ENERGY MODEL BASED CONTROL FOR FORMING PROCESSES

Patrick Girard
Industrial Materials Institute, National Research Council, 75 Boulevard de Mortagne, Boucherville, Canada
Patrick.Girard@nrc.ca

Vincent Thomson
Mechanical Engineering, McGill University, 817 Sherbrooke St.W. Montreal, Canada
Vincent.Thomson@mcgill.ca

Keywords: Model based control, forming energy, simulation, real time identification, intelligent agents, on-line diagnostics.

Abstract: Thermoforming consists of shaping a plastic material by deforming it at an adequate deformation rate and temperature. It often exhibits abrupt switches between stable and unstable material behaviour that have neither been identified nor controlled up to now. PID control, although adequate for simple parts, has not been able to control very well the forming of complex parts and parts made of newer materials. In this paper, the state parameters that allow the development of predictive models for the forming process and the construction of control systems are identified. A robust, model based control system capable of in-cycle control is presented. It is based on a simulator continuously tuned and supported in real time by intelligent agents that incorporate diagnostic capabilities.

1 INTRODUCTION

Forming processes are widely used in a number of industries, including automotive, aerospace and home appliances. Forming is an apparently simple process in which a sometimes pre-shaped sheet of plastic material is first heated to the correct forming temperature in a first phase, and then deformed in a second phase at the correct strain rate, generally by pressing it against a mould to impart a specific shape. The deformation of the sheet is insured by using either a vacuum or pressure at a given temperature and deformation rate, sometimes with the assistance of a mechanical plug. After the part is ejected from the mould some additional, post-processing steps may be required, such as cooling at a controlled rate, or annealing to relieve the built in stresses that were induced by this transformation process.

Effective control of forming needs to address the following issues.

- How energy is transferred to the part can be transformed into two separate processing steps, first to bring it to the correct forming temperature, and then to shape it (Figure 1).
- Depending on the rate that the material deforms, variations in the deformation rate produce enormous changes in the viscosity of the material, resulting in very high and unstable variations of the energy required for deformation as shown in Figure 2.

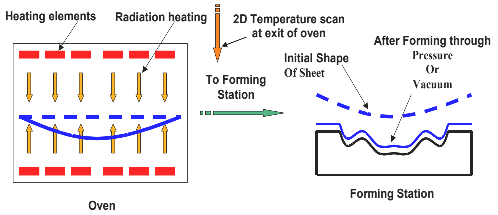


Figure 1: The thermoforming process (Girard et al., 2005).

Up to now forming has been controlled in a very empirical and indirect manner. For example, during the heating phase of the sheet only the temperature of the heating elements has been controlled. The rate of deformation during forming is controlled by applying pressure on the material either as a constant air or hydraulic pressure, or as the result of a semi-controlled explosion. As a result (Figure 2), the forming process is seen as a seemingly random succession of stable and unstable phases where the triggering point from stability to instability is often neither identified nor taken into account. This makes it very difficult to ensure robustness.

This paper proposes a model based control system based on a simulator that predicts the process energy requirements. A similar approach has been successfully applied to the control and on-line optimization of metal powder grinding (Albadawi et al., 2006).

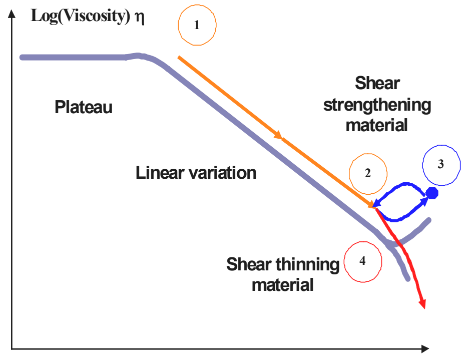


Figure 2: Typical variation of viscosity for thermoplastic materials as forming pressure is applied.

Once a relatively steady state is attained the simulator is tuned on-line and in real time by a number of intelligent agents that identify drifts and variations of the process. The tuned simulator is then used to generate a linear sensitivity matrix and it is upon this matrix that the control model is built, and it provides the response time required for in-cycle control, i.e., while the part is being made. Although the forming process is non-linear, linear control is quite adequate since the operating point predicted by the simulator is close to the actual operating point.

Also, the simulator by itself can actually predict and control the dynamic startup phase of the process. The startup procedure for thermoforming complex, technical parts, for example, can result in up to 5 rejected parts costing $100 each in material (from the thermoforming company, PlastikMP, Richmond, Quebec, Canada).

Further to this introduction, the thermoforming process along with key process parameters needed for effective control is described in Section 2. The present situation for control of thermoforming is given in Section 3. Section 4 outlines the model based control system. Process parameters that can be identified in real time are listed in Section 5. Section 6 presents the real time diagnostic capability of the system, and finally, there is a brief conclusion.

2 IDENTIFICATION OF STATE VARIABLES FOR CONTROL OF THE FORMING PROCESS

The first task is to identify the state variables of the thermoforming process that can be used to control the heating and the forming phase.

2.1 Heating Phase

The purpose of the sheet heating phase is to bring the whole sheet above the minimum forming temperature while remaining below the maximum allowable forming temperature, i.e., be within the forming ‘window’. By knowing this, the minimum and maximum amount of energy required for the heating process can be easily calculated. It is also very amenable to use energy as a control parameter since process energy is the main variable.

This means that the in-oven heating cycle can stop when the required energy has been transferred to the plastic sheet. However, the temperature profile inside the sheet still has to be appropriately distributed (usually uniform). This is presently realized in the real world by allowing the sheet to stand for a while outside the oven before forming.

2.1.1 Energy Transfer to the Sheet during Sheet Heating

Representing this transfer of power with transfer functions allows representation of the state of the system by using either the power or the temperature (Figures 3 and 4). It is a feature required of the control system since the operator needs to view the machine parameters for this phase in the usual manner, which is a temperature display in this case.

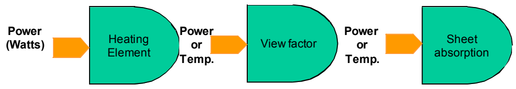


Figure 3: The heating phase as a cascade of energy or temperature transfer functions.

2.1.2 Heat Flux Matrix during the Heating Phase (View Factor)

In the thermoforming process a sheet of material is positionned in an oven and heated by an array of heating elements (shown at the right of Figure 5).

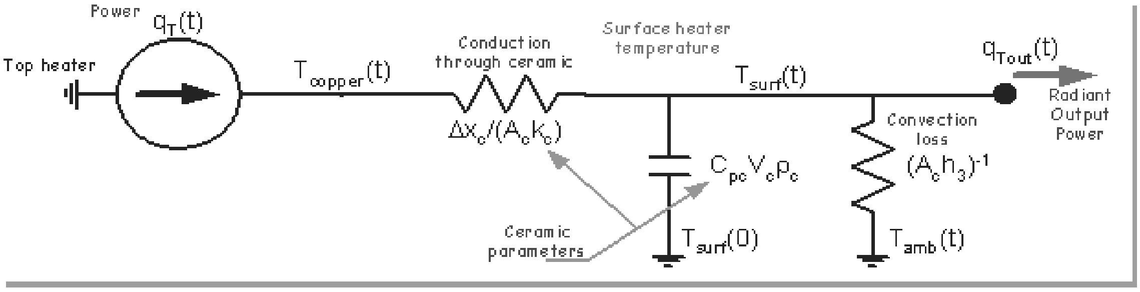
The view factor defines the relation W_{ij} between the heat flux produced by heating element i and the radiative power absorbed by sheet zone j in equation (1). This heat flux can be measured by a sensor as has been demonstrated by Kumar (2005).

$$[Welement_i]\ [W_{ij}] = [Wzone_j] \tag{1}$$

The left part of Figure 5 presents the temperature map at the exit of the oven with the holes provided for the heat flux sensors appearing in black. In this picture the heat flux sensor was located at the center.

2.1.3 Energy Absorption by the Sheet (Process Parameter)

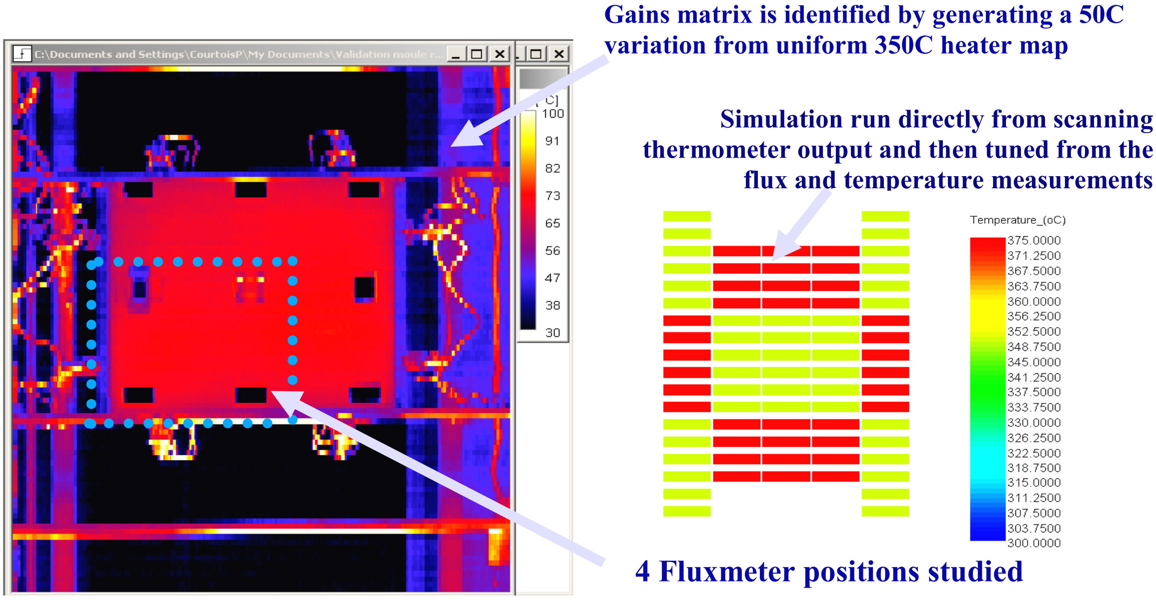
Energy is transferred throughout the sheet by two mechanisms: conduction from the surface and radiation absorption. The two related material parameters are the conductivity and the absorptivity of the material, respectively. A major source of uncertainty in the process stems from the fact that these parameters can vary widely from batch to batch, especially for absorptivity which can vary enormously when the colorant supplier is changed for example, and techniques were designed to detect on-line variations in these parameters.



$$q_T = \frac{1}{R_{cond}}\left(T_{copper} - T_{surf}\right) = \frac{R_{conv}C_{surf}s + 1}{R_{conv}}\left(T_{surf} - T_{amb}\right) + q_{Tout}$$

$$C_{surf} = C_{pc}V_c\rho_c \quad R_{cond} = \frac{\Delta x}{A_c k_c} \quad R_{conv} = \left(A_c h_3\right)^{-1}$$

Figure 4: Heating element transfer function (Gauthier et al., 2006).


Gains matrix is identified by generating a 50C variation from uniform 350C heater map

Simulation run directly from scanning thermometer output and then tuned from the flux and temperature measurements

4 Fluxmeter positions studied

Figure 5: Sheet heat map at the exit of oven and heating element array (Girard et al., 2005).

In general, the temperature increase in a given zone of the sheet and at a given depth for a steady heat flux can be represented with very good precision by the following empiric equation where θ is temperature, *t* is time, and *d* is depth into the sheet (Girard et al., 2005).

$$\theta_{t,d} = \exp\left(\left(\frac{a_1}{(1+d)} + \frac{a_2}{t}\right) * a_3\right) \tag{2}$$

Using this equation means that we know the constant heat flux that is required to heat the sheet to a given temperature θ_I at time *t* and depth *d*. The constants a1, a2 and a3 are determined by the fit with modelled data. Figure 6 presents the variation of temperature for a steady heat flux (constant heating element temperature) together with the repeated adjustments needed by a PID controller.

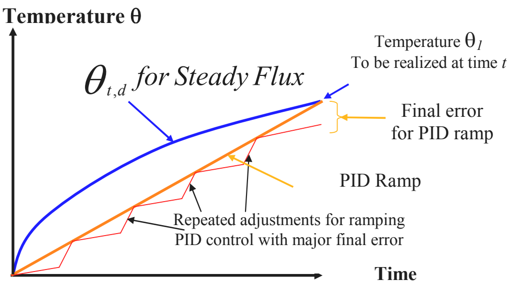


Figure 6: PID ramp and model based temperature control comparison. Model based control achieves final state temperature with more accuracy and less adjustment during heating.

2.1.4 Absorptivity (Material Parameter)

The measurement of the start of heating for a virgin (i.e., not colored) high density polyethylene thick sheet reveals that even at a depth of 11 mm the material temperature starts to increase nearly immediately with the start of radiative sheet heating (Figure 7). Since conduction heating requires several minutes to get to this depth, the only heating mechanism that can allow for such a behavior is radiation absorption.

The energy absorbed, q_{absn}, in layer 'n' contributes to the internal temperature change according to:

$$F_1\alpha(1-\alpha)^n = q_{absn} = \rho c_p \frac{\partial T}{\partial \tau} x \tag{3}$$

where F_1 is the heat flux at the surface of the sheet, α is the absorptivity, ρ is the sheet density, c_p is the heat capacity, ∂T is the sheet temperature difference during time ∂τ, and x is the n^{th} layer thickness. From equation (4) (Kumar, 2005), the absorptivity α can be calculated from the slopes of the temperature increase measured at layers 3 and 1.

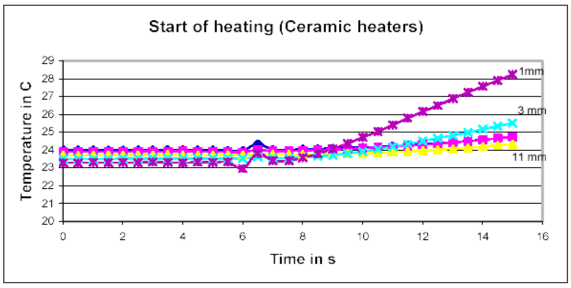


Figure 7: An enlargement of the start of sheet heating (Girard et al., 2005). The data show the temperature increase with time at different depths in a plastic sheet being heated from the surface.

$$\alpha = 1 - \sqrt{\frac{\left(\frac{\partial T}{\partial \tau}\right)_3}{\left(\frac{\partial T}{\partial \tau}\right)_1}} \tag{4}$$

2.1.5 Heat Capacity (Material Parameter)

The heat capacity C_p is evaluated during the cooling phase from the cooling rate with a given heat transfer coefficient at the sheet surface (Figure 8) (Zhang, 2004). The total energy, q_{tot}, can also be determined from the heat transfer coefficient as follows

$$q_{tot} \cong q_{conv} \cong \rho C_p x \frac{\Delta T}{\Delta \tau} \tag{5}$$

where the energy from the heating elements hitting the sheet is the convection energy, q_{conv}.

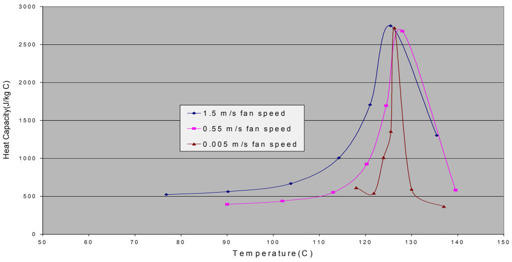


Figure 8: Experimental heat capacity curves determined by different cooling rates obtained on-line by varying fan speed (bottom heating of the sheet at 280°C).

Please note in Figure 8 that different cooling rates predict mostly the same heat capacity, and that the shape of this peak is directly related to the level of crystallinity of the material.

2.1.6 Elastic Modulus (Material Parameter)

During the re-heat phase of the thermoforming process the frozen in stresses induced in the material during the calendering process are relaxed. This results in anisotropic shrinkage of the sheet that causes variation of the sag in the heating oven. The forming of the shrunk sheet results in variations of the final thickness of the produced part. Also, the sag during heating must be adequately controlled since it can result in catastrophic variations in the distance from the sheet to the heating elements.

The elastic modulus, E, and level of frozen-in stresses are the main predictors for sag and shrinkage during the heating phase of the thermoforming process.

It is however difficult to get adequate data for process control and simulation purposes given the variability of sheet material properties from batch to batch and the fact that the variation of E is difficult to evaluate by the usual techniques in the vicinity of the melting point of the material where the experimental data reveals a very sharp inflection point related to the phase change of the material. Since forming takes place in this temperature region simulation models are quite deficient in this crucial area.

To address these issues an on-line identification technique was developed that uses two different steps of the blow forming process (Bahadoran, 2005). The low temperature variation of the elastic modulus is identified from the development of the sag at the entry in the oven (Figure 9) allowing for a better evaluation of E near the melting point. However, an existing forming mould can be used to produce a bubble on-line on the actual forming machine, and the value of the elastic modulus is characterized near the transition point of the material from the variation of the bubble and the blow pressure (Figure 10) (Bahadoran, 2005).

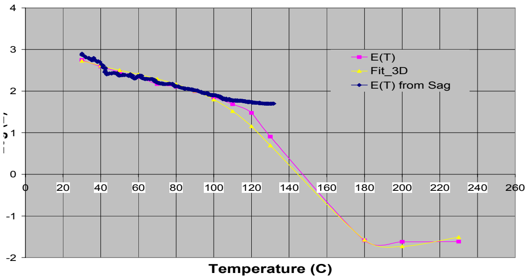


Figure 9: Experimental data obtained on-line showing the variation of the elasticity modulus with temperature at lower temperatures.

This provides a much better definition of the 'elbow' zone of E versus temperature. This technique requires minimal additional instrumentation to an existing machine. Also most any existing mould can be used for this purpose.

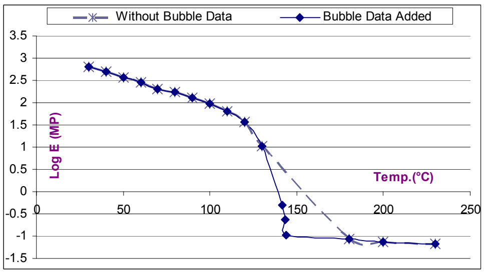


Figure 10: Experimental data obtained on-line showing the variation of the elasticity modulus with temperature, particularly near the melting point.

2.2 Forming Energy during the Forming Phase

Referring to Figure 2, after the sheet has been heated the forming process begins at point 1 by applying a constant pressure from one side of the sheet to be formed. The material starts taking a more or less spherical shape and its thickness diminishes. As the shear rate of the material increases, the viscosity of the material drops. Since the input pressure remains relatively constant, this results in an unstable and very fast evolution towards point 2 when the shear rate rises above a triggering level.

After this point, the forming process can behave either in a stable or an unstable manner depending on the type of thermoplastic.

- If the material is shear strengthening, deformation under constant pressure is relatively easy to control since it will be mostly spherical and bounded at point 3 and then revert back to a stable behaviour. Also, since the deformation is self-stabilizing the shape of deformation tends to be spherical. This is how the blow moulding of PET (polyethylene terephthalate) materials is controlled, for example.
- If the material is shear thinning, a pressure control scheme results in the sheet being ripped apart in an explosive manner. Also, any deformation that starts at a given location typically 'grows' in a random direction and pattern. In this case, the forming process needs to be either bound geometrically by a mould or by the flow rate that is applied to 'blow' the sheet.

Figure 11 presents how the volume and pressure develop for the free blow (forming without a mould) of a PET bottle. It can be seen that the formed part starts by expanding in a smooth manner in phase 1 until it suddenly expands very rapidly in phase 2. Since PET is shear strengthening it will then consolidate in phase 3.

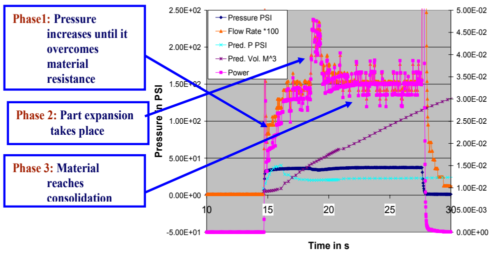


Figure 11: Measuring the pressure/volume relationship for free blow (blowing without a mould) of a PET bottle

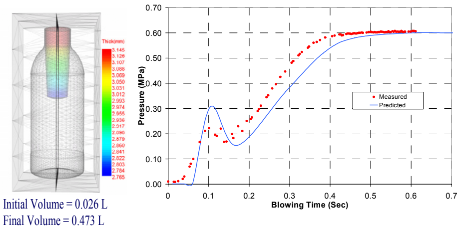


Figure 12: Predicted and measured pressure with the $W_{forming}$ simulation approach (PET bottle in mould).

It is easy to measure on-line the pressure and the flow rate for these processes, and recent developments show that simulations based on the forming energy are much more accurate than those relating constitutive equations to initial temperature and pressure conditions on the sheet (Figure 12) (Mir et al., 2007). Also, minimizing the amount of energy required by the process, which allows for the use of smaller machines, is often one of the objectives of the control system.

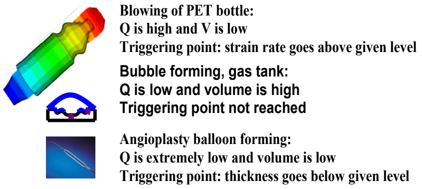


Figure 13: Development of volume flow Q and volume V for some thermoforming processes.

It must be noted that the start and development of phase 2 (Figure 11) is not predicted by the usual techniques, but that it poses no problem with the $W_{forming}$ approach (Figure 12). Also, the 'trigger' point (Figure 13) that starts the expansion phase is not predicted at all with the regular modeling approach.

3 CONTROL TECHNIQUES PRESENTLY USED FOR THERMOFORMING

The control techniques presently used are typically based on indirect sheet temperature control and a forming pressure that is set to a constant value. These techniques have major drawbacks.

- They do not directly control the main parameters of the process.
- They do not monitor and do not control adequately the primary process variables. This is especially true of the forming pressure since it is only regulated at the entry of the mould, and often very imprecisely.
- They do not identify nor take into account the switch point from stability to instability.
- During the unstable phases of the process, minor variations in the input variables of the process can develop into chaotic variations in the end process. These variations are presently not detected and are only taken into account in the system indirectly. They can be:
  - material properties that vary from batch to batch,
  - environmental variations such as ambient temperature or air flow, and
  - variations in machine parameters such as heating elements output or line pressure.
- Present temperature controllers, such as implemented by MAGI Control (Montreal, Canada), use a PID controller to track a ramp that is calculated from the θ_1 temperature to be realized. Figure 5 presents a comparison of the model based and PID ramping approach based on the results obtained by MAGI Control.
- These process uncertainties are compounded by the new 'designer' materials that typically have a very narrow processing window, and also by the very tight dimensional requirements that are required of technical parts

It can be seen that PID control based on a ramp requires repeated adjustments during the heating phase and ends up with a considerable final error. Model based control however only requires the adjustment of the heat flux by integration of the heating curve, which achieves much smoother control and better final temperature precision.

4 MODEL BASED CONTROL SYSTEM

In place of PID control, we are proposing to use a model based control system that is continuously tuned and based on on-line identification of the main parameters of the forming processes that were presented in Section 2. This 'tuning' is achieved by intelligent agents as defined by (Weiss, 1999): "Agents are autonomous, computational entities which sense their environment either by physical or virtual sensors, and then initiate actions by actuators and/or by communicating with other agents." In our case each agent is a fast response routine that monitors a specific aspect of the process, for example, the variation of the specific heat of the material. If this variation is above a specific level, the agent contacts the main system so that the process parameters are adjusted to reflect the change.

4.1 General Specifications of the System

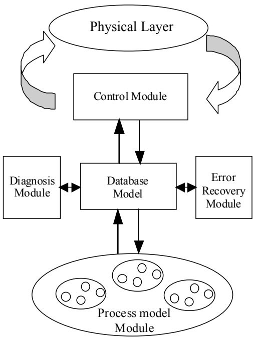


Figure 14: General architecture of the model based control system.

4.1.1 Objective

- Implementation of a generalized controller that is based on a model of the process to be controlled and that updates and tunes the process model in real time.

4.1.2 Inputs

- Real time measurements of the process and equipment data.
- Results of quality control.
- Process submodels implemented as intelligent agents that identify and track parameters and that calculate process state parameters.

4.1.3 Outputs

- Updated control model with control parameters that are sent to the forming process.
- Process and material parameters are estimated during part manufacture and are updated after each part is made.
- Diagnostics of the process are executed during part manufacture.

4.2 Main Control Module

4.2.1 Simulator Agent

The first step for the creation of a model based control system using intelligent agents is to build an accurate process model and simulator. The process model identifies critical state variables and the simulator predicts the parameter adjustments required for the desired outcome from the state variable history. A finite element simulation of the thermoforming process based on the $E_{forming}$ energy in equation (3) is very easy to correlate to real time machine measurements of the flow rate and pressure. This simulation typically requires:

- the geometric description of the part, machine and moulds,
- a material database for the rheological and physical properties of materials, and
- the processing parameters for the part, often called recipe by the manufacturer.

Also, two main challenges need to be addressed for adequate control.

- Inaccessible internal sheet temperatures need to be controlled precisely within the forming window for part quality.
- The execution time frames of the different agents need to be adjusted and synchronized.

4.2.2 Simulation of a Virtual Sensor

The tuned simulation can function as a virtual sensor, also called a soft sensor. The integrated history of the sheet surface temperature as measured directly by infrared sensors with the heat transfer simulation to predict the sheet internal temperature and to indicate the time required for adequate sheet heating inside the oven.

One of the main outputs of the simulation is the predicted heating curve for the material for a constant heat flux (Equation (2)) shown in Figure 6. From this, the system can control the heat flux by controlling the heating element input power, which results in a given temperature at a given depth at time *t* in the material.

4.2.3 Adjusting the Time Frames of the Different Modules

Unfortunately, the time frame of such a simulation is orders of magnitude greater than what is needed to control the thermoforming process in real time. This problem is solved by generating the sensitivity matrix of the simulation every time the simulation is updated. For example, the heat flux in equation (3) can be generated from the tuned simulation. Equations (2, 3) are used to predict the sheet temperatures at different depths for different sheet zones for the time sequenced trajectories of the heating element energy input allowing for heat flux control as shown in Figure 5.

Since the simulation is reasonably accurate, the control system only needs to apply the updated parameters in the vicinity of the initial prediction for the calculated operating point, which allows the use of linear interpolations to adjust the operating point as required, thus achieving a very fast response time.

4.3 Agent based Control

An intelligent agent based system is a loosely coupled network of problem solving entities (agents) that work together to find the answer to problems that are beyond the individual capabilities or knowledge of each entity (Florez-Mendez, 1999). An agent based system was chosen for model based control since it can deal well with multiple submodels and data streams, and can cope with submodels that are very different in size and that operate on dissimilar time scales. These features make agent technology especially suited for building control systems based on models of processes, where the processes are very complex and many process and material parameters are dynamic.

All agents in the architecture operate independently and asynchronously. The control agent acquires sensor data from the physical layer and sends control parameters as they become available. Similarly, the process agents retrieve sensor data and calculate state variables. The retrieval of sensor data and the calculation of state variables are interrupt driven based on detected variations from previous states; thus, calculations are only launched when needed and with the best information available. This design minimizes control cycle time while allowing data to flow asynchronously and implements just in time delivery of the different data streams, while still setting control parameters with complex, but validated parameters. The result is that during a short production period certain parameters are updated infrequently. This is not a problem, since they do not highly impact the operating point of the process. This architecture allows many processes to be controlled in-cycle, i.e., while a part is being made so that near perfect parts can be made every time. If the process is very fast or parameters cannot be measured during part manufacture, cycle-to-cycle control can be done, i.e., parameters measured during or after a part is being made are used to control the next part being manufactured.

Control can be done with a single processor, if the amount of computation is small. Nevertheless, for a complex process like thermoforming, the amount of calculation for process models tends to be large and distributed over different time frames; therefore, multiple processors may be required depending on the complexity of the heating process. With multiple processors, the control system can dynamically allocate the execution of different agents to different processors. Due to the asynchronous operation of the architecture, processes can be optimally controlled for submodel execution times from milliseconds to hours.

5 PARAMETERS IDENTIFIED ON-LINE

If the agent in charge decides that the drift or variation of the parameter warrants an adjustment of the simulator, parameters are changed and the simulation is then re-run and the control models regenerated. For the thermoforming process, the following parameters are continuously monitored in real time.

- absorptivity
- heat capacity
- elastic modulus of the material.

Machine parameters that are monitored on-line are:

- input power of the heating elements
- surface temperature of the sheet in the oven
- forming pressure
- forming energy flow rate
- mould temperature.

Ambient parameters that are monitored on-line are:

- ambient temperature
- oven air temperature
- air velocity in the oven during sheet heating
- air velocity during the cooling phase after forming.

6 DIAGNOSTIC SYSTEM

A diagnosis module monitors the behaviour of the process during control. The agents that monitor the system act to detect any abnormal behaviour based on previously accumulated know-how about the process. They then either try to correct the anomaly (error recovery agent) or stop the machine in the case of a non-recoverable error. In all cases the operator is advised. Diagnostics and error recovery operate independently and asynchronously with respect to the process and control modules. More detail is given in Albadawi et al. (2006).

7 CONCLUSIONS

The model based control system proposed here for the thermoforming process:

- uses the energy required as the main control variable, allowing for easy energy minimization,
- can target a specific temperature at a specific depth and a specific time by adjusting a single state parameter,
- can predict the switch from steady to unsteady state in the process,
- can detect and adjust for a range of variations of material and machine parameters,
- has a response time that is adequate for in-cycle control, and
- inherently minimizes cycle time while respecting the process and material limitations.

Agent technology is an excellent match for control based on process models since it allows distributed intelligence and decision making to be applied to the control problem.

Subsystems for the control system have been developed and a system is being built to test control of an industrial thermoforming process.

REFERENCES

Ajersch, M., 2004. *Modeling and real-time control of sheet reheat phase in thermoforming*. Master's thesis, Department of Electrical Engineering, McGill University.

Albadawi, Z., Boulet, B., DiRaddo, R., Girard, P., Rail, A. and Thomson, V., 2006. Agent-based control of manufacturing processes. *Int. J. Manufacturing Research*, 1(4) 466–481.

Bahadoran, 2005. *Online characterization of viscoelastic and stress-relaxation behavior in thermoforming*. Master's thesis, Department of Mechanical Engineering, McGill University.

Florez-Mendez, R., 1999. Toward a standardization of multi-agent system frameworks. *ACM Crossroad*, 5(4), 18-24.

Gauthier, G., Ajersch, M., Boulet, B., Haurani, A., Girard, P., DiRaddo, R., 2005. A New Absorption Based Model for Sheet Reheat in Thermoforming, *SPE Annual Technical Conference, ANTEC*, Boston, Massachusetts.

Girard, P., Thomson, V., Boulet, B., DiRaddo, R.W., 2005. *Advanced in-cycle and cycle-to-cycle on-line adaptive control for thermoforming of large thermoplastic sheets*. *SAE World Congress*, Detroit, MI, USA.

Kumar, V., 2005. *Estimation of absorptivity and heat flux at the reheat phase of thermoforming process*. Master's thesis, Department of Mechanical Engineering, McGill University.

Mir, H., Benrabah, B., Thibault, F., 2007. The use of elasto-visco-plastic material model coupled with pressure-volume thermodynamic relationship to simulate the stretch blow molding of polyethylene terephthalate, *Numiform*, Porto, Portugal.

Weiss, G., 1999. *Multiagent systems*, MIT Press, Cambridge, USA.

Zhang, Y., 2004. *Generation of component libraries for the thermoforming process using on-line characterization*. Master's thesis, Department of Mechanical Engineering, McGill University.