CONTROL OF SIMULATED DIE CASTING 2-DIMENSIONAL FINITE ELEMENT MODEL

R. Vetter, D. Maijer, M. Huzmezan* D. Meade**

* *University of British Columbia, Electrical and Computer Engineering*
huzmezan@ece.ubc.ca
** *Universal Dynamics Technologies Inc.*
dmeade@brainwave.com

Abstract. Process modelling, now a fairly common technique to improve and optimize industrial casting processes, can produce reliable predictions of process operational conditions and defect formation. Concurrently, advanced process control is used in a variety of industries to optimize process performance and maximize throughput. This work is seeking intelligent casting solutions by linking high fidelity process modelling with advanced control. This paper details how a simplified axisymmetric 2-dimensional finite element model, acting as a 'virtual' cyclic die casting process, is used together with an adaptive predictive control strategy for accurate die temperature control leading to reduced defect formation.

Keywords. Intelligent Casting, Adaptive Model Based Predictive Control, Advisory Systems

1. INTRODUCTION

Process modelling using finite element (FE) solutions has become a common technique to improve and optimize industrial casting processes. For low pressure die casting processes, mathematical models that describe the evolution of temperature in the casting and the die can be used to reliably predict defect formation (Vo *et al.*, 2001; Maijer *et al.*, 2000). Similarly, advances in control theory have lead to widespread use of online control for a variety of industrial processes (Huzmezan *et al.*, 2002).

Current research suggests that the formation of defects in cast products can be linked to the temperature history. Such results lead to the requirement that temperatures at various locations within the die need to be controlled to predefined set points. Before investigating regulatory control for casting cycles, the cyclic steady state temperature of the die, associated with slow startup times and disturbance rejection, has to be adequately controlled for improved overall casting performance.

A link between process modelling, traditionally used for design and troubleshooting, and advanced control solutions allows for: i)the evaluation of closed loop performance of industrial die casting and ii)optimal instrumentation placement and selection. Ultimately, this approach minimizes the perceived risk and cost to companies considering these solutions.

This paper presents a process overview of a simplified die casting process in Section 2 followed by a discussion of the integration technique used to link an ABAQUS model of the casting process and the BrainWave controller in Section 4. The process control strategy and its performance are detailed in Sections 5 and 6, respectively.

2. PROCESS DESCRIPTION

The simulated process represents the casting of an aluminum alloy (A356) cylinder in a steel mold. The mold has a radius of 5cm and a height of 2cm and has 2 square cooling channels that encircle the mold. The cooling channels are 0.5cm by 0.5cm and allow for the simulation of a forced air cooling system. The casting process produces an aluminum cylinder with radius of 4cm and height of 1cm. The incoming molten aluminum is 700°C. Solidification of the cast occurs at 550°C. Figure 1 shows a 3-D representation of the cylinder and mold with a cut-out exposing the cooling channels.

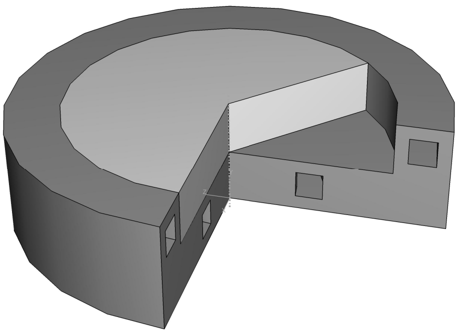

Fig. 1. Solid 3-D model of the Steel Mold and Aluminum Cast

The first step in the die-casting process is to fill the mold with molten aluminum and solidify the casting. In the simulation, it is assumed that the molten aluminum has a uniform initial temperature distribution once in the mold. This uniform temperature distribution is determined by the incoming metal temperature. Changes to the incoming metal temperature from the nominal value of 700°C provide a disturbance to the system. In practice, the casting easily solidifies in less than 15 seconds.

The second step of the die-casting process is to open the mold and eject the casting. During this second step, the operator may perform maintenance on the mold in order to prepare for the next cycle. While the mold is open, it is cooled by the surrounding environment. The simulation assumes the mold is open for 10 seconds and any change to this open time is considered a disturbance to the system.

3. THE ABAQUS MODEL

To represent the casting process, a 2-D axisymmetric finite element model was developed using a commercial software package, ABAQUS. The cross sectional geometry used in the ABAQUS model for the mold and casting is shown in Figure 2.

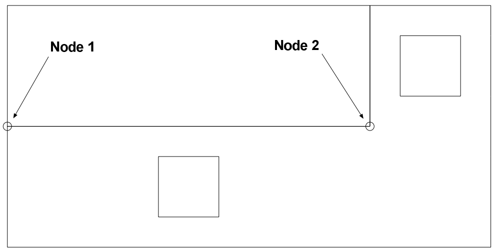

Fig. 2. ABAQUS Model with Process Variable Nodes

The model consists of 2 parts: the casting and the mold which includes two cooling channels. The casting and mold contain 48 and 72 4-node linear temperature elements, respectively. Heat transfer between the casting and the mold is approximated using a contact pair with a gap conductance heat transfer coefficient. Simulated air cooling occurs via a heat transfer coefficient boundary condition applied to the channel edges. Upon ejection of the casting, mold cooling to the surrounding environment is simulated through a heat transfer coefficient boundary condition applied to the mold surface. This condition models the mold cooling to the surrounding environment while the operator is preparing the mold for the next cycle.

The model of the casting process is similarly split into 2 Steps. The first step simulates the cooling of the casting in the mold. To simulate this step, the temperature of the incoming molten aluminum, the cooling channel heat transfer coefficients, and the mold's nodal temperatures from the previous cycle are required. If this is the first simulation cycle, the mold's nodal temperatures are specified to reflect the initial startup temperature. The second step simulates ejection of the casting and cooling of the mold with the casting removed. In this case, the only parameter required is the length of time the mold will be open. The ABAQUS model simulates a single cycle in the casting process. To restart the simulation for the next cycle, the parameters listed above must be specified.

4. INTEGRATION OF THE ABAQUS MODEL AND THE BRAINWAVE CONTROLLER

The casting process is a continuous cyclic process, and therefore requires the single cycle ABAQUS model described previously to be run in continuous cyclic mode. To achieve this cyclic behavior a Perl script was written. The current version of the script and the ABAQUS model were developed in the Windows^{TM} environment. Larger, more computationally intensive, ABAQUS models will require running in a Unix environment, taking advantage of the Perl script portability between Windows^{TM} and Unix.

A commercial controller, BrainWave MultiMax, was selected to automate the die casting process in its simulated ABAQUS version. BrainWave MultiMax, which runs on Windows^{TM}, was modified to accept an external trigger synchronized with the execution of the ABAQUS model. The Perl script was augmented to integrate the ABAQUS Model and the BrainWave Controller. The Perl script communicates with the BrainWave MultiMax controller via the TCP/IP protocol using an external read and write program to interface directly with the BrainWave internal database. The BrainWave User Interface can be used to monitor the simulation parameters in real time.

The ABAQUS software requires an input file that describes the process to be simulated. In the case of our cyclic process, this file changes with every iteration and therefore must be rewritten for every cycle. The file is written using the previous cycle's operational information, as well as the process variables, control variables, and disturbance information. Once this file is written, the current cycle is simulated. After the ABAQUS software has completed running a cycle, the process variables and feedforward data are extracted from the ABAQUS output files and placed into separate output files for future analysis and use when the next cycle starts.

The Perl script provides the user with 2 simulation modes: open loop and closed loop. Each of these 2 modes can also be simulated either automatically or manually. The open loop mode allows the user to specify the control variables to be applied to the process. The BrainWave controller is not required in open loop mode but can be incorporated in such a way that it can learn the process dynamics off-line. The models that are learned off-line can subsequently be employed for improved closed loop control. Additionally, the open loop mode allows the user to apply control moves and disturbances to the system and observe the effects via the process variables. This functionality is useful for both process identification and to demonstrate the effects that disturbances can have on an uncontrolled system. In the closed loop mode, BrainWave MultiMax controls the process model. This mode allows the user to specify the desired process variables set-points. The controller then computes the required control variables and passes them to Perl script for integration into the next process simulation cycle. The closed loop mode, like the open loop, runs the simulation cyclically for a predefined number of iterations.

Each of the 2 simulation modes can also be run in either manual or automatic operation. In manual operation, input values such as set-point and control variable values are read directly from the BrainWave User Interface. This type of operation is useful for short tests on the process where the user wants to manually adjust input values while the simulation is running. In automatic operation, all input values are read from an input file that describes when changes to the set-points, control variables, or disturbances are desired. Automatic operation is useful for long simulations where the user does not want to monitor the process.

Figure 3 shows a pictorial view of the communication between ABAQUS and BrainWave MultiMax facilitated by the Perl script. Each process cycle can be split into 4 main functions: i) retrieving the cycle startup data, ii) writing and reading data to and from the Controller, iii) preparing the input file and running the ABAQUS simulation, and iv) extracting the desired data from the simulation files.

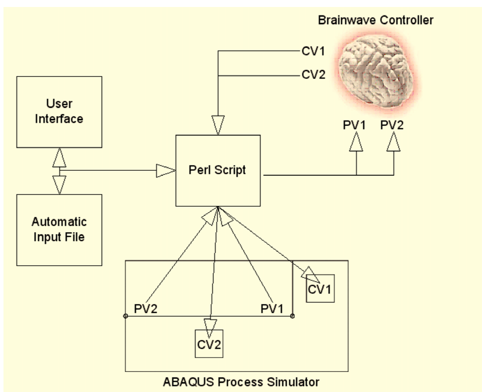

Fig. 3. Model and Controller Interface Diagram

Retrieving the cycle startup data involves reading the set-points, control variables, and measured disturbance variables. These values come from the automatic input file if the simulation is in automatic operation, or from the user interface if in manual operation. The measured disturbance variables can only be changed while running the simulation in automatic operation. If the simulation is running in manual operation, the feedforward variables are defined at startup. The reason for this limitation is that the user interface is designed for real controller operations and does not allow for changing feedforward variables.

After the cycle startup data is retrieved, the process variables, set-points, and feedforwards are written to the BrainWave database. If the simulation is in open loop mode the control variables are specified via the automatic input file or the user interface. If the simulation is in closed loop mode, then the Perl script reads the control variables from the BrainWave controller.

In the case of a cyclic process, a difficulty arises when the time required to simulate the process is much greater than the amount of time being simulated. For example, the "simulated" cycle time of the die casting process is 25 s which includes 15 s for the first step and 10 s for the second step, while the execution time of the cycle using ABAQUS is approximately 45 s. This discrepancy between "simulated" and execution time will become much larger when more complex models are simulated. To deal with this discrepancy, the BrainWave controller has been modified such that the sample time of the controller is controlled via an external flag. By writing to this flag, the Perl script signals to the controller that all of the process data has been loaded into the database and the controller can now calculate the next control move. Upon completion of the controller calculations, the control variables are read from the BrainWave Database and the next ABAQUS cycle can proceed.

5. PROCESS CONTROL

The purpose of actively controlling the system rather than operating the process at some predefined setting is to minimize the number of defects in the cast product. To achieve this goal, an optimal cooling profile throughout the casting cycle must be attained. In order to realize the optimal cooling profile, the mold temperatures must follow the desired set-points. The intermediate approach taken in this work was to control the mold's nodal temperatures at the end of the casting step, before ejection. The mold temperatures at two nodes, prior to each casting cycle, have been selected as the process variables since there is evidence that by choosing and ensuring optimal steady state cyclic temperatures defect-free castings can be produced. The optimal temperatures are constant under common operational conditions and hence the set-points will remain unchanged. Therefore, the only issue in maintaining these set-points after the process reaches steady state is to reject disturbances. Additionally minimizing temperature excursions during major upsets and startup represents another challenge for the process operators that can be dealt with by closed loop operation.

Typical disturbances to the process are variations in the incoming metal temperature and variations in the length of time that the mold is open. The incoming metal temperature is measured directly from the process while the length of time that the mold is open is measured indirectly through the nodal temperatures at the end of the casting cycle. Since both disturbances can be measured, they can be used as feedforward variables in the BrainWave controller.

In a real casting process, to drive the mold temperatures to a desired set-point requires control of the flow rate of the air in the cooling channels. If the temperature of the node being considered is above the set-point then the air flow rate must be increased. Likewise, if the temperature is too low, then the air flow rate must be decreased. In the ABAQUS model, the flow rate of air in the cooling channel is not directly modelled, instead a heat transfer coefficient relates the air flow to cooling rate. In this work the relationship between the air flow and the heat transfer coefficient is assumed to be linear. The control variables in our process thus become the heat transfer coefficients of each of the cooling channels. The flow rates in each of the cooling channels can be controlled independently and therefore 2 control variables are available for the process.

The temperatures of nodes 1 and 2 are chosen to be the process variables. Node 2 is located at the center of the mold and can be seen in Figure 2. The temperature at node 2 provides a good indicator as to when the casting is completely solidified because the center of the casting is the last to solidify. Node 1 is located at the corner of the mold where the casting first solidifies. Choosing a process variable at this node provides important information regarding the cooling profile of the casting. Node 1 is also chosen because controlling the temperature at this point will be greatly influenced by both cooling channels. In the future the cross-coupling between the 2 control variables and this process variable will allow an investigation of the efficiency of the multivariable controller in ensuring the desired levels of performance.

The BrainWave controller is based on a model predictive control algorithm and therefore requires an internal model to generate control moves. To specify the internal model at startup a number of first order model definitions are required. These first order models link the control and feedforward variables to the process variables. Each model is specified with a gain and a time constant. These models provide the start for the adaptive part of the BrainWave controller to build on.

To determine these first order models, step changes in the control and feedforward variables are applied to the process and the corresponding process variables are measured. Since the casting process is nonlinear and the BrainWave controller requires linear first order models, the process must be analyzed near its nominal operating temperatures. For the purposes of this research, the nominal values and therefore the set-points for nodes 1 and 2 will be 530°C and 540°C respectively. These values were found experimentally to give the desired cooling profile.

To perform the system identification using step changes in the control and feedforward variables, the open loop simulation was performed in automatic operation. The results of the system identification can be seen in Table 4. With these first order initial estimates of the nonlinear system, the BrainWave MultiMax controller can be activated.

	PV1	PV2
CV1	K=-0.435,$\tau = 5$	K=-0.315,$\tau = 5$
CV2	K=-0.195,$\tau = 5$	K=0.26,$\tau = 4$
FFWD1	K=0.8,$\tau = 4$	K=0.8,$\tau = 4$
FFWD2	K=0.77,$\tau = 5$	K=0.58,$\tau = 5$

Fig. 4. Process Gains (K) and Time Constants (τ)

6. RESULTS

The goal of this research is to determine if the process can be controlled so that disturbances that cause the system to diverge from its optimal operating points are rejected. As discussed in Section 5, an optimal control solution is attained if the process reaches cyclic steady state in reduced number of cycles during startup and rejects incoming metal temperature and die open time disturbances with minimum temperature variation from setpoint. Each of these criteria should be compared against open loop control responses, see Figure 5.

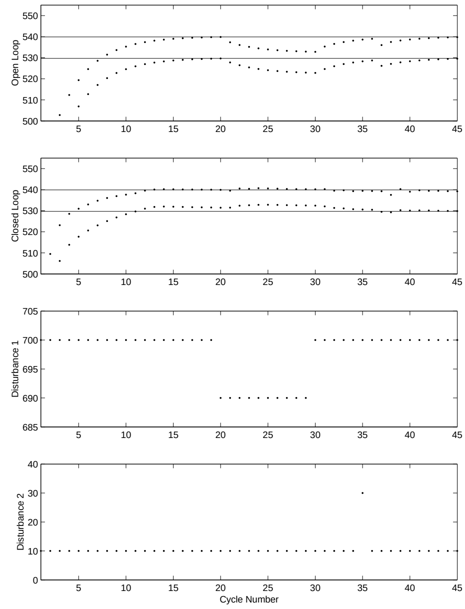

Fig. 5. Controller Measured Disturbances and Process Variables

Figure 5 shows the startup and disturbance rejection responses for the simulated process over 45 cycles. The process variables are represented by the dotted lines, while the set-points are represented by the solid lines. The setpoints were defined as 530°C for node 1 and 540°C for node 2. The initial challenge for the process is startup from approximately 500°C. The first disturbance that is applied consists of dropping the incoming metal temperature from 700°C to 690°C for 10 cycles and then returning the temperature to 700°C. The second disturbance is simulated by changing the open time of the mold in one cycle from the nominal value of 10 s to 30 s. Results were obtained by applying the same disturbance pattern to both the closed and open loop systems.

In open loop, it requires 15 cycles to reach steady state temperature operation. The deviation from the setpoint temperature reaches 10°C for a change in the incoming metal temperature of 10°C. Following the prolonged die open time of 30 s a drop in the die temperature of 5°C was experienced, which required 5 cycles to return to setpoint. In comparison with open loop behavior, the closed loop startup phase was reduced by approximately 5 cycles. While the process was disturbed, a minimal change in the temperature was experienced.

Figures 6 shows the process variables for the startup phase continuously throughout the entire cycle rather than discretely as in Figure 5. This figure presents the cooling profiles that each node

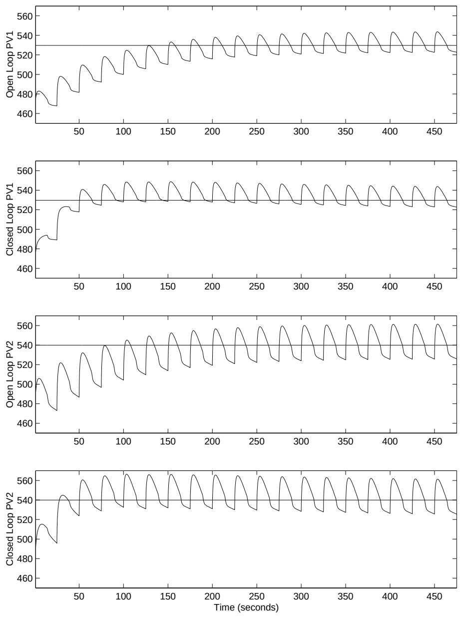

Fig. 6. Open vs. Closed Loop Process Response to Startup

exhibits during both closed and open loop operation. During open loop operation, 6 or 4 cycles are required for the maximum incycle temperature at PV1 or PV2, respectively, to reach the steady state operation temperature, whereas in closed loop only 3 or 2 cycles are needed, respectively.

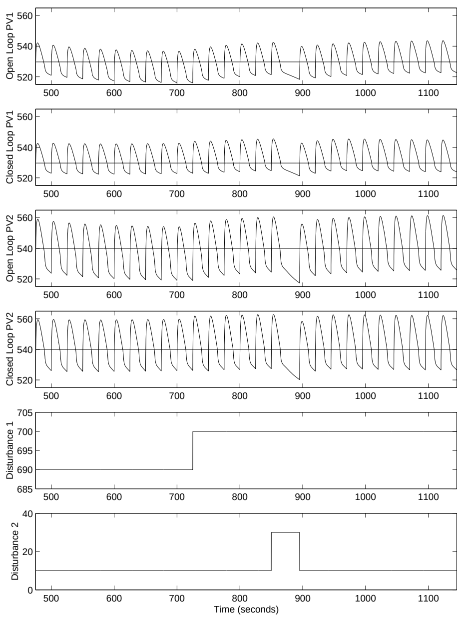

Fig. 7. Open vs. Closed Loop Process Response to Disturbances

Figure 7 shows the process variable response caused by the two typical disturbances described above. The closed loop response shows an effective rejection of the change in the incoming metal temperature. The return to setpoint occurs over one cycle in the case of prolonged die open time.

7. CONCLUSIONS

An advanced adaptive predictive control strategy has been used to control a 'virtual' industrial die casting process simulated using a 2-dimensional finite element model. This required establishing a communication protocol between the commercial finite element software, ABAQUS, and the adaptive predictive multivariable control solution, BrainWave MultiMax. This scheme provides a conduit for the exchange of process and control information, which can be applied to other similar simulation environments.

Under open loop operation, the 'virtual' process exhibited a cyclic steady state with common traits such as: i)slow startup time and ii)sensitivity to incoming metal temperature and die open time disturbances. The closed loop performance exhibited short startup times and good disturbance rejection. This capability encourages the extension of this technique to more complex die casting processes such as aluminum alloy wheels.

The long term goal of this project is to implement the researched control solution in the plant and determine the efficiency of using process models to setup and tune industrial control solutions. In this sense the performance of the presented scheme, acting in advisory mode, can enable the operator to revise their current control strategies for better performance with minimum investment and risks from the user's perspective.

8. REFERENCES

Huzmezan, M., W.A. Gough, G.A. Dumont and S. Kovac (2002). Time delay integrating systems: a challenge for process control industries: A practical solution. *Control Engineering Practice* **10**, 1153–1161.

Maijer, D., M.A. Wells and S.L. Cockcroft (2000). Mathematical Modelling of Porosity Formation in Die Cast A356 Wheels. In: *Proceedings of the Conference of Metallurgists*.

Vo, P., D. Maijer, S.L. Cockcroft, M.A. Wells and C. Hermesmann (2001). Mathematical Modeling of Heat Transfer and Microporosity Formation in Die Cast A356 Wheels. In: *Computational Modeling of Materials, Minerals and Metals, ed. M. Cross, J.W. Evans, and C. Bailey, TMS*. pp. 357–363.