ON-LINE ADAPTIVE CONTROL FOR THERMOFORMING OF LARGE THERMOPLASTIC SHEETS

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Abstract

Large sheet thermoforming is widely used for the manufacture of parts such as twin sheet formed gas tanks, body panels and windshields. These complex technical parts require a precise temperature map to be realized prior to forming. In particular, the material used for forming gas tanks incorporates an EVOH barrier layer that is susceptible to tearing when exact processing conditions are not strictly respected. The problem is compounded by the fact that the temperature is presently controlled at the heating elements, while the temperature distribution across the thickness of the sheet is the main process variable. This makes the thermoforming process very susceptible to perturbations and greatly increases the number of rejected parts. In order to increase productivity and quality, the actual sheet temperature distribution before forming must adhere to the optimized temperature map as predicted by a process simulation or the recipe as determined by previous runs. The system presented here controls the amount of energy received by every sheet zone, which is equivalent to controlling the sheet temperature. It is tuned on-line by identifying the heating zone to sheet zone gains matrix using a flux meter and by correlating the matrix to the output of an infrared scanning thermometer located at the exit of the heating oven. The control system will realize the map of the required sheet surface temperature by adjusting the heating elements temperature. The system has been implemented on a Monark twin-sheet thermoforming machine that has dual 1.8mx1.8m square ovens and 504 heating elements in re-configurable zones.

Introduction

Thermoforming of large plastic parts is a widely used process in a number of industries, including the automotive, aerospace and home appliances industries. Thermoforming is an apparently simple process in which a sheet of thermoplastic is heated in an oven until its temperature becomes adequate for molding. This stage is referred to as sheet reheat. Once this temperature is attained, the sheet is transferred to the molding station where the sheet is pressed against the mold to form the part using either a vacuum or pressured air, sometimes with the assistance of a mechanical plug. Finally, the part is ejected from the mold for the cooling stage of the process. Heater zones at the top and bottom of the oven provide heating on both sides of the sheet. One of the most important parameters of an oven is the geometric configuration of its heating zones with respect to the sheet. The radiant power from each heater to each sheet zone is a function of this geometry through the so-called view factors. These view factors must be adjusted during the sheet reheat phase as the sheet sags (Figure 1), thus changing the sheet-to-heater distance.

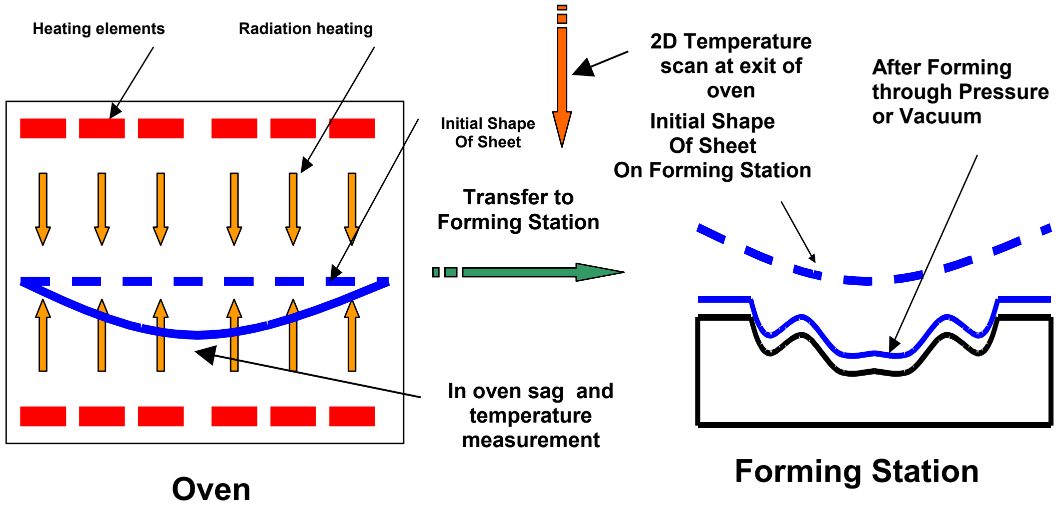


Figure 1: Thermoforming process.

Some of the heat is transferred to the sheet by convection, though it is very difficult to quantify as thermoforming ovens are relatively open structures subject to air drafts or accumulation of hot air in certain areas. Thus, the convection heat transfer coefficients on different areas on the sheet can vary considerably. Significant heating inside the sheet occurs by conduction from the surface where the infrared energy from the heaters is first received. However, a large proportion of the heat increase inside the sheet comes from the infrared energy directly absorbed by the plastic material at any given depth according to the Beer-Lambert law [1].

Today's stringent manufacturing requirements of part surface quality, thickness accuracy, low energy consumption, cycle time and yield, compounded with the small processing window of new designer polymers and multi-layer sheets has led researchers [2],[3],[4],[5] to try to improve the control of this process. Although thermoforming is conceptually simple, its dynamics are fairly complex as sheet heating occurs through radiation, convection and conduction. These mechanisms introduce a great deal of uncertainty as well as time-variations and nonlinearities in the heat transfer dynamics. Furthermore, sheet heating is a spatially-distributed process best described by partial differential equations.

A lot of research effort has been directed at obtaining accurate analytical and finite-element simulation models of the thermoforming process. However, process uncertainties such as perturbations and differences in material properties from batch to batch are often impossible to account for, which often makes even sophisticated simulation models unable to properly predict sheet temperatures, part thicknesses and warpage, etc. In this paper, we present a cycle-to-cycle sheet temperature control strategy applicable to thermoforming machines equipped with an infrared line scanning thermometer that allows for the realization of a pre-determined temperature map through the tuning of a simulated or experimental process model.

In this paper, we consider a cycle-to-cycle control strategy in which the detailed dynamics of the heaters are not relevant because the heater setpoints are assumed constant throughout a cycle, and the sheet temperature measurements are only taken at the end of the reheat cycle in order to compute heater setpoints for the next part. However if temperature measurements are available inside the oven during heating are available the model can be extended to in-cycle control, which will be presented in a separate article.

Model based control and simulation tuning

A simplified one-dimensional dynamic model of sheet reheat whose accuracy is usually sufficient for auto adjusting control purposes is now described. In this model, heat transfer is assumed to occur only through the thickness of the sheet, perpendicular to its surface. The 1D heating equation for the sheet is:

$$\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2} + q_{abs} \qquad (1)$$

where ρ, C_p, and k are respectively the material's density, heat capacity and conductivity; and variables T and q_{abs} are the sheet temperature and the radiated power from the heating elements absorbed at depth z. Equation (1) has been spatially discretized in order to get a set of ordinary differential equations in a state-space format in [2],[4],[5]. This type of model is more amenable to the design of an in-cycle feedback controller. For a given sheet zone i, the spatially discretized energy balance equation at the top surface layer 1 with the absorption terms is given by:

$$\frac{dT_{i1}}{dt} = \frac{2}{\rho C_p \Delta z}\left[\left(Q_{T_{i1}} + Q_{B_{i1}}\right) + h\left(T_{\infty_1} - T_{i1}\right) + \frac{k}{\Delta z}\left(T_{i2} - T_{i1}\right)\right], \qquad (2)$$

where T_{i1} is the temperature of the top surface layer in zone *i*, $Q_{T_{i1}}$, $Q_{B_{i1}}$ are respectively the total absorbed radiant powers from the top and bottom heaters, T_{∞_1} is the ambient temperature, *h* is the convection heat transfer coefficient, and T_{i2} is the temperature of the layer just below the surface layer. Equation (2) is similar to Equation (1), except that it is discretized and it includes convection, see [1]. The energy balance equation for internal layer *j* with absorption included is [1]:

$$\frac{dT_{ij}}{dt} = \frac{1}{\rho C_p \Delta z}\left[\frac{k}{\Delta z}\left(T_{i(j-1)} - 2T_{ij} + T_{i(j+1)}\right) + \left(Q_{T_{ij}} + Q_{B_{ij}}\right)\right]. \qquad (3)$$

The heaters, usually ceramic elements, have their own dynamics[4],[5]. The wavelength of maximum radiated output by the heaters varies with temperature and age. This means that the heater system behaves as a bandpass filter with variable frequencies whereas the sheet acts as a bandpass filter of more or less constant frequency. The heaters are often grouped in zones sharing the same electrical circuit, each zone being typically individually temperature controlled by a thermocouple embedded in a single heater in the zone. This means that the regulated temperature may actually be quite different from the surface temperatures of the zone heaters that radiates energy according to the Stefan-Boltzmann law. However, a transfer function can been identified that relates the temperature at any point in the heater to the input power. Figure 2 shows a schematic representing the dynamics of a ceramic element.

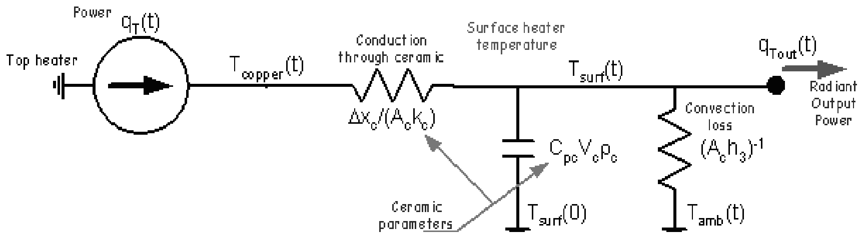


Figure 2: Heat transfer schematic relating heating element temperature to input power

This type of model allows us to represent the thermoforming process as a transfer of power from the heating elements to the sheet while being able to display the heating element average power as temperatures, see Figure 3.

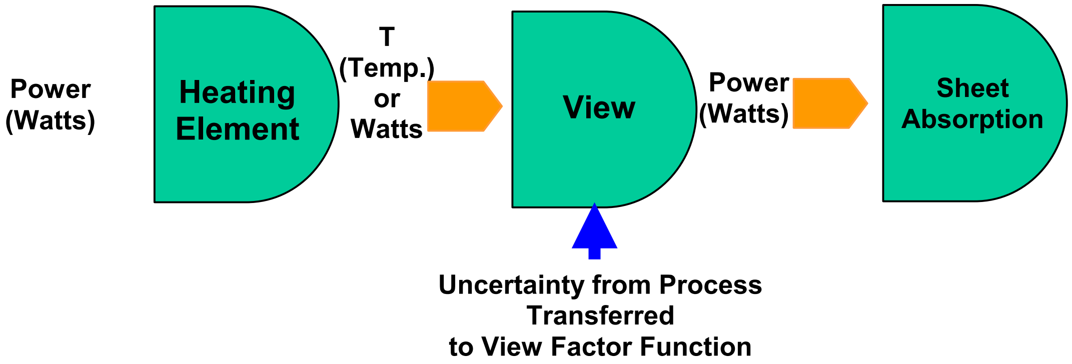


Figure 3: Power/Temperature Transfer functions in Oven
from Heating Elements to Sheet

Model-based feedback control techniques can help in reducing the effect of uncertainties in material and process parameters, and in regulating the outputs against disturbances affecting the process such as air drafts, ambient temperature, or moisture content. Feedback control of the reheat stage can be implemented both in-cycle and cycle-to-cycle, depending on the availability of the required sensors. Such a multivariable control system is currently being developed for commercial applications by MAGI Control Inc. in collaboration with McGill University and the National Research Council of Canada at their Industrial Materials Institute (IMI). The present goal of the control system is to attain on the sheet the desired temperature map as determined by trial-and-error or by process simulation.

Monark Machine Implementation

The machine used for the experiments was a Monark twin-sheet thermoforming machine installed at the IMI large scale laboratory, as shown in Figure 4. The Monark has dual 1.8mX1.8 m (6'X6') ovens, each equipped with 504 heating elements in re-configurable zones.

Figure 4: Monark Twin Sheet Thermoforming Machine

In order to tune the simulation to the machine the fluxes were measured on the machine using a fluxmeter made from a block of aluminum insulated on 5 sides and embedded with thermocouples as shown in Figure 6. The power input to each element zone was measured on the machine through the use of integrated current sensors mounted on the power supply of each zone.

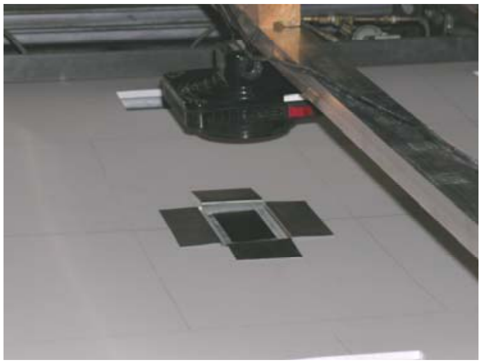
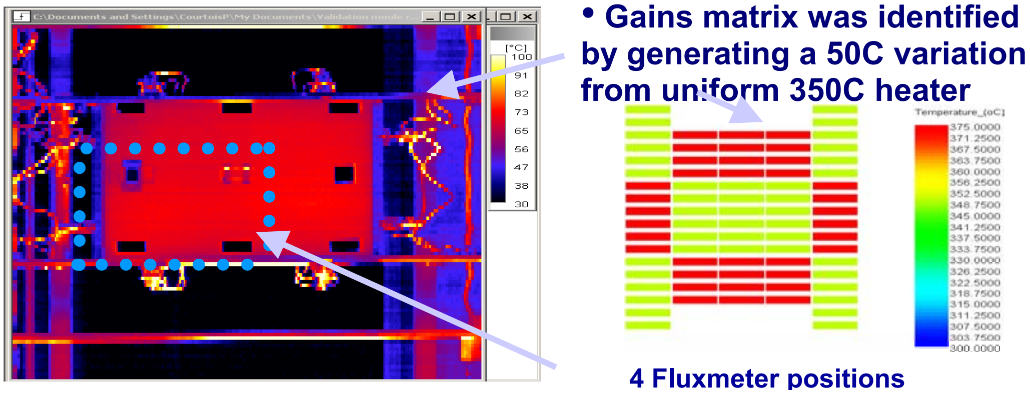


Figure 6: Fluxmeter installed on sheet.



- Gains matrix was identified by generating a 50C variation from uniform 350C heater

4 Fluxmeter positions

Figure 7: Gain matrix identification from line scanner temperature measurements

The layout of the sheet relative to the heaters was then modeled by simulations as shown in Figure 7.

Cycle-to-Cycle Sheet Temperature Control Strategy

In this section, we discuss the design of a cycle-to-cycle terminal sheet temperature controller for a large thermoforming machine, where *terminal* refers to the fact that sheet surface temperatures are only measured at the end of the reheat cycle. Assuming a fixed cycle time, the proposed strategy comprises four steps, of which only the fourth is applied on-line:

1- The heat flux sensitivity matrix (Box 2 in figure 3) is obtained experimentally on the machine using step responses measured with a fluxmeter.
2- The view factors in the finite-element simulator are tuned to obtain the same flux sensitivity matrix as the measured one.
3- The temperature gain matrix linking heater zone temperatures to terminal sheet surface temperatures is obtained from the simulator.
4- The inverse of the temperature gain matrix is applied to the error between the measured and desired terminal sheet surface temperatures in order to compute a heater setpoint correction for the next cycle.

The heat flux coming from the heaters is completely determined by the view factors. The theory of view factors is generally accurate, so that the values of the fluxes is calculated with good precision by a sophisticated finite-element models such as IMI's FormView package. The sum of the view factors, each representing the amount of energy received from heater zone *j* to a sheet zone *i* determine the heat flux (received power per unit area) received by that zone.

$$\text{Heat\_Flux}_{sheet\_zone\_i} = \sum_j V_{i,j} P_j \qquad (4)$$

where P_j is the average power of heating zone *j*.

The heat fluxes were measured by using a flux meter. The experimental procedure was to place the flux meter on the sheet in a particular zone, and to apply a step in temperature in the heater zone of interest, while keeping all the other heater zones at a constant temperature. This is repeated for each heater zone and the changes in flux as recorded by the flux meter are used to compute a sensitivity matrix relating changes in heater zone temperatures to changes in energy received by sheet zones. This procedure was carried out on the Monark machine with the heater zones maintained at 325C and applying a step change of 50C on the heater zone of interest. The heat flux sensitivity matrix was built from these measurements.

Once the experimental flux sensitivity matrix has been obtained, the view factors of the finite-element simulator can be tuned so that it achieves a very similar flux sensitivity matrix under the same simulated heater conditions. The tuned finite-element software can then be used to generate the heater zone temperatures required for a desired sheet surface temperature map at the end of the reheat stage. This can be done by trial and error or using an optimization technique.

Finally, another type of sensitivity matrix must be obtained to account for the fact that sheet surface temperatures, not fluxes, will be measured at the end of the reheat stage during production. The tuned simulator can be used to generate this matrix, with a procedure completely similar to the one described for the heat fluxes, except that here the sheet zone temperatures at the end of the desired cycle time are used. We shall refer to this sensitivity matrix as the *temperature gain matrix* Ψ.

On-line sheet temperature control

During production, a cycle-to-cycle temperature control strategy can be implemented as follows. A line scanner measures the temperature map on the sheet at the exit of the oven after reheat. The measured 2D temperature map is then subtracted form the desired map in order to produce a temperature error map. The temperature gain matrix is then inverted and applied to the temperature error map to produce a vector of heater temperature adjustments which will make the terminal surface temperature map of the *next* sheet much closer to the desired one. For instance, assuming the simplest oven with a one-heater, one-temperature system, after cycle $i-1$ the heater temperature setpoint correction for the next cycle $\Delta T_h(i)$ is computed as:

$$\Delta T_h(i) = \Psi^{-1}\left(T_{sh\_des} - T_{sh}(i-1)\right) \qquad (5)$$

where $T_{sh\_des}, T_{sh}(i-1)$ are the desired and actual sheet surface temperature at the end of cycle $i-1$. For a multi-input multi-output oven, the gain Ψ^{-1} is the inverse of the temperature gain matrix if it is square, or the pseudoinverse if the matrix is nonsquare and the desired temperature T_{sh_des} is in the span of the columns of Ψ.

Thus, after only one cycle, the updated heater setpoints will improve the quality of the formed parts. This simple control strategy can be made more robust to changes in sheet properties or heater drift by adding the integral of the temperature error in the calculation of the heater temperature corrections, which essentially results in a terminal integral iterative learning control (I-ILC) scheme [6]. For instance, assuming the simplest oven with a one-heater, one-temperature system, after cycle $i-1$ the heater temperature setpoint for the next cycle $T_h(i)$ is computed as:

$$T_h(i) = T_h(i-1) + k_{ILC}\left(T_{sh\_des} - T_{sh}(i-1)\right) \qquad (6)$$

where $T_{sh\_des}, T_{sh}(i-1)$ are the desired and actual sheet surface temperature at the end of cycle $i-1$, and k_{ILC} is the gain of the I-ILC controller. For a multi-input multi-output oven, matrix gain k_{ILC} as proposed above would in fact be the inverse or pseudoinverse of the temperature gain matrix Ψ^{-1} [6].

Conclusion

The system proposed above is based on the use of a scanning infrared thermometer to compare the temperature map on the sheet at the exit of the reheat oven with the desired temperature map as predicted by a simulation or from a knowledge base.

- It allows for cycle-to-cycle control and on-line tuning of the simulation model.
- It actually controls the surface temperature of the sheet instead of the elements temperatures as was done previously.
- It allows the control system to adjust for batch-to-batch variations of material properties and ambient conditions.

In future developments, the system will be extended to in-cycle control through correlation of the temperature maps at the exit of the oven to infrared sensors inside the oven as presented in [7]. In this approach fast-responding local models are overseen by intelligent agents that detect and act on any deviations from the desired plant model.

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