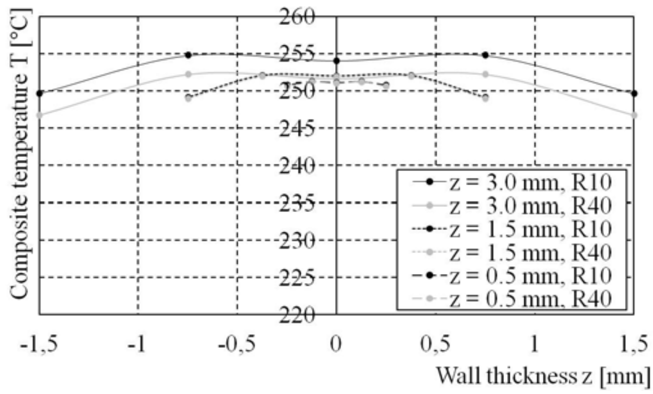

Fig. 15 Temperature distribution through composite sheets using *HS2*

A further improvement for the temperature distribution through the thickness can be reached by *HS3* regarding Fig. 16. But the temperature variation through the width, caused by major convection and heat transfer in the border areas of the composite sheet, increases.

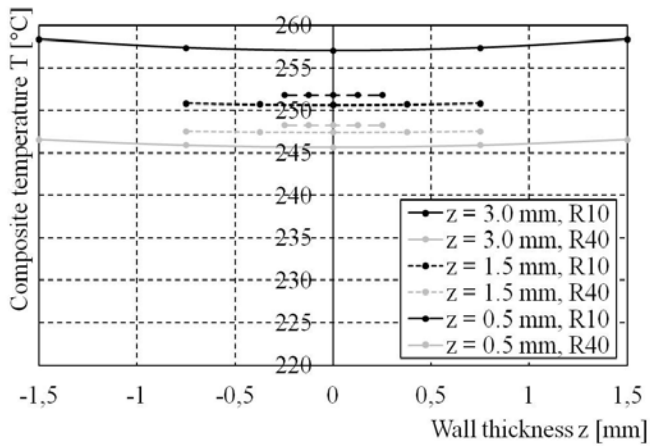

Fig. 16 Temperature distribution through composite sheets using *HS3*

D. Regression Functions

To enable short heating times and an almost homogeneous temperature distributions the strategy *intersecting temperatures* is the most effective for a wide range of wall thicknesses. However, the different distributions of surface and center temperature complicate the determination of the instant of transfer and the calculation of the transfer velocity to reach the required forming temperature. Using numerical simulation many iteration loops are necessary to determine the specific process parameters. In addition, during industrial processes only the measurement of the surface temperature is possible. Hence, a model has been developed to calculate the instant of transfer and its velocity using the surface temperature.

Fig. 17 shows the procedure to determine the process parameters. First of all, the forming temperature T_{Form} has to be defined. Simultaneously, the instant of forming t_{Form} can be calculated using equation (2).

$$t_{Form} = k_1 \cdot d_R^2 + k_2 \cdot d_R + k_3 \quad (2)$$

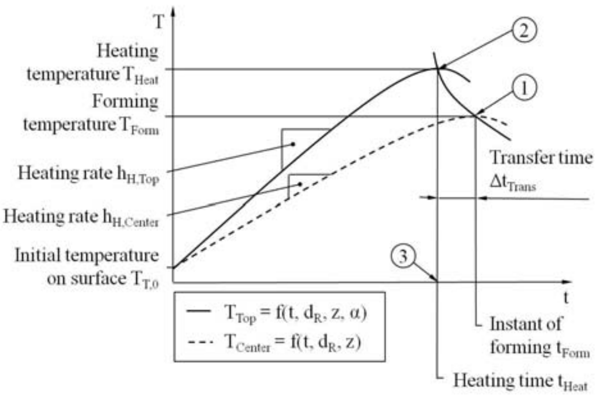

Fig. 17 Procedure for the determination of process parameters for composite heating

The variables k_1 to k_3 have to be calculated by linear functions in respect to the wall thickness s and the defined forming temperature $T_{Form.}$ The intersection point of the heating and cooling curve has to be calculated using equation (3) and (4).

$$T = h_{C,Center} \cdot (t_{Form} - t) + T_{Form} + k_6 \quad (3)$$

$$T = h_{H,Top} \cdot (t - t_{\min}) + T_{\min} \quad (4)$$

$h_{C,Center}$ is the cooling rate for the center layer and depends on a linear function of the heat coefficient α, as well as the variable k_6. The heating rate of the top surface $h_{H,Top}$ can also be described by a linear function using the radiator distance d_R. t_{min} as the lowest heating time, which is required to reach the forming temperature and depends on the wall thickness s. The corresponding lowest temperature is T_{min}. The heating time t_{Heat} can be calculated setting equation (3) equal to equation (4) and transpose to t:

$$t_{heat} = t = \frac{-h_{C,Center} \cdot t_{Umf} + k_6 + h_{H,Top} - T_{\min}}{h_{H,Top} - h_{C,Center}} \quad (5)$$

IV. Conclusion

Based on the finite element simulation the temperature distribution on the surface and through the thickness has been analyzed. While a homogeneous temperature distribution in the center area of a heated composite sheet is possible, the temperatures decrease in the border areas due to convection and heat transfer through touching guidance components. Thus, a housing of the heating and guidance with reduced contact to the composite sheet are recommended. Radiators with independent heater circuits in the center and border areas of the sheet could be used, alternatively. However, the conversion of different heater circuits requires further analysis regarding heat output and geometry.

For the simulation model, thermal-coupled data are necessary to describe the material properties. Analyzing the temperature distribution through the wall thickness, three heating strategies have been developed for middle-wave infrared radiators using a fiber-reinforced polyamide 6.6 with a fiber volume content of 45 % as example. Comparing the heating strategies with each other the strategy *intersecting temperatures* is the most effective method for a wide range of wall thicknesses and a homogeneous forming temperature is obtained.

Concerning the determination of the heating process parameters the regression functions have to be determined for further fiber-reinforces thermoplastic systems.

References

[1] G. Kempe, *Duroplastische und Thermoplastische Faserverbundwerkstoffe - Vorteile - Eigenschaften - Verarbeitung und Anwendungsgebiete beider Werkstoffgruppen in: Faserverbundwerkstofe mit thermoplastischer Matrix*, Expert Verlag, 1997, pp. 64-68.

[2] A. M. Murtagh., J. J. Lennon, and P. J. Mallon, *Surface friction effects related to pressforming of continuous fibre thermoplastic composites. Composites Manufacturing* 6. Elsevier Science Limited : s.n., 1995, pp. 169-175.

[3] C. Ludwig, *Glasfaserverstärkte Kunststoffe unter hoher thermischer und mechanischer Belastung*, Dissertation, Institute for supporting construction and constructive designing, University of Stuttgart, 2009.

[4] F. R. Jones, *Glass fibres – type and form* in Handbook of polymer-fibre composites, Longman Scientific & Technical, Harlow, GB, 1994.

[5] U. Berthold, *Beitrag zum Thermoformen gewebeverstärkter Thermoplaste mittels elastischer Stempel*, Dissertation, Faculty of Mechanical Engineering and Process Technology, University of Chemnitz, 2001.

[6] L. Bottenbruch, R. Binsack, *Technische Thermoplaste, Kunststoffhandbuch, Band ¾*, Carl Hanser Verlag, Munich Vienna, p. 221, 1998.