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Optimization of the IR-Heating Phase in Thermoforming of Thermoplastic Sheets: Characterization and Modelling

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Abstract. The thermoforming industry is currently seeking for methods to increase process monitoring and control. The present paper addresses this topic by focusing on the heating phase in thermoforming. A coupled experimental-modelling approach was developed to characterize the heating equipment on site. This allows taking local effects such as ambient air or machine specific heating efficiencies into account. The characterization results in a machine specific data set which is subsequently used to optimize the heating of the thermoplastic sheet. An optimization script was developed which proposes directly applicable machine settings in order to obtain a through-thickness temperature profile within the desired forming range.

Keywords: Thermoforming, infrared heating, finite difference.
PACS: 44.10, 44.27, 44.40

INTRODUCTION

The thermoforming process for thermoplastic sheets consists out of three different phases: (1) heating of the sheet, (2) forming of the product by means of vacuum and (3) cooling and demoulding of the product. In industry, process start up and control is still based on personal experience and trial & error methods. This leads to varying machine settings, excessive material waste and eventually high start-up times and costs. There is a clear need for a higher level of process control in the thermoforming industry [1]. Since the importance of a well heated sheet cannot be overestimated, the present paper focusses on this phase of thermoforming process. As the complexity of the heating phase increases with increasing sheet thickness, heavy gauge thermoforming of sheets with a thickness larger than 3 mm is the main area of interest. Nevertheless, the methods and results presented in this paper can be applied to thin gauge thermoforming as well.

A controlled heating phase resulting in a as uniform as possible through-thickness temperature distribution is key in thermoforming of thermoplastic sheets. In practice, the heating is done by means of infrared radiation via ceramic, quartz or halogen elements. Since this type of contact-free heating is based on a (constant) heat flux, a perfectly uniform through thickness temperature distribution is very difficult to obtain with standard industrial thermoforming equipment [2].

This paper presents a framework to characterize the heating phase of the thermoforming process based on an equipment specific dataset. This dataset is derived from experimental measurements which are used in a reverse engineering fitting step. The parameters which are used in this fitting step are: absorbed radiative power, IR penetration depth, convective heat transfer coefficient, temperature of the convective environment and a “switch-on” delay time in case of halogen heater elements. The results of the fitting step help the machine operator to understand and optimize the heating phase of the actual thermoforming process.

MODELLING THE HEATING PHASE

As described in literature, the heating phase of the thermoforming process can be modelled by means of the standard transient heat balance equation in which conduction, convection and radiation are taken into account:

$$\frac{dQ_{in}}{dx} - \frac{dQ_{out}}{dx} = mC_p(\theta)\frac{d\theta}{dt} \tag{1}$$

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In the current paper the heat flow is considered to be uniform in plane. Therefore only the through-thickness orientation x is taken into account in equation (1). In this equation Q denotes the heat flow, m is the mass, $C_p(\theta)$ is the temperature dependent specific heat capacity, θ is the temperature in °C and t is the time variable.

Equation (1) is solved by means of the explicit finite difference method [3]. Depending on a one or two-sided heating set-up in the thermoforming process the following boundary conditions are applied to the outer surfaces:

$$Q_{in} = \alpha A(\theta_\infty - \theta_i) + q_{rad} A \tag{2}$$

In this equation α represents the convective heat transfer coefficient, θ_∞ the temperature of the environment, A the exposed surface area and q_{rad} the radiative heat flux absorbed by the thermoplastic sheet. The through-thickness transport of heat in the sheet is modelled using the Fourier's law:

$$Q_{conduction} = -\lambda A \frac{dQ}{dx} \tag{3}$$

With λ representing the thermal conductivity of the thermoplastic material.

The combined set of equations can be used to model the through-thickness temperature distribution in the heating phase as a function of time. These equations assume however a complete absorption of the incident radiative flux at the surface of the sheet. Since a thermoplastic material is semi-transparent in practice [4], this needs to be taken into account by implementing the optical penetration depth, d_p [5,6]. This parameter represents the distance measured from the irradiated surface where the intensity has decreased to $1/e$ (≈36,8%)of the intensity at the surface. The higher the optical penetration depth is, the deeper the IR radiation will penetrate into the thermoplastic sheet resulting in a more volumetric heating rather than a surface heating effect. The optical penetration is both material and process (in casu the type of heater element) dependent.

In the present paper, the method proposed by Gauthier et al. [7] has been used to model the penetration of the radiative heat flux and to determine the through-thickness radiative heat flux distribution:

$$\beta = 1 - e^{\Delta x / d_p} \tag{4}$$

$$q_i = \beta (1-\beta)^{i-2} (1-\beta) q_{rad} \tag{5}$$

Next to the implementation of the penetration depth, a second effect is added to the model. This addition deals with the experimentally observed time delay present in the heating process when using halogen heater elements. In case halogen heater elements are used, the elements require a certain period to reach the requested power setting. This delay in the heating process was modelled by implementing a time constant τ in a first order approach:

$$q(t) = q_{rad}\, e^{-\tau / t} \tag{6}$$

The described set of equations allows to calculate the through-thickness temperature distribution as a function of time based on one-dimensional heat transfer by means of convection, conduction and radiation taking both radiative penetration and halogen heater element start-up delay into account. This model will be used to characterize the used thermoforming heating equipment by reverse engineering the different parameters (heater power, optical penetration depth, convective environment and start-up time delay) based on experimental measurements.

EXPERIMENTAL TEMPERATURE MEASUREMENTS

In the thermoforming industry, temperature measurements are usually done by pyrometers. These devices are able to measure surface temperatures in situ and are based on IR radiation. Experimental observations have however proven that pyrometer measurements are highly influenced by reflection and transmission of the IR waves [8]. Obtaining reliable absolute temperature data is therefore not straightforward by means of a pyrometer. To overcome these difficulties, an instrumented vulcanized silicone sheet was developed. This sheet contains 15 thermocouples in total: 3 thermocouples through thickness at 5 different locations in-plane. The sheet is 3.9 mm thick and 50x50 cm wide. The sheet allows to determine the through-thickness temperature distribution as a function of time, as well as the in-plane temperature distribution. The sheet can be used for any type of heater elements and for one- or two-sided heating approaches.

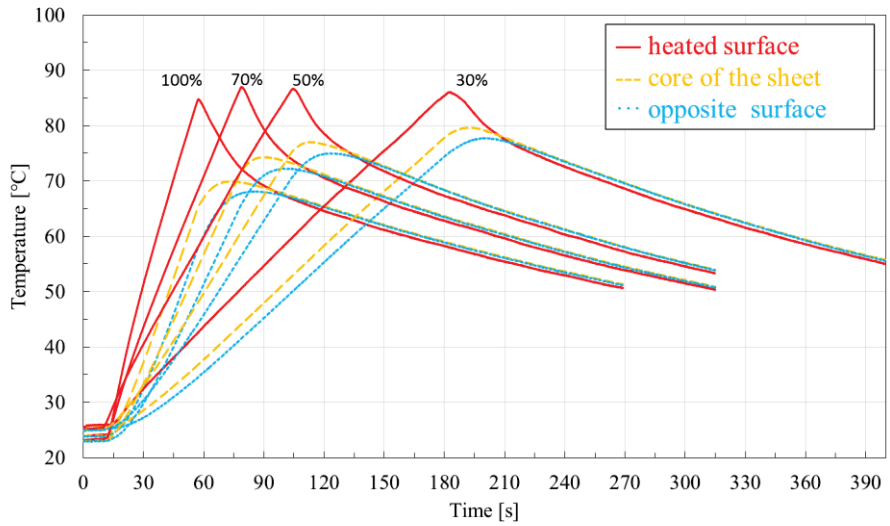

FIGURE 1. Experimental through-thickness temperature vs. time data for one-sided heating on a Geiss U8 thermoforming machine equipped with halogen heater elements. Different power settings (100-70-50-30 %) were applied with respect to the maximum heat flux of 51,5 kW/m².

The data in figure 1 clearly show that the higher the power setting of the heater bank is, the faster the sheet surface is heated. This is a desired effect in industry where a shorter heating time would result in a gain in productivity. The measurements indicate however an increasing temperature difference between the heated surface and the core and non-heated (opposite) surface of the sheet. Since a uniform through-thickness temperature distribution is required for the forming step, this puts a limit on the maximum feasible heating rate and thus applied heating power setting. Since exact temperature data or heating characteristics of the heating equipment is often not known in industry, process control remains based on trial and error or on operator experience.

REVERSE ENGINEERING

In this section the developed Finite Difference model is combined with the experimental temperature measurements. Experimental temperature data of different heater settings will be used to characterize the heating equipment of the thermoforming machine. As a result of this reverse engineering step, a dataset is derived which characterizes the heating equipment. This dataset can afterwards be used to optimize the heating step. All types of heating elements can be characterized. In the case of halogen elements, experimental measurements are performed for different power settings (e.g. 100-90-80-70-60-50-40 % of the maximum heat flux), while in the case of ceramic and quartz elements different temperature settings are used (e.g. 250-300-350-400-450 °C). This approach creates the link between machine settings and modelling work, which is not always included in literature.

The thermal material data of the silicone sheet are: a density of 1380 kg/m³, a thermal conductivity of 0.18 W/mK and a specific heat capacity of 1330J/kgK. The parameters which were used in the fitting procedure are summarized in table 1. All parameters in this table are determined for each heater setting in order to fully characterize the equipment. Since the temperature of halogen heater elements is an order of magnitude higher than the sheet temperature, a constant radiative heat flux was implemented. The lower operating temperature of quartz and ceramic elements does not allow this assumption.

In figure 2 the result of a single fitting procedure for a specific heating setting (ceramic heaters at 400°C) is shown. All curves in this graph are fitted using a single set of heating parameters. The good correlation between the experimental and fitted curves justifies the extraction of the heating parameters (table 1). The small differences between the experimental and fitted data are explained by uncertainties in silicone material data and the exact through-thickness positions of the thermocouples.

TABLE (1). Used parameters for the fitting procedure.

Parameter	Halogen heater elements	Ceramic/Quartz heater elements
Constant radiative heat flux	V	-
Temperature of the heater elements	-	V
Radiative number (Boltzmann Law)	-	V
Convective α top side	V	V
Convective α bottom side	V	V
Environment temperature top side	V	V
Environment temperature bottom side	V	V
Optical penetration depth	V	V

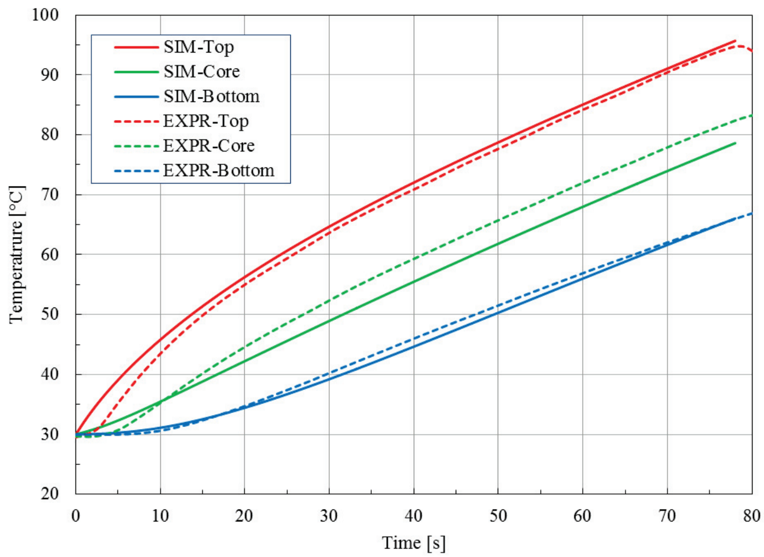

FIGURE 2. Experimental and reverse engineered time-temperature curves for one-sided heating of the silicone sheet. The sheet is heated from the top side by means of ceramic heaters set at 400°C

OPTIMIZATION PROCEDURE

In industry, an as uniform as possible through-thickness temperature distribution in the shortest possible time is desired. The theoretically fastest way of obtaining this result would be a two-step heating in which the outer surface is first heated up to the forming temperature. Secondly, the surface temperature is kept constant at the forming temperature in order to allow conductive heat transfer to reach a uniform through thickness temperature. This second step requires a fast response heating element in combination with a feedback loop coupled to an in situ accurate temperature measurement. The response times for ceramic and quartz elements are too long for this application, and the required low power settings will significantly decrease the expected lifetime of halogen elements. Despite the availability of fast responding heating methods like metal foil or ceramic surface heaters, they are seldom applied in thermoforming industry due to the high investment costs [9].

The optimization procedure presented in this paper is based on the temperature forming range of the processed thermoplastic material [2]. The procedure runs an iterative loop in which the heating power settings are adjusted. In this loop the heated surface of the sheet is heated up to the maximum allowable forming temperature. Next, the through-thickness temperature profile is checked. In case the temperatures in this profile are not completely within the specified forming range, the power setting is adjusted. This loop is repeated until the complete temperature profile fits within the forming range. As this procedure takes the fitted parameters from the reverse engineering phase into account, the result of the optimization can directly be linked to the actual machine settings.

In figure 3, illustrations of thermoformed parts have been added to demonstrate the efficiency of the proposed optimization procedure. Only when the through-thickness temperature profile was completely within the forming range, the sharp edges at the top of the part could be formed.

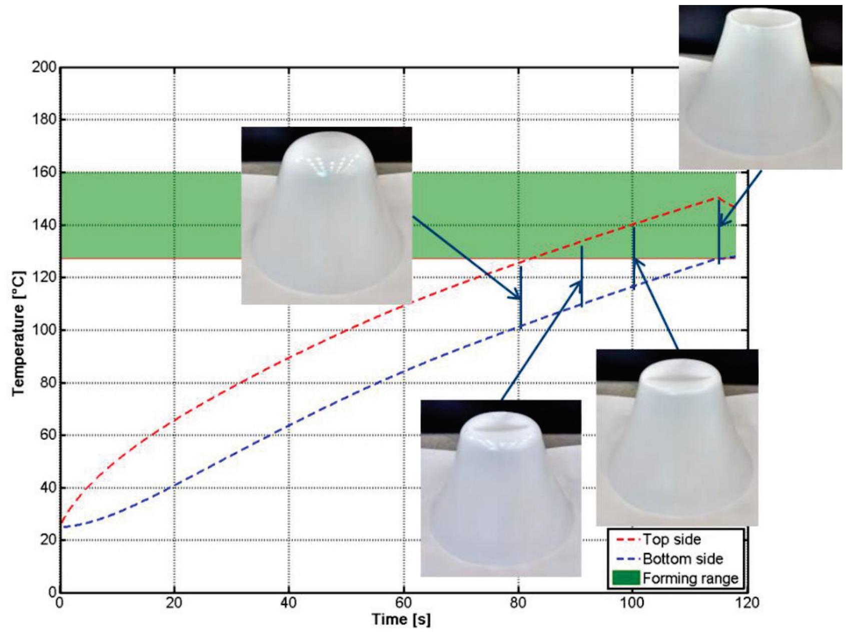

FIGURE 3. Illustration of the effects of different heating times, resulting in an accurate part when using the proposed heating optimization procedure, i.e. the shortest heating time that guarantees a through-thickness temperature profile within the forming range (green zone).

CONCLUSIONS

The current paper presents a procedure in which experimental temperature measurements are coupled to finite difference modelling in order to characterize the heating equipment of a thermoforming installation. This characterization gives the industry a better understanding and an optimization of the heating procedure. A heating strategy is proposed that guarantees through-thickness temperatures that fall within the forming range of the material at hand. Applying the proposed procedure will result in shorter start-up times, a decrease in material waste and a more controlled thermoforming process.

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