Simulation, On-Line Modelling And Optimising Control Of A Continuous Aluminium Billet Homogenising Oven

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It was identified by operational and process personnel that a newly installed continuous aluminium billet homogenising oven could be improved in terms of its ease of operation and throughput. Initial attempts to arrive at a new operating strategy involved work sessions based on simple models of the process. Due to the interactive nature of the process, these attempts were not successful in formulating a solution. It was therefore decided to build a realistic dynamic simulator of the process for the purposes of improving understanding, and developing a new operating strategy.

Based on the simulator, a new control strategy was developed and tested against the existing mode of operation. It was evident that significant improvements could result from implementing the new control strategy. This was done by first implementing an on-line process model to solve some of the measurement problems inherent to the process, and followed by the implementation of an optimising controller based on the on-line model.

The end results of the project provided significant benefits, more than what was initially expected. The project provided a good example of how important simulation can be in an optimising control project. It also provided some insights into how simple on-line modelling can solve measurement problems, thereby paving the way for optimising control. The delivered system also facilitates maintenance by on-site personnel.

Introduction

In 2004, Bayside Aluminium experienced some difficulties with the operation and control of a new billet heat treatment oven that had been in operation for around five months. To bring about the required improvements an advanced process control system was developed. The life cycle of the project included process analysis, simulator development, control strategy development, control system development and commissioning. The system is currently in operation and being maintained and supported.

This paper demonstrates and discusses the project life cycle of this advanced process control project. It also aims to demonstrate the benefits of process simulation during control strategy development, and the benefit of simple on-line process models to solve measurement problems and improve the feasibility of advanced process control solutions. Finally it demonstrates how relatively simple technology can be used effectively to add value through advanced process control.

Background

Process Description

The continuous homogenising oven at Bayside is used to process 6xxx series aluminium alloy billets with diameters between 152 mm and 254 mm. The process receives as-cast billets from a number of casting stations as input material. Homogenised billets leave the oven for cooling, sawing packaging and dispatch to clients. Clients use the product in their extrusion processes to produce a variety of extruded profiles.

Walking beams are used in the oven to move billets from the inlet towards the outlet. These ovens can typically contain between 50 to 150 billets. The interior is divided into two or more heat transfer zones. The zones at the inlet side are controlled with the objective to get the billets to the soaking temperature as quickly possible, without damaging the material. The zones at the outlet side are controlled to regulate billet temperature very accurately at a level where transformation occurs at the highest possible rate. Different oven manufacturers use different air flow schemes. Air can either flow horizontally along the length of the oven, or vertically onto each individual billet.

The benefits of homogenising billets before extrusion are as follows[2]:

- Billets can be extruded at higher rates, significantly benefiting clients.
- Extrusion profiles produced from homogenised billets have better surface finish.
- Extrusion profiles produced from homogenised billets have better tensile properties.

In terms of microstructure, the purpose of homogenising is to[2]:

- produce a homogeneous solid solution with all Mg_2Si dissolved, and
- transform all plate-like β-AlFeSi to more globular α-Al(Fe,Mn)Si.

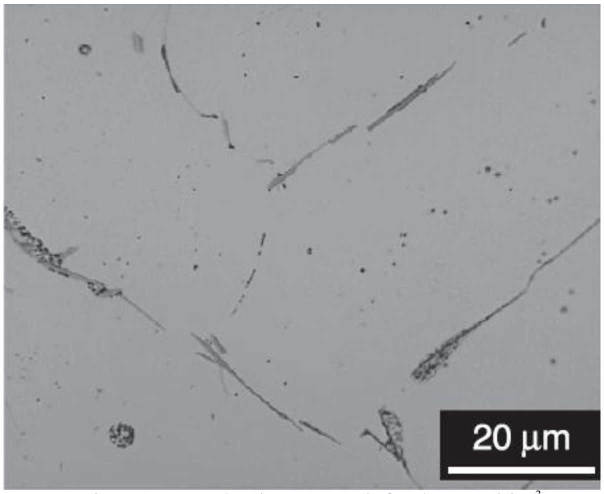

Figure 1 - Example microstructure before homogenising[3].

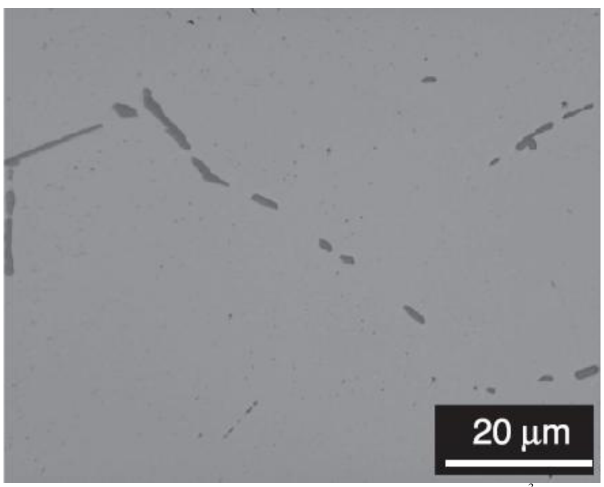

Figure 2 - Example microstructure after homogenising[3].

Figure 1 and 2 shows example microstructures before and after homogenising.

The purpose of the subsequent cooling step is to precipitate as much Mg_2Si as possible in a form that can be dissolved easily during subsequent processing[2].

In the oven, it is important not to heat up the billets too fast since low-melting-point phases can be melted, which will be detrimental to product quality. The material must therefore be given time to dissolve much of the Mg_2Si before reaching its final soaking temperature. Once at the soaking temperature, the material must be given enough time for the slow β-AlFeSi → α-Al(Fe,Mn)Si transformation to complete.

Increasing temperature significantly increases the rate of the slow $\beta \rightarrow \alpha$ transformation. The temperature cannot, off course, be increased beyond a point where either other low-melting point phases (e.g. Mg_2Si) or the bulk metal will melt.

Operational Description

Producers of aluminium extrusion billet usually produce billets of various product types (combinations of diameter and alloy). Some producers are able to focus on only a few product types, while others are forced to produce a more complex product mix. Traditionally, continuous homogenising ovens have been used to process a relatively simple product mix, while complex product mixes have been handled by batch homogenising ovens.

Bayside found themselves in a situation where they not only had a complex product mix consisting of numerous product types, but also a highly variable product mix in the way that casts of different product types were sent to the oven. The reason for this is the fact that fulfilling orders to clients takes higher priority than scheduling sequences to the homogenising oven. This means that casts of different product types can be fed to the oven in any sequence.

This is not good news for oven performance when one uses the conventional operating strategy. This strategy is based on the belief that one and only one very consistent heat treatment cycle is able to yield the required product quality. Any deviation in processing time or temperature is prevented if at all possible. To ensure this consistency, the first zone of the oven is run empty when changing from one product type to another. This translates to a loss of possible oven throughput during each product type change. The extent of the throughput loss depends on the number of saddles in the first zone, the frequency of product type changes, and the processing rate (walking beam step time) of the old and new product types.

Bayside realised that the widely held belief on which the conventional operating strategy is based, is not true. Because the changes occurring in the billet material involves phase transformations and diffusion, there is not only a single temperature and processing time that could yield the required product quality, but a wide range of combinations of temperature and time. In general, the rate of diffusion and phase transformation increases with increasing temperature. The temperature limits between which one must work is the lowest temperature at which the desired phases are thermodynamically stable, and the highest temperature at which the material can exist without any of the phases melting.

With this in mind, Bayside started to operate the oven different from the conventional approach. They started leaving less empty spaces between different product types, thereby attempting to reduce the loss of oven throughput. The improved throughput came at a price. It was not possible to simply rely on a fixed set of recipes for each product type. Different product types following one another in the oven had to be viewed in combination when making decisions on air temperatures and walking beam step times. An operator and a process engineer was required virtually full time to manage these setpoint changes. The process had become very operator intensive, increasing the risk for human error significantly.

The Need for Improvement

Bayside believed that it must be possible to gain the full benefit of increased throughput by eliminating as many as possible empty saddles, while not paying the price of having two people constantly supervising the process and calculating setpoint values. They required the following improvements:

- *Improved operability*
  If the calculation of setpoints could somehow be automated, at least one of the two people closely supervising the process could be freed from this task.
- *Reduced risk of operator error*
  The risk of operator error was simply too high. By automating setpoint calculation, this risk could be reduced.
- *Increased throughput*
  There was still a significant number of open spaces being left in the oven. If automated setpoint calculation could eliminate more of these, throughput could be improved.

Starting the project

A project to devise an automated control strategy was started. The first step in this process involved a thorough analysis of the existing process, equipment, instrumentation and control system. The next step was devise the new control strategy. A number of working sessions were held using a number of simple spreadsheet-based process models that Bayside personnel had developed. Vigorous discussion resulted. The silver bullet control strategy remained elusive, however. It was realised that the dynamic and interactive nature of the process did not lend itself to arriving at a solution to the control problem by using intuitive reasoning and simple process models. It was therefore decided that a dynamic process simulator should be built on which further development work can be based.

Process Simulation

The scope of the simulator included the following areas of the process:

- The inlet buffer from which material is fed into the oven.
- The oven itself.
- The cooling chamber following the oven.
- The outlet buffer receiving material from the cooler.

The equipment in the various process areas were modeled in just enough detail to make accurately represent the process, and to make it possible to manipulate the equipment and process similarly to what is done in reality. The important heat transfer and metallurgical aspects of billets traveling through the oven were also included. The combination of equipment models and process models yielded a plant model, or virtual plant that could be used as the basis for the process simulator. The virtual plant was created using Microsoft Visual Basic.

Similar to what is the case in reality, it was then necessary to provide some form of basic automation of the various pieces of equipment so that the virtual plant could be operated easily. This was done by using Wonder ware's In Control soft PLC. The basic automation included on/off switches, interlocks, and automated sequences. A SCADA interface was also added so that a human "operator" could easily manipulate the virtual plant. This brought the simulator to the point that it corresponded to the actual plant when it was operated in manual mode.

The next step was to implement a process control component that corresponded to the existing recipe-based mode of operation. This made it possible to operate the virtual plant in the same way as how the actual plant was being operated at that point. This provided a starting point from which the new control strategy could be developed, and it provided a reference against which the new control strategy could be compared.

At this point it was decided to validate the simulator to determine whether it is an accurate representation of the actual process. This was done with one of the process engineers involved in operating the plant and doing set point calculations. The simulator was found to be a good representation of the actual process, and it could therefore be used with confidence in further development work.

The Simulator System

The layout of the simulator system is shown in Figure 3.

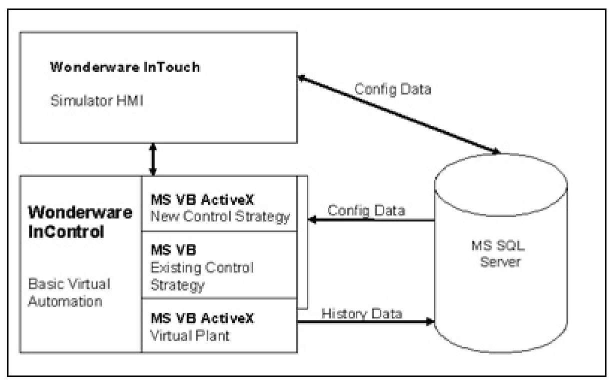

Figure 3 – Simulator system layout.

- *Visual Basic Components*
  The virtual plant, the existing process control strategy and the new control strategy were implemented using Microsoft Visual Basic. The general nature of the programming environment made it possible to quickly create representations of all components of the virtual plant, and do the detailed and sometimes complex calculations required in the optimisation scheme that formed part of the new control strategy. It also provided an easy means of integrating the virtual plant module with InControl, and reading configuration data from Microsoft SQL Server.
- *Wonderware InControl Component*
  InControl was used to implement basic automation logic for the virtual plant. Because it is by nature a

PLC, it was easy to replicate some of the interlocks and sequences used on the actual plant in the simulator. It also has the ability to include ActiveX controls as part of its automation application, which made it possible to include the Visual Basic modules very easily. Finally, since it is equipped with an I/O server, the InControl application could easily exchange data with the SCADA application.

- *Wonderware InTouch Component*
  InTouch is used as the SCADA software on the Bayside plant. By using the same software as the human machine interface (HMI) of the simulator, it was possible to use some visual components that already existed. It further meant that the simulator HMI looked very similar to the HMI used in reality. Bayside personnel could therefore identify with the simulator SCADA application quite easily.
- *Microsoft SQL Server*
  SQL Server was used to store all of the simulator's configuration data. Such data included, for example, heat transfer coefficients, recipes, definitions of simulation scenarios, etc. This data was read, manipulated and saved by components in the SCADA application, and then read and used by the Visual Basic components. The virtual plant component also wrote back simulation details to the database so that reports could be drawn from it.

No sophisticated simulation software was used to build this simulator. Because the simulator was required to represent an industrial plant together with automation and control, using simple technologies used for these purposes in reality made it possible to develop an accurate and functional simulation system in just over one month's time. This, and not the sophistication or reusability of the simulator was of importance in this project, since the schedule for the entire advanced process control project was unusually tight.

Benefits of Simulation

As was mentioned previously, the dynamic and interactive nature of the process made it difficult to arrive at a new control strategy by intuitive reasoning and simple modelling. Therefore, the greatest benefit of the simulator in this project was the fact that it made development of a new and sophisticated optimising process control strategy possible.

The simulator also eliminated the need for doing experiments on the actual process. This made it unnecessary to take risks on the actual plant, whereby the product and the equipment could have been damaged, and production could have been lost.

It was possible to speed up and slow down the rate at which the virtual plant model executed. One could therefore operate the virtual plant at the same speed as the actual plant, or much faster or slower. By slowing down the simulator, it was possible to observer closely how the process behaved during certain conditions. By speeding it up, the user was able to gain valuable "operational" experience on process in a relatively short space of time, thereby developing important new insights into the process.

The simulator also made it possible to compare the existing control strategy with the new strategy and estimate the value that would be added by implementing the new option. This made it easier to make a decision on whether to continue with development of an on-line system, and reduced the risk of such a decision.

THE NEW CONTROL STRATEGY

Before it was possible to create a new and improved control strategy, it was necessary to gain a proper understanding of the control problem. This learning process was greatly assisted and accelerated by the use of the process simulator. The control problem is outlined below:

The Control Problem

The control problem can be described in a simple way by listing the control objectives, controlled variables and manipulated variables.

Control objectives:

- Homogenise billets as quickly as possible.
- Do not damage billets or equipment.

Controlled variables:

- Billet microstructure
- Billet temperature

Manipulated variables:

- Zone air temperature setpoints
- Walking beam step time set point

It can be recognised very easily that there is a measurement problem associated with this control problem.

The Measurement Problem

In an oven with more than 100 positions, the actual temperature of each billet is only measured at 5 or less of these positions. This roughly means that one does not know the temperature of the billet 95% of the time. This means that the billet temperature controlled variable in the control problem is unmeasured to a large degree.

Perhaps a more serious problem is the fact that microstructure is only evaluated after the billets have been cooled, and then only 1 out of a cast of 30 to 60 billets are analysed. The second controlled variable, billet microstructure, is therefore virtually completely unmeasured.

If these measurement problems could not be solved, it would not have been possible to develop and implement a control strategy that rigorously optimises the values of the manipulated variables to optimise the process.

The On-line Model

Because rate at which the billet microstructure transforms from one state to another, is a strong function of the temperature of the billet, more detailed measurement of billet temperature had to be addressed first. A simple model of convective heat transfer from air to billet was formulated. For each billet product type, this model only had one unknown parameter, namely the heat transfer coefficient. Since the air flow in each heat transfer zone differed slightly, the heat transfer coefficient had to be determined for each zone, for each product type.

By using the values of billet temperatures measured in the oven, air temperatures in the various zones, and the residence time of billets in each zone, it was possible to calculate all the required heat transfer coefficients. Because the temperature in the soaking section of the oven remains fairly constant over long periods of time, the heat transfer coefficients calculated for this section proved to be very inaccurate. A number of experiments were therefore done to calculate accurate values for these parameters.

The heat transfer model was tested and found to be very accurate. It could now be used as the basis for modelling the microstructural state of the billets. A very simple, empirical approach was used to model billet microstructure. Based on known operational conditions and resulting product quality, an empirical model was constructed that described the change in billet microstructure as a function of billet temperature with an adequate degree of accuracy.

The combined heat transfer and microstructure model, when implemented on line, would solve the measurement problem. It would be possible to calculate the temperature and microstructure of each billet in the oven continuously. This provided a sound basis for the developing a sophisticated optimising control strategy.

The Control Strategy

For the control strategy to achieve the first objective of the control problem, it was recognised that the rate of transformation of the metal increases with increased temperature. The controller must therefore firstly attempt to heat billets up to a soaking temperature as quickly as possible so that transformation can start occurring at a high rate as soon as possible. Secondly, the controller must derive the highest possible soaking temperature so that the rate of transformation can be maximised. Both of these sub-objectives are achieved by manipulating air temperature setpoints in the various heat transfer zones.

Finally, the controller must ensure that the billet proceeds from saddle to saddle through the oven at the highest rate so that billet residence time is minimised and oven throughput is maximised. This is done by aiming for the lowest possible step time set point.

To ensure that that the second control objective is achieved, the air temperature setpoints have to be constrained to safe values. Because a safe value for a billet early in its treatment cycle is not the same as a safe value later in the cycle, a dynamic constraint was formulated to ensure that a billet's history and current state are taken into account when calculating its temperature constraint.

Similarly, the walking beam step time setpoint had to be constrained to ensure that the first control objective is met. This setpoint is therefore minimised while ensuring that each billet in the oven is allowed adequate residence time for reaching its microstructural quality target.

By using the approach described above, a constrained optimisation routine is executed in which an optimal set of setpoints is calculated for each billet in the oven by predicting the effect of setpoint values on each billet. A global optimal set of setpoints is then derived from the setpoint sets of each billet.

This control strategy proved to be robust, reliable, and a significant improvement when compared to the existing control strategy.

IMPLEMENTATION

The System

Once the new control strategy had been developed and proved to be a worthwhile improvement, it was decided to implement the combined thermal and microstructural model and the optimising control strategy in an on-line system. The layout of this system is shown in Figure 4.

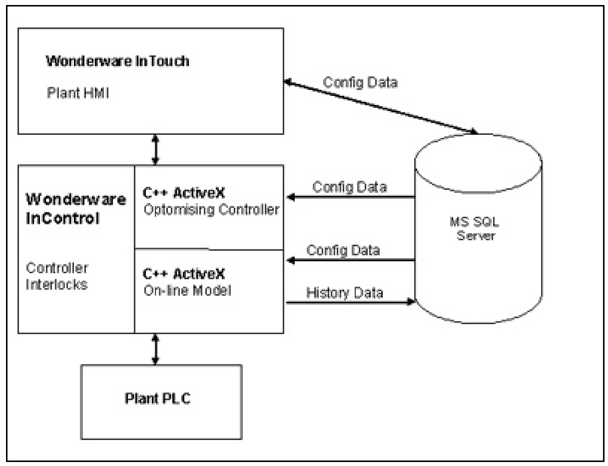

Figure 4 – Layout of implemented advanced process control system.

The similarities between the layout of the simulator system and the on-line control system are immediately evident. One important difference between the two layouts is the use of C++ rather than Visual Basic to develop the ActiveX controls plugging into InControl.

- *C++ ActiveX Components*
  The on-line model calculating billet temperature and microstructure, and the optimising control algorithm were implemented in the form of two ActiveX controls. The reason for using C++ here is the significantly faster execution speed compared with Visual Basic code. Because the model and controller had to run on-line, synchronised with the actual process, it had to be ensured that the system as a whole would never run slower than the actual process. If this would happen, the system would produce inaccurate and unreliable results. The components were also developed in such a way that it could effectively use multiple processors in parallel to further accelerate execution.
- *Wonderware InControl Component*

InControl was used to implement basic automation logic for the virtual plant. Because it is by nature a PLC, it was easy to replicate some of the interlocks and sequences used on the actual plant in the simulator. It also has the ability to include ActiveX controls as part of its automation application, which made it possible to include the Visual Basic modules very easily. Finally, since it is equipped with an I/O server, the InControl application could easily exchange data with the SCADA application.
InControl had an added benefit in the fact that it is a PLC programming environment, something with which Bayside's control and instrumentation personnel were familiar. These persons were therefore able to maintain the new optimising control system without being exposed to a completely unfamiliar environment.

- *Wonderware InTouch Component*
  InTouch was already in use as the SCADA system on the plant. It therefore only had to be modified with components associated with the new optimising control system.
  A configuration interface was added to the InTouch application with which process engineers could configure the on-line model and optimising controller. Process engineers therefore do not have to go into the InControl application to modify model and controller parameters.
- *Microsoft SQL Server*
  SQL Server was used to store all of the optimising control system's configuration data. Such data included material properties, heat transfer coefficients, microstructure model parameters, temperature constraints, etc. This data is read, manipulated and saved by components in the SCADA application, and then read and used by the C++ components. The on-line model also writes detailed information (position, temperature, microstructure) of each billet to the database for reporting purposes.
- *Plant PLC*
  Before implementing the optimising control system, two control modes were implemented on the plant PLC. The first was manual control in which all equipment could be manipulated independently by the operator. The second control mode was the automated recipe-based approach that was in use most of the time. Since the new optimising control system did not have to replace any one of the existing control modes, it could simply be added as another mode of control. This limited the extent of modifications that had to be made to integrate the new system into the existing PLC application.

Installation, Commissioning and Support

A very limited time window was available to install the new system and integrate it with the existing systems on the plant. This was done successfully, and final system commissioning could start when the oven was back on line after maintenance. The system was commissioned with plant personnel on site for a period of two weeks. After completing initial commissioning, remote system support was provided from Ex Mente's offices in Centurion.

BENEFITS

Once the system had been implemented, the following benefits became evident:

- *Improved operability*
  The new control algorithm adapted automatically to a new product type entering the oven. In addition to automating the management of product type transitions, the system also automatically adjusted setpoints safely when the walking beams stopped stepping due to some constraint. This prevented damage to product and equipment during unexpected times of interruption. Finally, the system also safely managed air temperature and step time setpoints safely when the walking beams restarted stepping. This was another problematic aspect when using the old control strategy.
  The operability of the oven had been improved to the point where the process engineer is no longer required to supervise the process, and the operator can simply switch the optimising control system on and focus on equipment issues while knowing that control of the process is completely taken care of.
- *Reduced risk of operator error*
  Because the operator is no longer required to make setpoint adjustments to manage the process, the risk of making errors had been eliminated.
- *Improved throughput*
  When the optimising control system is on line, different product types can follow one another into the oven without leaving any open spaces. This directly resulted in an increase in oven throughput when the oven was the rate limiting process step.
- *Maintainability*
  Separate interfaces were provided to control and instrumentation personnel, and process engineers. This meant that the control system and the control system parameters could be maintained independently from one another, each by personnel most suitable for the task.
- *Detailed information*
  The system logs detailed information about the processing cycle of each billet. This means that process engineers can compare laboratory quality data and customer feedback with the exact process details of individual billets. Such comparisons can be used to adjust system parameters to correct quality deficiencies, or to improve oven throughput further.

CONCLUSIONS

This paper describes the life cycle of an advanced process control project from process basic analysis to successful operation. A process simulator provided an invaluable basis for developing a new control strategy. Simple on-line process models solved measurement problems that could have prevented a successful advanced control implementation. Simple technologies were applied in all phases of the project with positive results. The system has satisfied all of the initial requirements, and is providing additional benefits that were not initially envisaged. In-house maintenance is facilitated by providing control and instrumentation personnel, and process engineers with separate environments, each most suitable for the specific maintenance task. The system has now been in continuous use for more than 20 months.

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