ON THE THERMAL BEHAVIOR OF THERMOPLASTIC LAMINATES DURING TRANSFER – A NOVEL WIND-TUNNEL APPROACH

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Keywords: thermoplastic, composites, transfer, polypropylene, wind-tunnel

Abstract

The thermal behavior of continuous-fiber reinforced laminates during the production process is essential for both, the processing and the resulting component properties. The transfer step of the molten laminates has an important influence on the temperature distribution of the laminates and is therefore investigated in the present study.

The relative velocity between the laminate and its surrounding air environment is artificially mimicked in a wind-tunnel, where laminate orientation, laminate thickness and air speed span a three dimensional parameter space for the conducted experiments. It is shown that the laminate thickness is the most significant influencing factor. Moreover, the commonly assumed homogeneous temperature distribution is demonstrated to be an oversimplification of the problem at hand, especially in consideration of long transfer times. Compared to laminates with horizontal orientation in the flow, experiments with vertical orientation reveal lower cooling rates. From the above insights it is concluded that high transfer velocities with vertical orientation optimize the thermal properties of the laminate, which is therefore recommended for the respective process control.

1. Introduction

Thermoplastic hybrid components comprising local continuous-fiber reinforcement in combination with injection or compression molding offer a high potential for a cost-effective use in automobile mass production. Further to the advantageous short cycle time, the additional possibility of designing complex and functionalized components is one of the major benefits of these material systems. The temperature control of the laminate along the entire process chain (Fig. 1) is crucial for the production process [1, 2] and has a significant influence on important component properties. One of the most relevant properties in such hybrid components is the bonding strength between the laminate and the injection molding compound. Numerous investigations [3–5] show that the temperature distribution is one of the main influencing factors for fusion bonding. Consequently, it is crucial to consider the transfer process and the resulting temperature distribution of the composite, where the former is mainly characterized by the

Excerpt from ISBN 978-3-00-053387-7

cooling of the molten laminate due to forced convection. Even though the transfer process has already been considered in some experimental studies [2, 6–8], there is a lack of systematic investigations into the temperature distribution inside and on the surfaces of the laminate. The present study, therefore, systematically addresses the character of various performed maneuvers during transfer. Particularly, the relative velocity between the laminate and its quiescent air environment is artificially mimicked in a wind tunnel, where laminate orientation (horizontal, vertical), laminate thickness and air speed span a three dimensional parameter space for the conducted experiments. The drawn conclusions from this study apply to a large number of processes and can be used to optimize process control and, consequently, component properties.

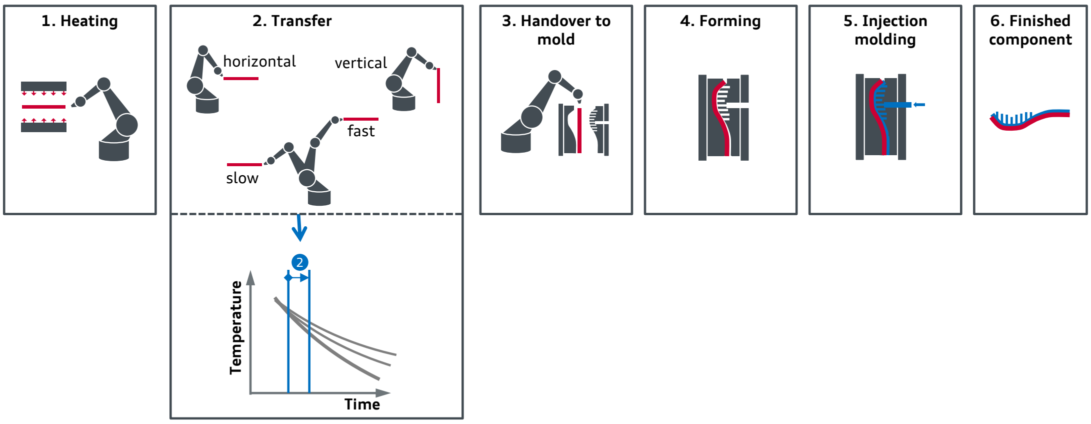

Figure 1. Schematic drawing of the process chain for the production of hybrid thermoplastic components, where continuous-fiber reinforced laminates are formed and back-injection molded. The transfer process (step 2) can be performed differently, which has an important effect on the cooling behavior of the laminate as indicated by the diagram.

2. Experimental procedure

2.1. Material

The considered specimens are laminates comprised of thermoplastic pre-impregnated tapes with unidirectional fiber reinforcement. Three different tape materials are used in this study, which are Polypropylene matrix with glass fiber (PP-GF) and Polyamide 6 with either carbon fiber or glass fiber (PA6-GF, PA6-CF). The square laminates (stacking sequence: [0/90]) have a side length of 150 mm and are preconsolidated using a variotherm press mold. Table 1 gives an overview of the materials, including the resulting laminate thickness after consolidation. Note that only the results for PP-GF are shown in this article for brevity; however, the insights and drawn conclusion hold for all three considered materials.

Table 1. Chosen materials and parameter settings.

Specimen Type	Matrix Type	Fiber Type	Laminate Thickness [mm]	Stacking Sequence	Fiber Content by Wt. [%]
A1	PP	GF	1,06	[0/90]	70
A2	PP	GF	2,12	[0/90]	70
A3	PP	GF	3,18	[0/90]	70

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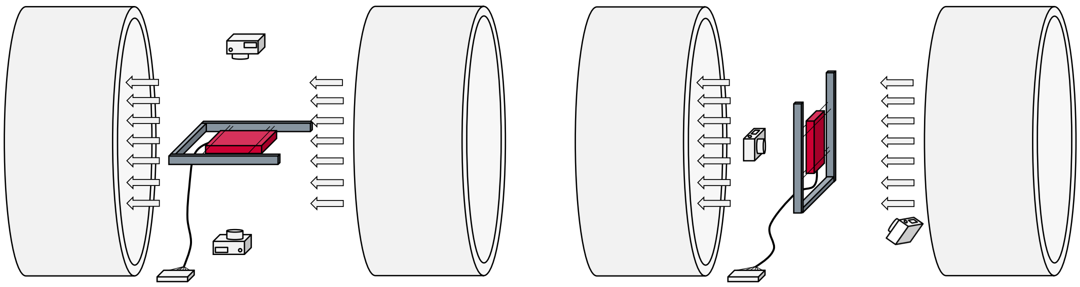
2.2. Experimental setup

The transfer process is artificially mimicked in a Göttinger-type wind tunnel with open test section; see Figure 2. In the first step each test specimen is heated beyond the melting temperature of the polymer in the immediate vicinity of the test section and is then instantly moved to the free stream of the wind tunnel. Figure 2 indicates the experimental setup for both vertical and horizontal laminate orientations. The temperature distribution within the laminate is measured with six embedded temperature sensors (type K). Additionally, the surface-temperature distribution of the laminate is recorded with two thermal imaging cameras (FLIR T420) as indicated by the inserts of Figure 2.



(a) horizontal (b) vertical

Figure 2. Schematic drawing of the wind-tunnel experiment; the temperature is measured with six embedded sensors, the surface-temperature distribution of the laminate is recorded with two infrared cameras.

Further to the above introduced boundary conditions (orientation, flow speed), additional emphasis is placed on the influence of the fiber material (glass/carbon), the matrix material (PP/PA6) and the laminate thickness, which are varied during experimentation. Table 2 summarizes the parameters of the experiments, including the Reynolds Number for the two different flow speeds.

Table 2. Overview of the experiments

Matrix Type	Fiber Type	Heating Temperature [°C]	Laminate Thickness [mm]	Air Speed [m/s]	Reynolds Number	Laminate Orientation
PP	GF	200	1; 2; 3	3	28809	horizontal; vertical
PP	GF	200	1; 2; 3	5	48015	horizontal; vertical

2.3. Data processing

Emission coefficient
Temperature measurements with thermal imaging cameras are sensitive with respect to the emission coefficient. Particularly, this coefficient has to be set for each material and for the appropriate environment of the experimental setup. Therefore the strategy to identify the emission coefficient is briefly described here. At first, the emission coefficient is set to a default value and the laminates are heated, up to a temperature above the melting temperature of the matrix. During the following cooling process (free convection) both the surface temperature and the temperature distribution inside the laminate are measured. For the temperature measurements inside the laminate six thermocouples are used. Figure 3 shows that the obtained temperature distribution in thickness direction can be represented by a poly-

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nomial (quadratic) regression. In the next step this regression curve is extrapolated to the surfaces of the laminate. The extrapolated temperatures are then compared to the measured thermal imaging temperatures and used to adjust the emission coefficient in the camera settings. The such derived emission coefficient is then used for the rest of the study.

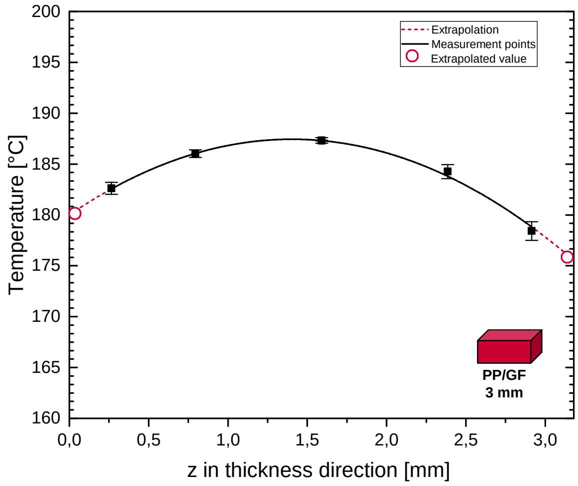

Figure 3. Calibration method for the emission coefficient, exemplified on the cooling of PP-GF laminates with thickness of 3,18 mm. The polynomial regression of the measurements is extrapolated to the laminate surfaces. These extrapolated surface temperatures are compared to the measured thermal imaging temperatures and used for the calibration of the emission coefficient.

Cooling rates

Cooling rates are used for the analysis of the thermal behavior during transfer. Hence, cooling rates in two different areas of the temperature curve are calculated. Figure 4(a) shows a typical temperature curve of the laminate core temperature. As illustrated, a cooling rate (CR1) is set within the first 8 s after placing the laminate in the test section of the wind-tunnel and a second cooling rate (CR2) over a wider temperature range is defined until the temperature drops to 200°C in case of PA6 and 135°C in case of PP. CR1 is relevant to numerous processes, because it is a realistic transfer time for the application of thermoforming. Nevertheless, CR2 provides the investigation of processes with long transfer times. Thus, Figure 4(b) compares CR1 and CR2 of a PP-GF plate during a vertical transfer with a flow speed of 3 m/s.

Recrystallization

The crystallization of semicrystalline polymers is characterised by a plateau in the temperature curve as indicated in Figure 4(a). The crystallisation depends on the cooling rate and is examined for all experiments. For the determination of the crystallisation-peak temperature, initially the derivation of the cooling curve is calculated. Subsequently, the maximum turning point is identified and the resulting crystallisation-peak temperatures are compared.

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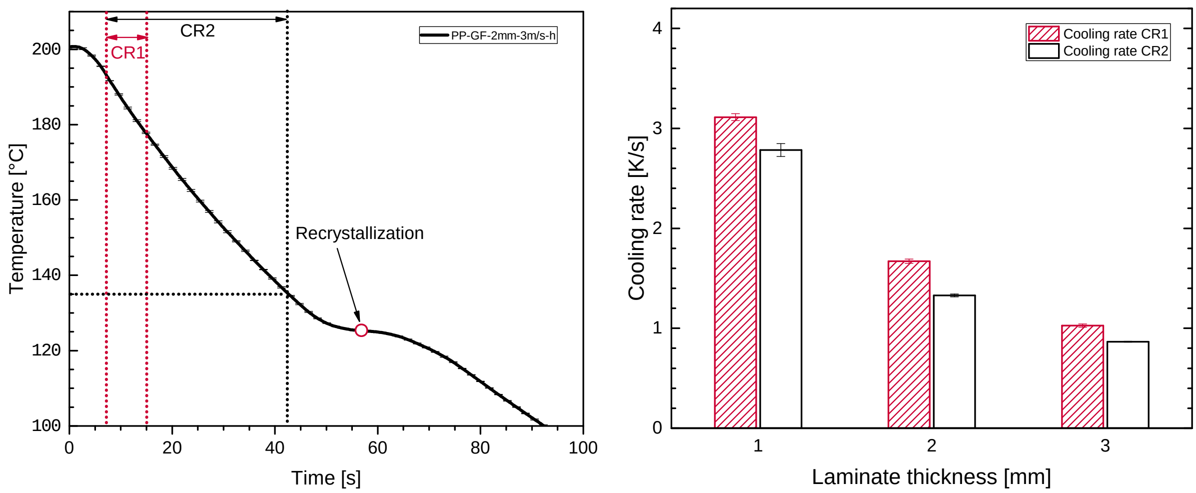
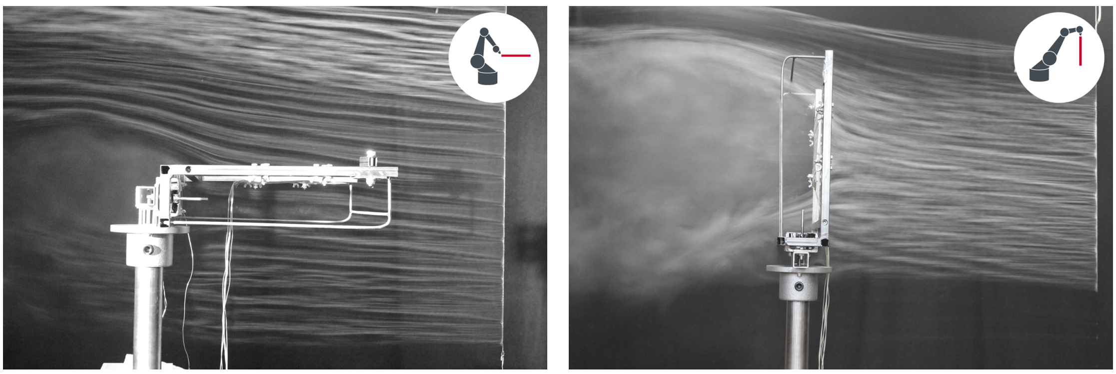


(a) (b)

Figure 4. Typical cooling curve (core temperature) of a PP-GF laminate with two time intervals CR1 and CR2 to distinguish the cooling rates within this areas (a). A comparison of the cooling rates CR1 and CR2 is shown in (b) for PP-GF laminates with verical orientation and a flow speed of 3 m/s.

3. Results and discussion

In order to evaluate the influence of the clamping system on the flow in proximity of the plates, smoke-wire visualizations have been recorded. Figure 5 shows such visualizations for both laminate orientations, which demonstrate that there is no significant influence on the laminates.



(a) horizontal (b) vertical

Figure 5. Experimental setup in the wind tunnel facility for both laminate orientations, horizontal (a) and vertical (b), during the cool-down experiment; the flow is visualized with streaklines from a smoke wire.

Flow speed and laminate orientation affect the thermal behavior, especially the surface-temperature distribution. Figure 6(a) shows the measured, almost homogeneous temperature distribution on the laminate surface in case of natural convection (flow speed: 0 m/s and horizontal orientation. In contrast, experiments with forced convection (flow speed: 5 m/s), relate to an inhomogeneous temperature distribution as indicated in Figure 6(b). The temperature is normalized by means of the crystallization temperature T_C. The value T/T_C thus can be used to indicate the process limit. Since thermoforming requires the

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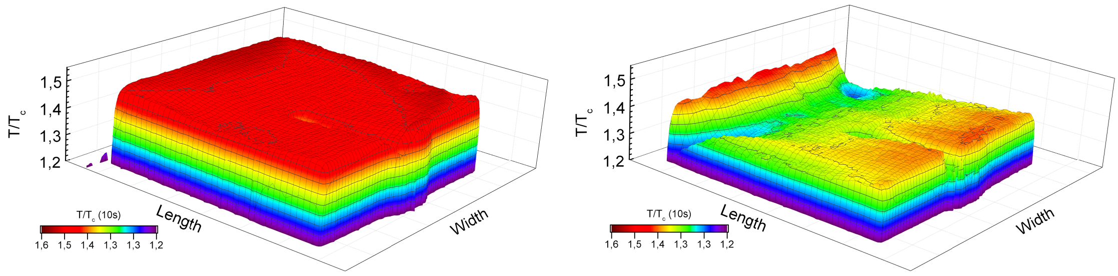
polymer in the molten state, the process limit can be set to

$$\frac{T}{T_c} = 1\,. \tag{1}$$



(a) horizontal (b) vertical

Figure 6. Surface-temperature distribution of PP-GF laminates after 10 s of cooling in horizontal orientation. Comparison of a laminate in quiescent environment (a) and with 5 m/s flow velocity (b).

At this point it is important to note that T_C shifts to lower temperatures with increasing cooling rate [9]. This non-isothermal crystallization behavior can be seen in Figure 7(a), where the recrystallization-peak temperature is plotted over a wide range of cooling rates. The Levenberg-Marquard algorithm [10] is used for nonlinear square curve-fitting of measurements and an exponential regression of the type

$$f_R = a_0 + a_1 e^{\frac{-(x-x_1)}{t_1}}\,. \tag{2}$$

can be found with the following coefficients: $a_0 = 120,44$; $a_1 = 7,65$; $x_0 = 1,03$; $t_1 = 1,633$.

Furthermore, influence of laminate thickness is shown in Figure 7(b) for flow speed of 3 m/s. Here, the temperature is measured in the mid-plane of the laminates and the corresponding curves represent the average values of the core temperature measurements.
The above-discussed three dimensional parameter space is merged into one characteristic diagram (Figure 8), where the interrelation of cooling rate, transfer speed, laminate orientation and thickness is summarized.

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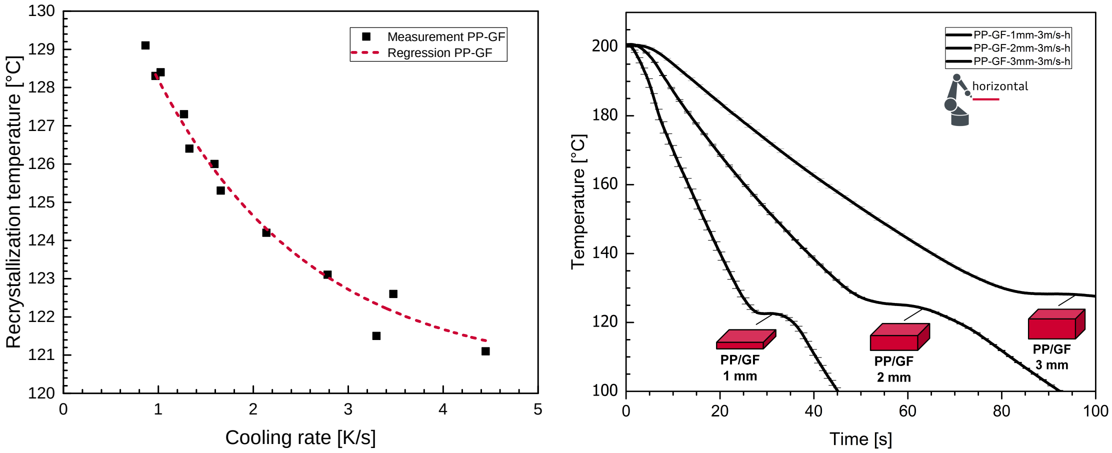

(a) (b)

Figure 7. Influence of cooling rate on the recrystallization temperature as result of the non-isothermal crystallization kinetics of PP-GF as measured in the wind-tunnel experiments, including exponential regression curve (a). The influence of laminate thickness exemplified by PP-GF laminates with horizontal orientation (b).

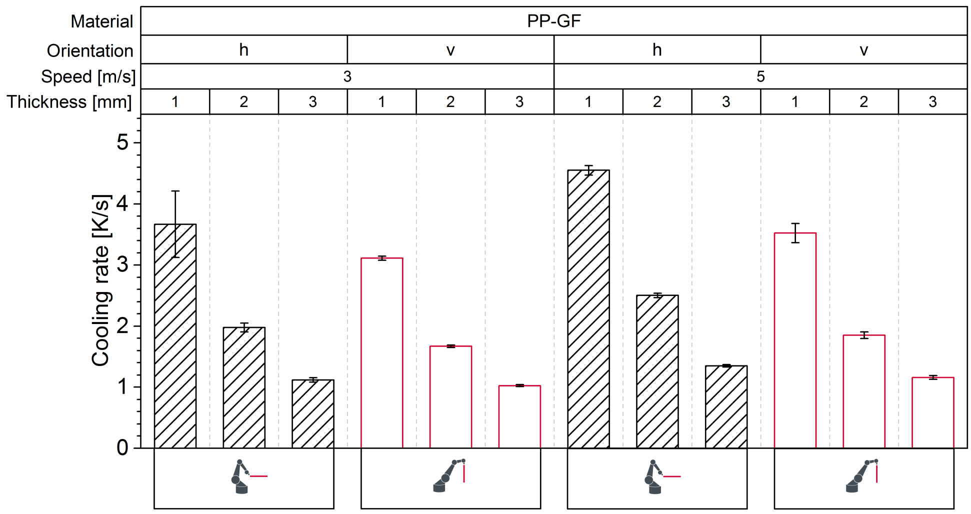

Figure 8. Overview of the results, including measured cooling rates depending on laminate thickness, transfer speed and laminate orientation in the flow.

4. Conclusions

In the present study, a novel wind-tunnel approach for the investigation of the thermal behavior of continuous-fiber reinforced thermoplastics during transfer is presented and discussed. Particularly, temporal cooling curves and corresponding cooling rates, recrystallization temperatures and spatio-temporal surface-temperature distributions are compared for various parameter combinations. A method for the calibration of emission coefficient using polynomial regression of the measured temperature distribution inside the laminate is presented and applied in this study. The effect of cooling rate on recrystallization temperature can be fitted using exponential regression. The shift of crystallization to lower temperatures with increasing cooling rate is demonstrated to be relevant to the process. Minimal cooling and short cycle times are desired for optimal process control. It is therefore concluded from the presented insights that vertical transfer with high transfer speeds should be recommended for the transfer process.

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