CHARACTERIZATION OF HEAT TRANSFER PARAMETERS IN THE COMPRESSION MOLDING OF GLASS MAT THERMOPLASTICS

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Abstract

A long fiber reinforced glass mat thermoplastic (47 vol.% glass fiber with PA 6, Tepex Flowcore) was selected for the manufacture of demonstrator automobile parts through compression molding. Thermal modeling to predict charge temperature within the production cycle is essential for determining process windows and hence, optimizing process steps. The key inputs for thermal modeling include charge surface heat transfer parameters during each step. In this study, these heat transfer parameters were characterized and validated. The sample core temperature was recorded during each process step, then heat transfer parameters were estimated by fitting experimental data to a one-dimensional thermal model. The estimated parameters were validated by applying them in the modeling of additional samples. Overall, the model predictions show good agreement with experimental results. This suggests that heat transfer parameters have been accurately captured. By knowing these parameters, charge thermal history through the entire molding process can be evaluated. As a result, the time window of each process step can be assessed and adjusted for better part molding outcomes. Furthermore, these parameters can be adopted in thermomechanical simulations of the forming process.

Key Words: thermoplastic, GMT, compression molding, heat transfer, simulation

1. Introduction

In modern automotive industry, polymer composites have been used to produce automobile parts, which enables light-weighting while still maintaining good thermal and mechanical properties. Glass mat thermoplastic (GMT) composites are a widely chosen material category for this purpose. This type of material system, when compared to alternatives such as sheet molding compounds (SMC) and thermoplastic pellets, possesses the feature of both re-meltable matrix and long-fiber reinforcement. Coupled with compression molding, the material system is suitable for high volume manufacturing with cycle times on the order of one minute. In this study, a long fiber reinforced GMT (Tepex Flowcore) was selected in the production of demonstrator parts.

In the forming process chain of thermoplastic composites, charge temperature is an important process parameter that can eventually contribute to forming outcomes [1-4]. Generally, temperature directly affects charge mechanical properties such as viscosity or elastic modulus, which then dominates the behavior of charge when it is deformed [3]. As so, final component properties such as bonding strength between the laminates or between the laminate and injection molding compound can heavily depend on the charge temperature profile when it is formed [5]. At each stage of the process chain, the temperature profile of the charge is determined by its heat transfer with either the environment or the mold. Therefore, knowing these heat transfer parameters allows the model prediction of the charge temperature profile at each stage, which then gives insights into process optimization for better forming outcomes, e.g. guiding the time windows of stages.

In the case of this study, the compression molding process of the selected GMT material can be divided into four stages in sequence: pre-heating, transfer from oven to mold, open mold cooling and closed mold cooling. Where open mold cooling is the period when sheet sits on mold before mold closes, and closed mold cooling refers to the compression molding phase.

At each stage, the GMT sheet exchanges heat with the surroundings. The flat geometry of the sheet means that the dominant heat transfer takes place at its top and bottom surfaces, making through thickness temperature profile the main point of interest. Consequently, this study focuses on investigating important heat transfer parameters at sheet top and sheet bottom during the process chain. Table I below summarizes the heat transfer at both sides of sheet during each process stage.

Table I: Heat transfer mechanisms at sheet surfaces during each process stage

Process Stage	Heat Transfer at Top Surface	Heat Transfer at Bottom Surface
Pre-heating	Forced Convection	Forced Convection
Transfer	Forced/Natural Convection	Forced/Natural Convection
Open-Mold Cooling	Natural Convection	Contact Conduction with Mold
Closed Mold Cooling	Contact Conduction with Mold	Contact Conduction with Mold

Natural convection coefficients on flat geometries have been well studied and can be easily obtained from heat transfer books such as [6]. On the other hand, thermal contact conductance between tool and sheet remains a challenge. Some researchers have studied the contact conductance between metal and polymer melts under the situation of injection molding [7-10]. However, differences in the material and forming mechanism can cause the magnitude of heat transfer to be very different in injection molding compared to compression molding. Kugele et al. [5] also studied this topic for thermoforming, which shares some similarities to compression molding. Therefore, based on their approach, an experimental setup was designed to characterize the tool-sheet contact conductance during open mold and closed mold cooling. In addition, due to complex flow pattern in the convection oven, the forced convection coefficient during pre-heating cannot be estimated by usual boundary layer equations. Therefore, a similar approach was developed to also characterize forced convection coefficient within the oven.

2. Methods

2.1. Materials and Sample Preparation

The GMT material used in this study was Tepex Flowcore from Lanxess. This composite can be characterized with PA 6 matrix, 47 vol.% glass fiber, random fiber orientation and consistent fiber length. The density of the material is 1800 kg/m^3. Other necessary thermal properties required by this study were measured by sending the GMT to Moldex3D Material Testing Lab and are summarized in Tables II and III.

Table II: Thermal conductivity of Tepex Flowcore measured at Moldex3D Material Testing Lab

Temperature (°C)	Thermal Conductivity (W/m.K)
30	0.423
100	0.473
200	0.397

Table III: Heat capacity of Tepex Flowcore measured at Moldex3D Material Testing Lab

Temperature (°C)	Heat Capacity (J/kg.K)
35	1067
90	1384
110	1484
160	1702
170	1809
175	1973
180	2671
185	4134
190	2016
195	1684
230	1687
290	1657

Pre-consolidated sample sheets were prepared from several layers of Tepex Flowcore. During consolidation of each sample, a thermocouple was embedded between middle layers to capture the core temperature of the sample. The thermocouple was also centered in the plane directions, so that it would not be affected by sidewall heat transfer. Two types of samples were prepared for each process stage: 4-layer consolidated samples and 6-layer consolidated samples. Each layer of Flowcore was 2 mm in thickness. The consolidation process results in fusion between the layers of Flowcore, and the thickness of the consolidated sheet was reduced to around 6 mm for the 4-layer samples, and around 9 mm for the 6-layer samples. The consolidated sheets had near square geometry with roughly 400 mm side length. Figure 2-1 below illustrates the location of thermocouple in each type of sample.

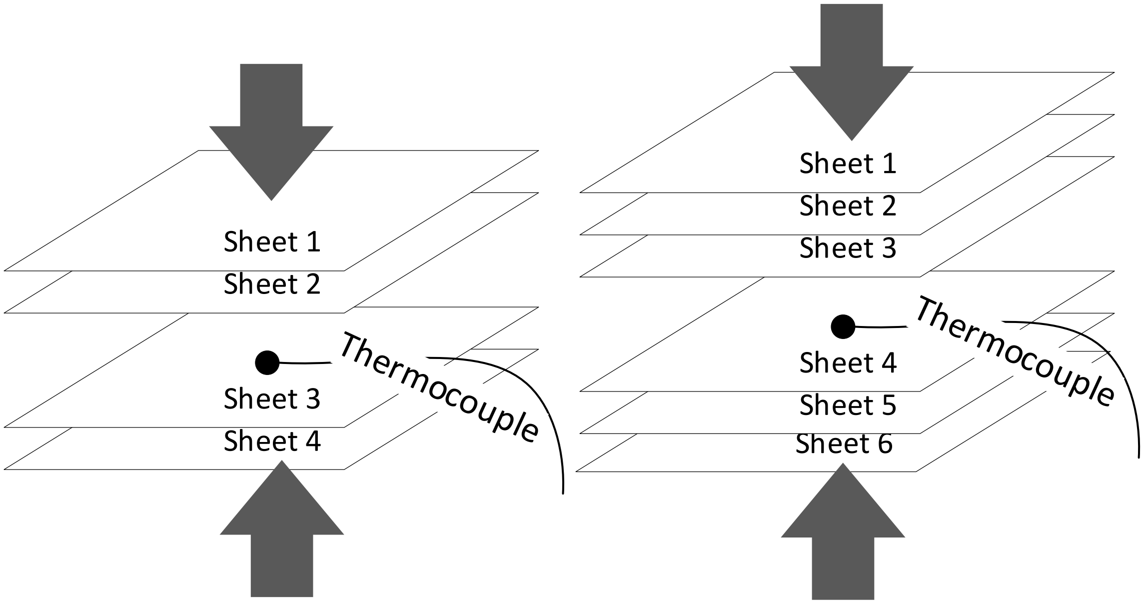

Figure 2-1: Consolidating GMT sheets into experimental samples

2.2. Experimental Set-up

The experimental procedure involved recording sample core temperature over time during process stages of interest. For the pre-heating stage, each sample was heated in a forced convection oven (HK--Präzisonstechnik) from room temperature. The oven was set at 300 ^oC. The sample core temperature was measured by the embedded thermocouple. A laptop was connected to the thermocouple wire for recording time evolution of measurements (Figure 2-2(a)).

For open mold cooling and closed mold cooling, each sample was first pre-heated for over 15 minutes so that it reached as close as possible to homogenous temperature distribution. After pre-heating, the sample was transferred to a press in the immediate vicinity of the oven. The sample then cooled mainly due to the heat transfer between its surface and the mold. The mold used for these experiments had flat geometry, which was temperature controlled at 150 ^oC. For open mold cooling situation, only the bottom mold was in contact with sample. The upper half of the mold remained open (Figure 2-2(b)). For closed mold cooling situation, the upper mold closed and was in contact with the sample. The upper mold was set to stop pressing once the force build-up reached 400 kN (Figure 2-2(c)). Based on sample area, this forced could convert to a pressure estimated at 16 bar. In both types of cooling experiments, the sample core temperature was measured by embedded thermocouple and was recorded by a laptop. Schematics of the pre-heating experiment, open mold and closed mold cooling experiments are shown in Figure 2-2.

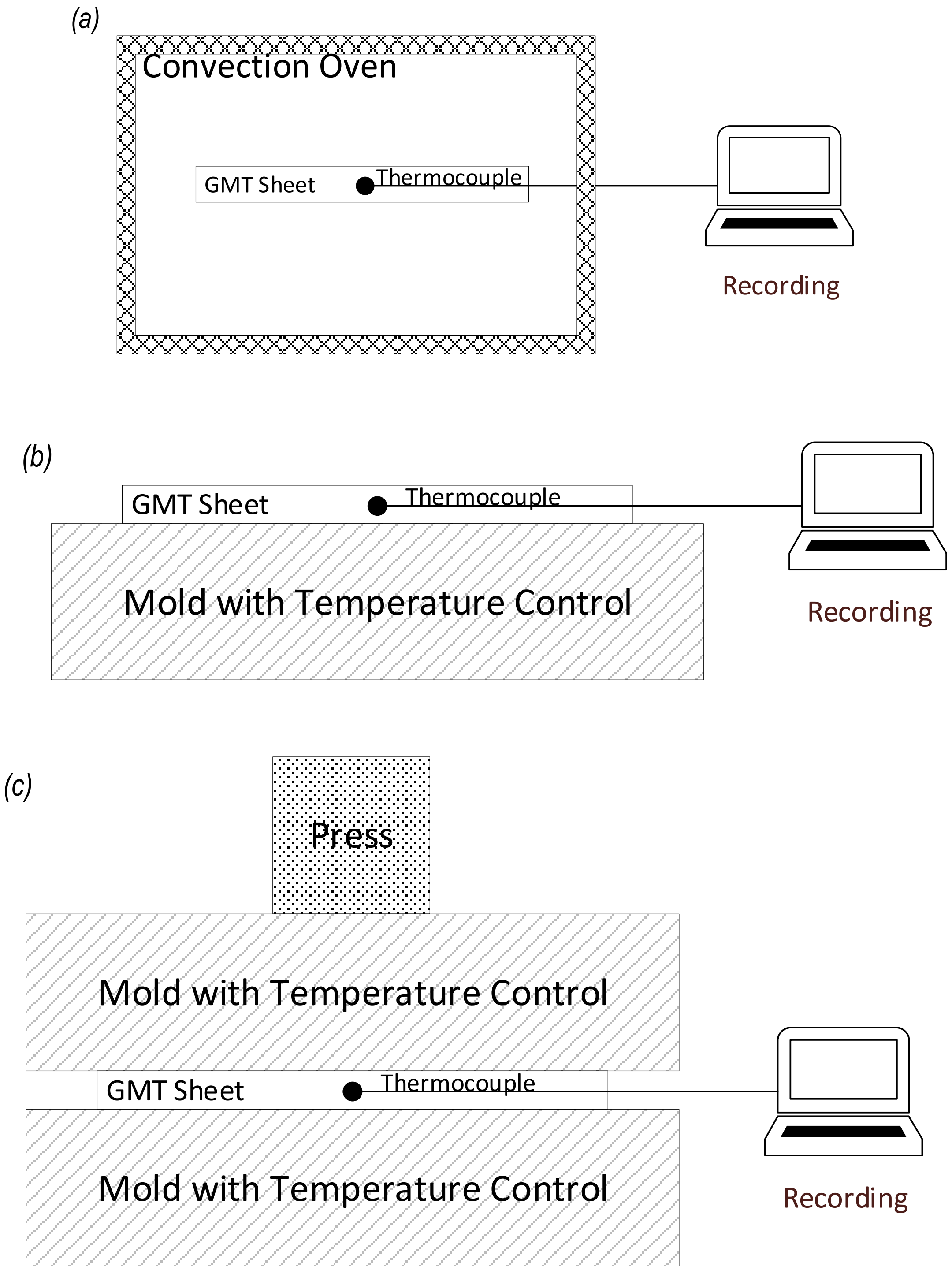

Figure 2-2: Schematics of experimental set-ups (a) pre-heating stage (b) open mold cooling stage and (c) closed mold cooling stage

2.3. One-Dimensional Thermal Model

The through-thickness temperature profile within the sample sheet was predicted using a 1-D transient conduction model. The heat transfer at sheet surfaces during each process stage was also modeled by applying corresponding boundary condition.

The 1-D conduction model was derived from Fourier's Law and is given as:

$$k \cdot \frac{\partial^2 T}{\partial x^2} = C_p \cdot \rho \cdot \frac{\partial T}{\partial t} \quad (1)$$

Where k is the temperature-dependent thermal conductivity, C_p the temperature-dependent heat capacity, and ρ the density of Tepex Flowcore.

For the pre-heating stage, a forced convection boundary condition was applied at both surfaces of the sheet. In this case, the magnitude of convection coefficient was assumed to be the same at both the top and bottom surfaces. The boundary conditions are given as:

$$-k \cdot \frac{\partial T}{\partial x}(L,t) = h_f \cdot (T_s - T_{oven}) \quad (2)$$

$$-k \cdot \frac{\partial T}{\partial x}(0,t) = h_f \cdot (T_{oven} - T_s) \quad (3)$$

Where L represents the entire thickness of the sheet, and h_f is the forced convection heat transfer coefficient.

During open-mold cooling, the top surface of sheet exchanged heat with the environment. Therefore, a combined radiation and natural convection boundary condition was used. The bottom surface of sheet contacted with the mold, thus the heat transfer here was modeled by thermal contact conductance.

$$-k \cdot \frac{\partial T}{\partial x}(L,t) = h_n \cdot (T_s - T_{environment}) + \sigma\epsilon \cdot (T_s^4 - T_{enviornment}^4) \quad (4)$$

$$-k \cdot \frac{\partial T}{\partial x}(0,t) = h_c \cdot (T_{mold} - T_s) \quad (5)$$

In equation (4), h_n (8.5 W/m^2-K, calculated using Nusselt Number correlations from [6]) is the natural convection heat transfer coefficient at top surface, σ is the Stefan-Boltzmann constant, and ϵ is the emissivity. In equation (5), h_c is the contact conductance at sheet-mold interface.

During closed mold cooling, both sides of the sheet were in contact with the mold. Therefore, equation (6) and equation (5) were applied at top and bottom surfaces respectively in this case. Here, the magnitude of h_c was assumed same at both sides.

$$-k \cdot \frac{\partial T}{\partial x}(L,t) = h_c \cdot (T_s - T_{mold}) \quad (6)$$

Homogeneous temperature distribution was used as initial condition for modeling of all the three cases mentioned above.

2.4. Parameter Estimation

The parameters to be estimated were the heat transfer coefficients given in previous section, i.e. h_f during pre-heating, h_c during open mold cooling and h_c during closed mold cooling. The estimation was achieved by an iterative fitting method.

In a first step, initial guesses were assigned for these coefficients, based on which the modeling of 4-layer samples were solved using a FEM simulation software (Abaqus CAE). Uncoupled heat transfer analysis and element type DC3D8 were defined for the simulations. Figure 2-3 illustrates an example simulation created for the closed mold cooling stage. The simulated core temperature-time curve was then compared to the experimental measurement. Afterwards, the values of these coefficients were iteratively altered until simulation curves matched the experimental ones.

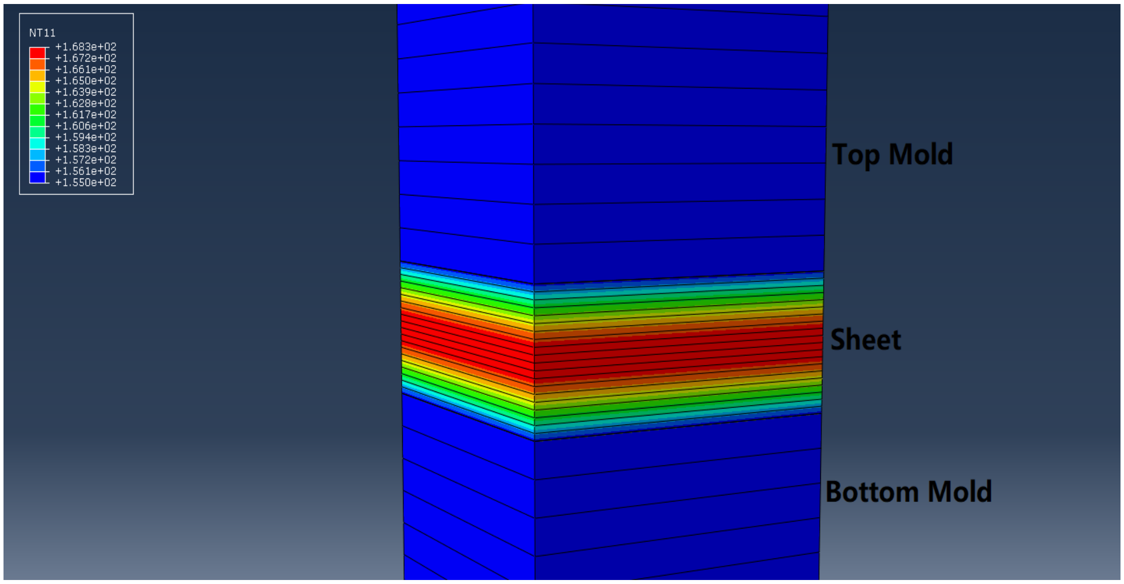

Figure 2-3: Abaqus simulation of closed-mold cooling stage

2.5. Parameter Validation

As was mentioned, two types of samples were used for each process stage. The main difference between the two was the number of consolidated layers, and therefore the thickness and mass. The heat transfer coefficients estimated using 4-layer samples were then applied to the modeling of 6-layer samples. These coefficients can then be validated by checking if they predict the thermal behavior of the 6-layer samples.

3. Results and Discussions

3.1. Pre-Heating Stage

Figure 3-1 compares the experimental temperature-time curve and simulated temperature-time curve for pre-heating sample sheets in the oven. Figure 3-1(a) shows the results after fitting forced convection (h_f) coefficient using 4-layer sample. Figure 3-1(b) shows the validation by applying this coefficient on 6-layer sample.

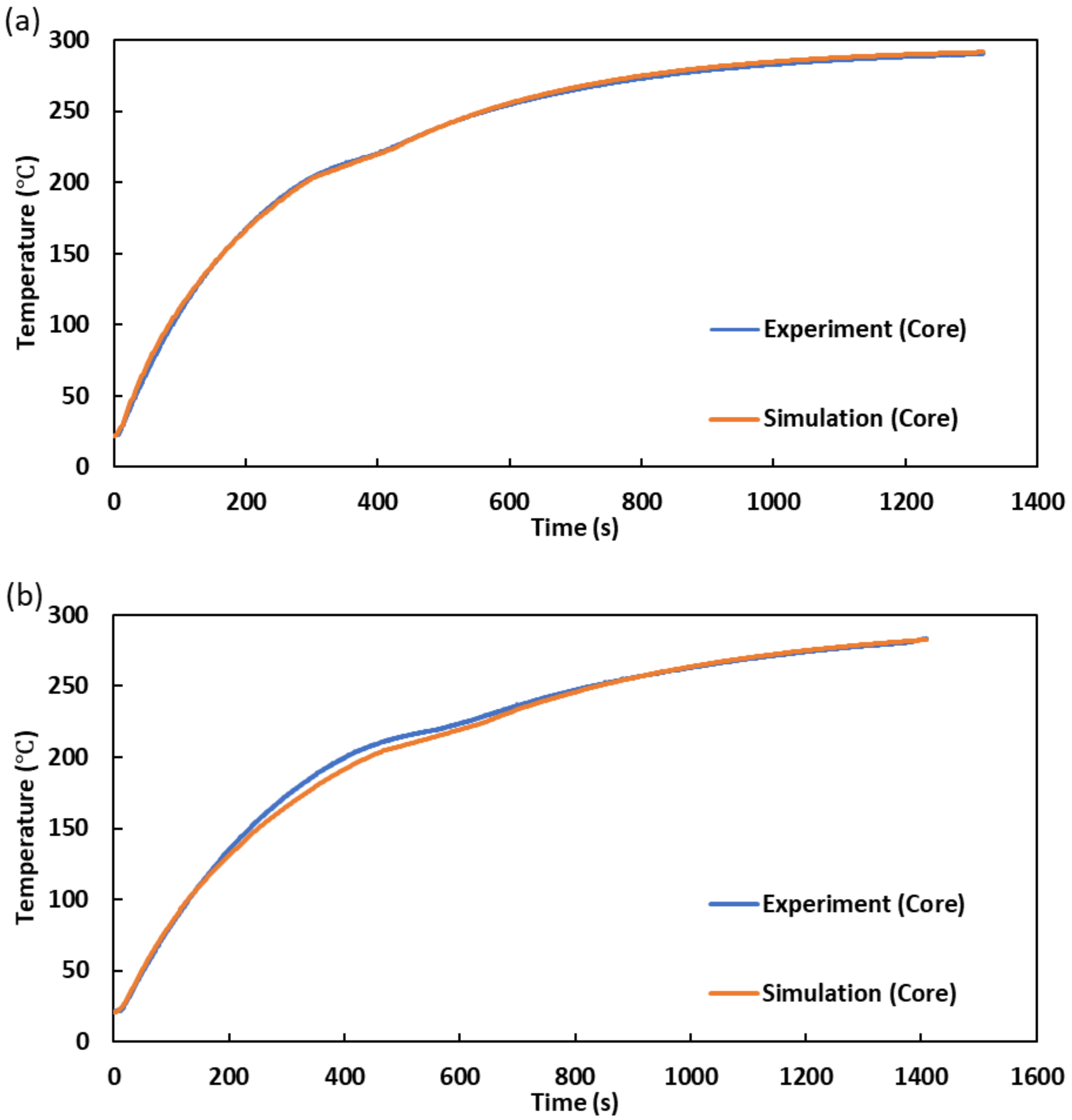

Figure 3-1: Simulated core temperature compared with experimental core temperature during pre-heating stage (a) parameter estimation using 4-layer sample (b) parameter validation using 6-layer sample

In both cases, the simulation matches well with experiment over the entire heating period. In experimental curve, the melting of polymer matrix (the sudden drop of curve slope near 220 ^{o}C) has been captured. This was predicted by including latent heat in the simulation.

3.2. Cooling Stages

Figure 3-2(a) presents the simulated curve and experimental curve for 4-layer sample in the case of open mold cooling. Good agreement was obtained by fitting the thermal contact conductance value between the sheet and mold interface. However, after applying this value to the 6-layer sample, the simulation predicted significantly higher core temperature than experiment. This suggested that the contact conductance fitted from 4-layer sample does not apply to 6-layer sample. It is possible that heavier sample created more pressure on the lower mold half and led to a better contact at the interface. This phenomenon was also observed by Kugule et al. [5] in their study for thermoforming process. Consequently, in the case of open mold cooling, a separate fitting was performed for the 6-layer sample to determine a different conductance value. Figure 3-2(b) compares the predicted cooling curve against experiment after performing the fitting for 6-layer sample.

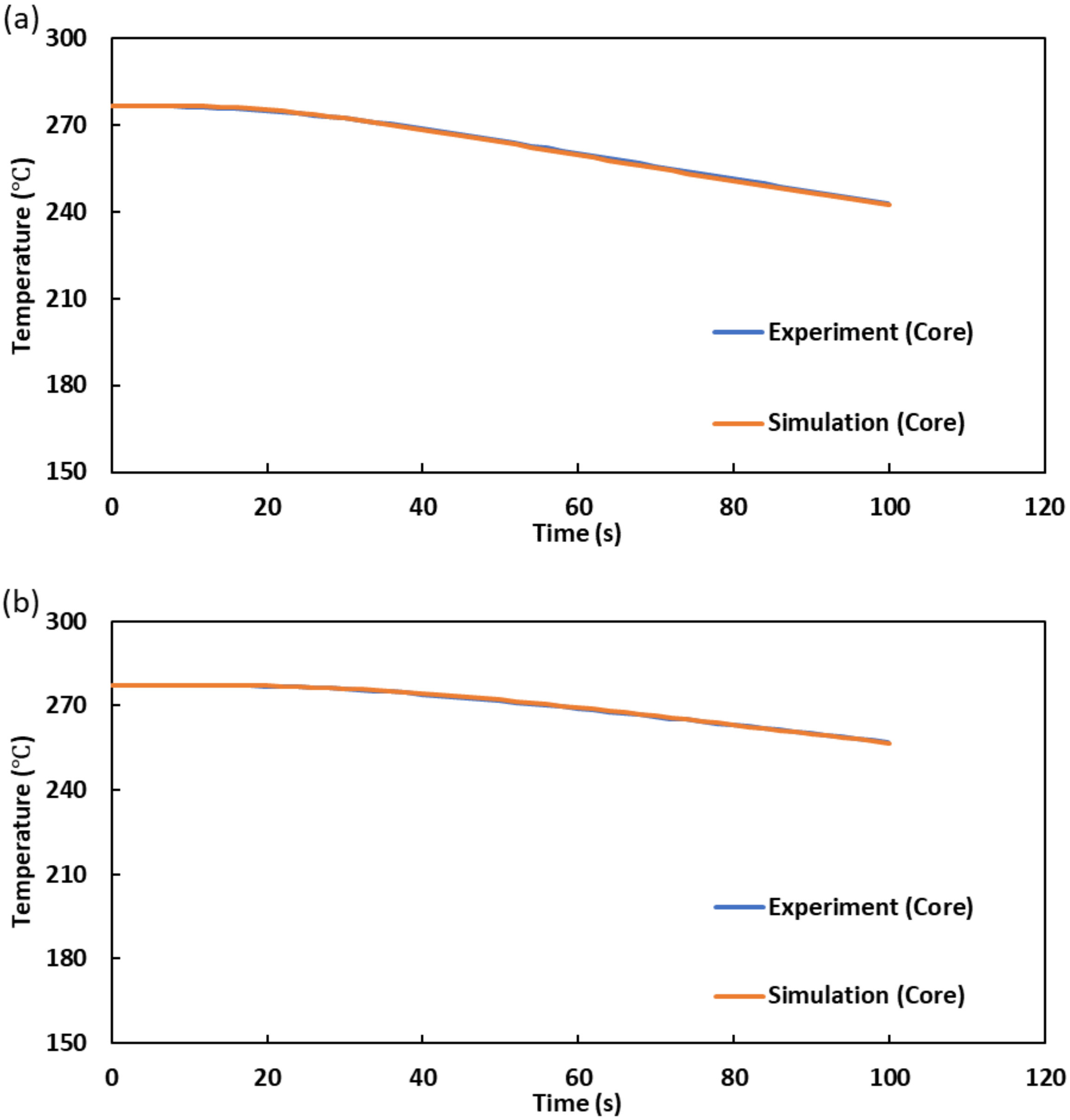

Figure 3-2: Simulated core temperature compared with experimental core temperature during open mold cooling stage (a) parameter estimation using 4-layer sample (b) parameter estimation using 6-layer sample

During closed mold cooling, the press exerted additional force on sample that was much greater than sample weight (400 kN vs. 0.013-0.019 kN), making the difference between the two sample types negligible. In other words, the sheet-mold contact conductance can be considered equal for 4-layer and 6-layer samples in this case. Figure 3-3(a) shows the estimation of the conductance using 4-layer sample and Figure 3-3(b) shows the validation using a 6-layer sample. Again here, simulation predictions match well with experimental measurements for both types of samples.

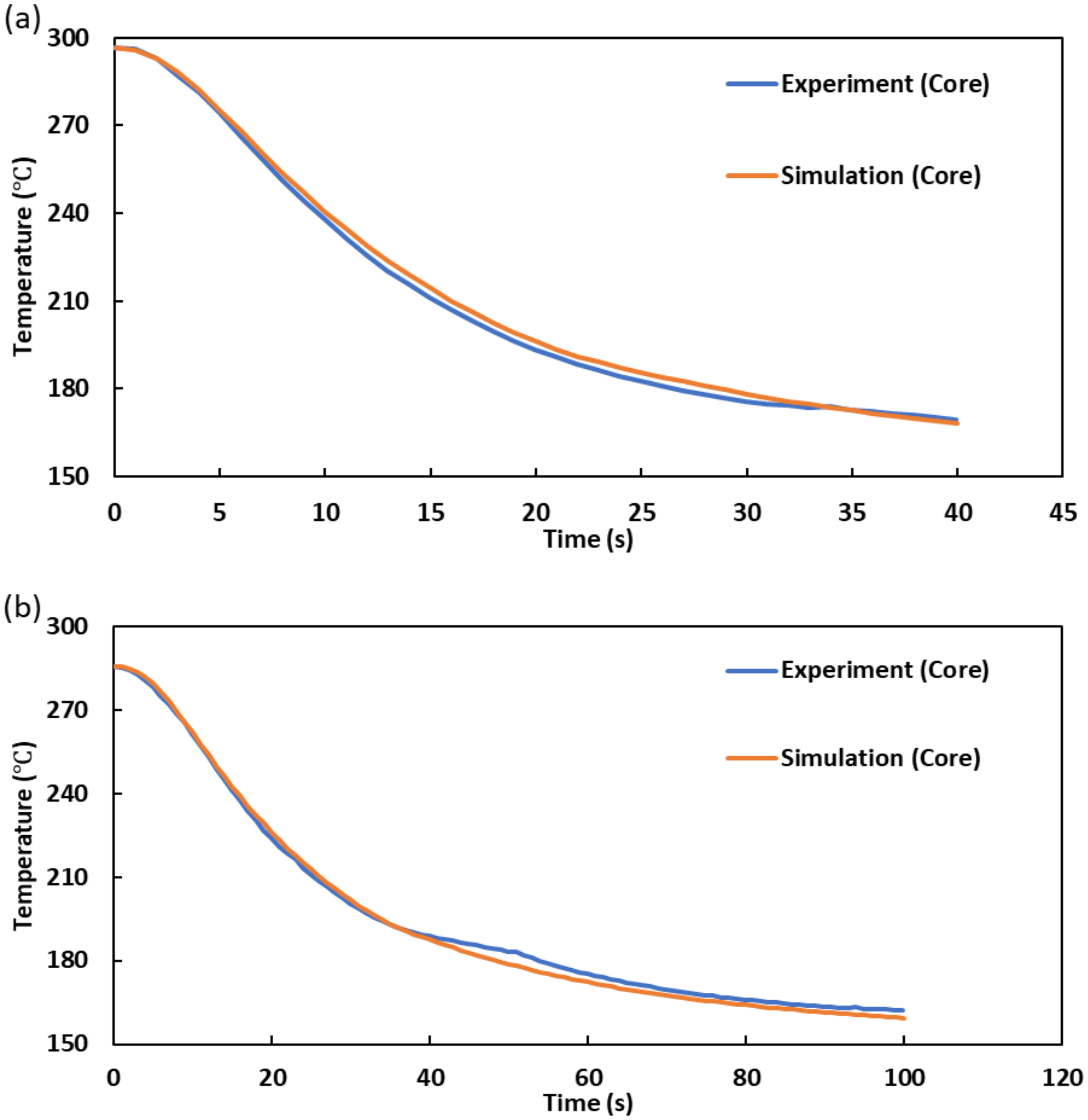

Figure 3-3: Simulated core temperature compared with experimental core temperature during closed mold cooling stage (a) parameter estimation using 4-layer sample (b) parameter validation using 6-layer sample

3.3. Estimated parameters

Table IV summaries the estimated heat transfer coefficient in each studied process stage, where h_f is the forced convection heat transfer coefficient in oven, and h_c is the contact conductance between sheet and mold surfaces.

Table IV: Summary of estimated heat transfer parameters during studied process stages

Process Stage	Estimated Heat Transfer Parameter	
Pre-heating	$h_f = 36\ W/m^2 \cdot K$	
Open Mold Cooling	4-Layer Sample	$h_c = 280\ W/m^2 \cdot K$
	6-Layer Sample	$h_c = 490\ W/m^2 \cdot K$
Closed Mold Cooling	$h_c = 7500\ W/m^2 \cdot K$	

As can been seen in open mold cooling, heavier samples lead to greater sheet-mold contact conductance due to the reasons explained in Section 3.2. In the cases of pre-heating and closed mold cooling, a single heat transfer coefficient value was adequate for modeling sheets with different thicknesses. Additionally, the closed mold h_c value was found to be much higher than open mold h_c values because of the press force applied. This would explain the rapid cooling of sheet usually observed during the forming (closed mold) stage.

Characterizing these heat transfer parameters enables accurate prediction of through-thickness temperature profile within charge, which further enables better process optimization. Sensitivity analysis is an essential step in process optimization, as it studies the impact of process conditions on process outcomes. In compression molding process, conditions such as mold temperature and sheet thickness can significantly affect the evolution of charge temperature distribution which directly impacts the final molding outcome. Knowing the heat transfer parameters, the effects of these process conditions can be easily analyzed by varying them in the thermal modeling. To illustrate this application, a sensitivity analysis was performed by simulation with several combinations of sheet thicknesses and mold temperatures, while keeping all other process conditions (e.g. heating time, transfer cooling time, on-mold cooling times) the same. The resulting sheet temperature profiles at the final closed mold stage are plotted in Figure 3-4. In the figure, the recrystallization temperature of polymer matrix was marked with a vertical red line (at 190 °C).

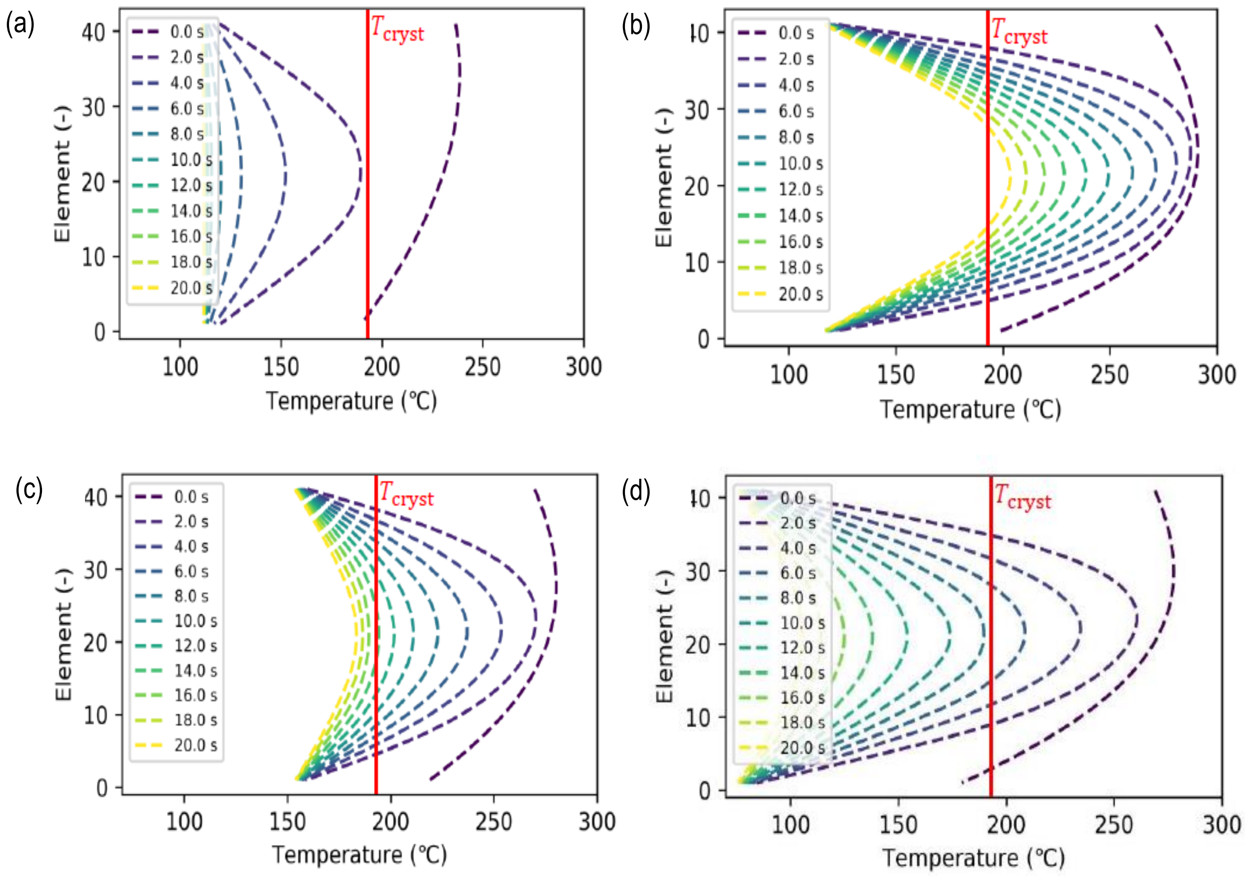

Figure 3-4: Simulated through-thickness temperature profile for studied process conditions (a) single layer sample and 110 °C mold temperature (b) 3-layer sample and 110 °C mold temperature (c) 2-layer sample and 150 °C mold temperature (d) 2-layer and 70 °C mold temperature

In all conditions, the sheet temperature profiles are initially asymmetric as a result of open mold cooling prior to mold closure. After the mold closes, large h_c values at both sides of sheet lead to rapid cooling of surfaces to mold temperature, and consequently an evolution toward a symmetric temperature profile. The main effect of the studied process conditions is considered at core of the sheet. Figure 3-4(a) shows that a single layer sheet will solidify completely in 2 seconds at 110 °C mold temperature. The core of a thicker 3-layer sheet can remain above recrystallization temperature for much longer at the same mold temperature (Figure 3-4(b)). Figures 3-4(c) and 3-4(d) suggest that elevated mold temperature (150 °C vs. 70 °C) can significantly lengthen the time to solidify the core of sheet. A complete summary of all simulated conditions and the resulting time to solidify the core of sheet are given in Table V. For thickest sheets and highest mold temperature (Table V), the sheet core can remain molten for over 20 seconds. In the case of thinnest sheet and lowest mold temperature (Table V), however, complete solidification takes place in 2 seconds. Based on this data, the time window of forming can be estimated accordingly with respect to different mold temperatures and types of sheet used.

Table V: All simulated conditions and corresponding time to complete solidification after the mold closes

Sample Thickness	Mold Temperature (^oC)	Time to Complete Solidification After Mold Closes (s)
Single Layer	70	1.7
Single Layer	110	2.5
Single Layer	150	3.5
2-Layer	70	9.2
2-Layer	110	13.0
2-Layer	150	>20.0
3-Layer	70	>20.0
3-Layer	110	>20.0
3-Layer	150	>20.0

4. Conclusions

In this study, an experimental setup was designed to measure the core temperature of GMT sheets at each stage of the compression molding process. A one-dimensional thermal model was used to predict the through thickness temperature profiles of sheets. By fitting model prediction to experimental data, the heat transfer parameters at sheet surfaces during different process stages were characterized. With these heat transfer parameters, the evolution of charge temperature profile through process chain can be accurately simulated. The application of accurate thermal modeling can further assist in the optimization of the molding process, for example sensitivity analyses and time window determination. In addition, the thermal modeling can be coupled with mechanical modeling, developing thermomechanical approaches to simulate the material forming behavior [11].

5. References

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