Proceedings of the American Control Conference
Anchorage, AK May 8-10, 2002

In-cycle dynamics of forming operations

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1. Introduction

Forming operations are commonly employed for the manufacturing of parts for the automotive, aeronautical, packaging, electronics and recreational sectors. Thermoforming is one such forming operation and is the process of choice for the manufacturing of hollow tub-shaped plastic parts such as car doors, signs, children pools and electronic housings [1].

The absence of control of state parameters has been one of the major problems plaguing this process as material property changes, environmental factors, and machine operating drifts can significantly change the operating point of thermoforming machines. This work focuses on the dynamics and in-cycle corrective control action of the sheet reheat stage in thermoforming, which is the most critical and difficult to control phase of the process. This is the first documented work that deals with the development of a model-based, feedback controller for the control of in-cycle dynamics in thermoforming.

2. Processing

The thermoforming process is composed of three phases: (i) sheet reheat, (ii) sheet forming with plug movement and vacuum application as well as (iii) part solidification. The first and most critical phase of the thermoforming process is the sheet reheat, as the results of this phase directly affect the subsequent process phases.

The sheet is heated in an oven between an upper and lower bank of ceramic heaters. The control of sheet reheat is complicated by the uncertainties associated with the radiative and convective heating, as well as the high level of coupling between individual sheet and heater zones. Furthermore, while the sheet is being heated it sags due its own weight. Sheet sag results in changing radiation view factors and sheet thinning, both of which directly affect the heating of the sheet. Once the sheet is heated for the specified heating time, it exits the oven and moves to the forming station. The forming process is strongly dependent on the temperature profile of the heated sheet and consequently on the sheet reheat phase. Sheet zones that are hotter will deform first and yield thinner part locations, whereas sheet zones that are cooler will deform slower and yield thicker part locations.

All of the experimental trials are performed on an industrial scale thermoforming machine located at the IMI facility. The operating conditions considered are summarized in Table 1. Surface temperatures of the sheet at (i) its top side centre inside the oven and at (ii) its bottom side centre inside the oven are obtained with non-contact infra-red pyrometers.

Table 1: Operating conditions

Parameter	Value
Sheet material	HIPS 3.175 mm thick
Heating time (seconds)	180
Sheet size (cm x cm)	27 by 40
Heater type and rating	Ceramic and 650W
Number of potential heating zones in the oven	Six zones top and bottom
Distance sheet to heaters (cm)	14

3. In-Cycle Dynamics and Control

Control of discrete moulding systems can be performed on two time scales, in-cycle and cycle-to-cycle [2]. For in-cycle control, the sensor measurement, process projection, and the corrective control action are taken within a cycle. Current state of the art in computational power and sensor tools have some limitations for the use of in-cycle control in thermoforming; however, some level of in-cycle control can be undertaken in thermoforming, in particular for the control of the sheet temperature during the reheat stage. The goal of the control strategy is to reach the desired sheet temperature distribution by the end of the heating cycle.

The actuator input parameters are the transient heater band settings during the heating cycle. The measured output parameters are the transient heater and sheet surface temperatures during the heating phase. Once the output parameter is measured during the heating stage a projection is needed to obtain the projected sheet temperature distribution at the end of heating. Full order finite element simulations are a potentially viable alternative for the projection.

4. Deterministic Models

Process control models are identified experimentally by performing steps of various magnitudes, directions, and step locations during the heating stage. Some of the results are plotted in Figures 2-4. For each of these, the step in the heater setting is for the bottom heater. The plotted temperature differentials are the difference between the sheet surface temperature for the step being considered and the sheet surface temperature for the base case experiment at a constant heater band setting of 350 °C.

$$\text{Temperature differential } (i) = T_S(i) - T_S(i)_{\text{BASE CASE}} \quad (1)$$

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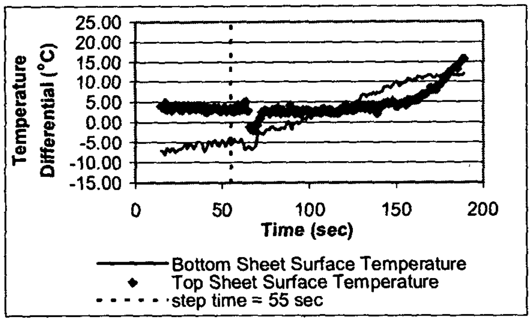

Figure 1: In-cycle dynamics of temperature differential, for top and bottom of sheet, to a step input in the heater setting from 350-400 °C at 25% of the cycle time.

Figure 1 shows the in-cycle response for the top and bottom surface of the sheet. The bottom surface of the sheet follows a typical first order response with a finite lag time of approximately 15 seconds; however, the top surface of the sheet starts responding approximately 100 seconds after the introduction of the step. The additional energy supplied by the step, that arrives at the bottom surface after 15 seconds, takes an additional 85 seconds to arrive at the top surface of the sheet. The heat transfer through the sheet then becomes an important consideration in the design.

Figure 2 shows the effect of step magnitude on the in-cycle dynamics. The step magnitude does not appear to have as significant an effect as expected. The final temperature differential varies by only 3 °C for the two cases. The speed of the dynamics (time constant) also appears to be equivalent.

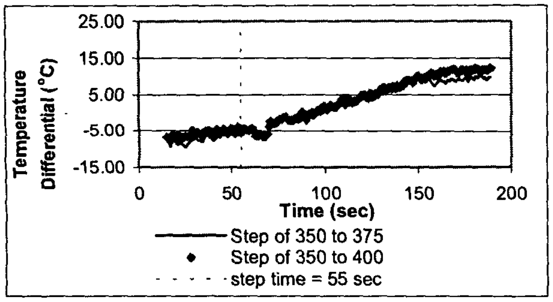

Figure 2: In-cycle dynamics of temperature differential of the bottom surface of the sheet, for step inputs in the heater setting from 350-400 °C and 350-375 °C, at 25% of the cycle time.

Figure 3 shows the effect of step location on the in-cycle dynamics. The step at 50% of the cycle time does not have enough time, before the end of the cycle, to stabilize at the new steady state. Also, the dynamics are faster for the step taken earlier in the cycle. One can conclude that a sensor measurement and corrective action should be taken as early as possible in the cycle in order to have as beneficial and rapid a response as possible.

A finite element coupled heat transfer and solid mechanics simulation is also performed for one of the case studies in an effort to evaluate the potential use of FEM as (i) a forecaster of the sheet temperature distribution and (ii) a tool for identification of the process control model. The simulation is performed by ramping the heater band settings during the iterations of the reheat simulation. A ramp input is necessary for the simulation as the input to the simulation is the actual heater band temperature and not the heater band setting.

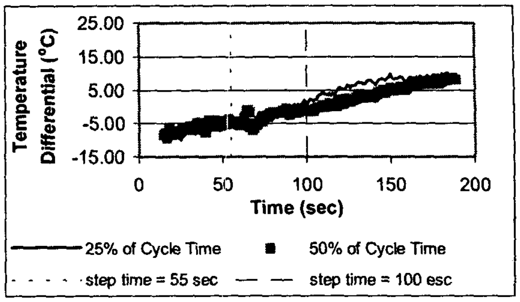

Figure 3: In-cycle dynamics of temperature differential of the bottom surface of the sheet, for a step inputs in the heater setting from 350-400 °C at 25% and 50% of the cycle time.

Temperature differentials were also obtained via finite element simulation. The slope of the predicted in-cycle response is steeper than the slope for the experimental response. The offset between the two responses is initially 6 °C, and reaches 18 °C at about 120 seconds of heating. The simulation predicts excessive heating of the system, probably due to the improper estimation of the heat transfer coefficient inside the oven as well as the uncertainties involved with radiation heat transfer. Further work needs to be done to better estimate the heat transfer within the oven.

An attempt was made to obtain a process model using standard system identification techniques; however, the results were not reliable due to the fact that the step inputs considered did not produce sheet surface temperatures (on both sides) that reached their steady state values. This suggests that step inputs at earlier points in the cycle should be used in order for the energy to fully transfer through the sheet thickness.

5. Conclusions

A study of the in-cycle dynamics of thermoforming has been performed. Results indicate that further work is required to better understand the reheat dynamics. Furthermore, it is also necessary to fully evaluate the viability of a "black box" modeling approach on larger systems with many heater and sheet zones. For these larger systems, the development of reduced order FEM based dynamical models may prove to be effective.

References

1. J.L. Thorne, Technology of Thermoforming, 1996, Hanser, Munich.

2. R.W. DiRaddo and A. Garcia-Rejon, 1992, In-Cycle Deterministic and Stochastic Dynamics of Extrusion Blow Moulding. *Intern. Polym. Process.* 7, 3, 257-263.