Chapter 1

Introduction

THE continuous casting of steel slabs is an established technology to solidify molten steel into its solid form. Surface defects form during the continuous casting process. As a consequence of these defects, an intermediate stage between casting and hot-rolling is needed to remove these defects. The intermediate grinding stage causes large delays before slabs can be rolled, implying throughput losses for the steel-making company. These delays also mean that energy costs are increased, because grinding can not take place at the elevated temperatures of a cast slab; and hot-rolling must occur at an elevated temperature. The slab must therefore be cooled, grinded and reheated. These defects also make technologies such as direct rolling and hot charging infeasible, since the defects have a detrimental effect on post-casting operations.

The problem addressed in this thesis is to determine a model to relate mould variables to surface defects. This model can be used as a predictor to determine when defects will occur, thus making scheduling for direct rolling or hot charging of some slabs possible. Only defected slabs are then sent for treatment. The model can also be used to design controllers to eradicate or reduce the defects so that higher throughput is obtained.

1.1 Background

During the past fourty years, continuous casting has become the predominant method to solidify molten steel into semi-finished shapes [1]. The advent of continuous casting has overshadowed the traditional method of ingot casting [2]. Continuous casting allows the uninterrupted constant casting of steel from its molten state to its solidified state, whereas ingot casting requires a cooling period before final solidification takes place so that the ingot mould can be used again [1].

The continuous solidification of steel means that more steel is cast per unit time compared to ingot casting, thus increasing the throughput of the cast product and ultimately the final product.

In continuous casting, metallurgically prepared molten steel is poured from the ladle into a tundish which ensures that steel is always available for casting into a mould. When all steel from the ladle is cast, the ladle is changed, but casting continues because some steel remains in the tundish. The open-ended mould is the primary extractor of heat. During solidification in the mould, a solidified shell of steel forms which is strong enough to withstand the ferro-static pressure of the liquid steel within. The strand moves out of the mould at the casting speed and enters the secondary cooling zone where further solidification takes place by spraying water onto the surface of the strand. On exit from the secondary cooling zone, the strand cools off naturally in air until fully solidified and is then cut. The cut slabs are then sent for further processing such as grinding, rolling *etc.*

During the casting operation, internal and external defects form which are detrimental to the post-casting processes. The external (surface) defects form in the mould (see Chapter 2), with possible aggravation in the secondary cooling zone.

The purpose of this thesis is to explore methods to predict and control surface defects in continuous casting.

1.2 Motivation

To increase the throughput of rolled product and to decrease the cost due to energy consumption, steel companies are required to optimise their continuous casting processes in such a way that hot charging or direct rolling becomes possible [3, 4].

In hot charging, the cast product is sent for rolling before the slab cools off below $650°C$ [3]; thus reducing the time required for reheating of the slab [5] and minimising the cost of energy required [6]. In direct rolling, the casting process and slab scheduling are optimised to such an extent that the slabs are directly sent for rolling, thus eliminating the energy and time required for the reheating furnace. Direct rolling is however impossible if the extent of surface defects is so severe that post-casting treatment of the slab is required. The treatment usually implies grinding or spot treatment of the slab surface. The treatment cannot be done at the elevated temperatures which are required for hot rolling (1150°C [3]) and thus the throughput of the product is reduced due to the time required to 1) cool, 2) treat, 3) reheat the cast slab. The cost of energy consumed in the reheating furnace also implies unnecessary financial losses.

If hot charging (rather than direct rolling) is practised, surface treatment does not appear to imply as great a loss, since some reheating is required whether surface treatment is applied or not. However, the time taken to treat the surface implies a reduction in throughput.

Grinding is always performed at some steel-making companies, because of the fear of defects slipping by the inspection line. Some steel-making companies report hot charging of 30% of their slabs without any conditioning [7] while other companies report direct rolling and hot charging of up to 80% of their cast slabs [8, 9] and blooms [2] without any conditioning. Some companies even implement direct rolling when the caster is far from the hot-rolling mill [10]. In general, hot charging is more successful in billets than in slabs [6, 11].

Many researchers have attempted to improve the surface quality of the cast product by Computer Aided Quality Control (CAQC) methods [12–16]. In these methods, some form of non-human surface defect measurement is employed and used to "train" a database linking mould and secondary cooling zone conditions to the different defects. The database can then be used in conjunction with continuous casting process measurements to

1. predict the quality of the cast product,
2. determine whether the slab can be hot charged or direct rolled,
3. update the database in cases where new defects or steel types occur, and
4. apply control to eradicate the occurrence of defects.

The defect detection databases are usually in-house, and literature on the matter is very limited (see *e.g.* Hatanaka, Tanaka, and Kominami [17], Hunter, Normanton, Scoones, Spaccarotella, Milone, Vicino, Lamant, Morand, and Do Thong [18] and Creese *et al.* [15]); with most discussions covering only a fraction of the procedures (see *e.g.* Matsuzuka, Fujita, Yabuta, and Itoh [19]).

The motivation for this work is that if defects can be eradicated through the *control* of mould parameters, direct rolling will be made possible by removing the grinding stage. If, at least, defects can be *predicted* with high accuracy, more slabs can be sent for hot charging directly after casting. Those slabs which do have defects will be sent for grinding, making the scheduling task easier.

A further motivation is that an industrial partner was found in South Africa which was very willing to aid in this study by providing data and allowing the researcher to test most of the techniques in practice.

1.3 Aims

To be able to predict when defects are going to occur, a model must be found which relates mould parameters to the defects. The aim of this work is therefore to determine such a model. A further aim is to use the model to design controllers which manipulate casting parameters such that defects can be eliminated or reduced considerably.

The specific defects that will be considered are transversal and longitudinal cracks, inclusions, oscillation marks, stopmarks, bleeders and depressions, as these are the foremost defects that occur. These defects are the *outputs* of the model.

The *inputs* of the model are the casting parameters. Since it has been found that the above defects originate in the mould, only mould parameters will be considered as inputs. Pre- and post-mould processes are assumed to compound any defects which may occur, and thus act as disturbances.

Since first-principle models presented in the literature are usually 1) vague in terms of effectiveness or accuracy, 2) do not clearly show that they work, 3) have no relation to mould parameters so that prediction can not be performed, 4) and are complicated; a system identification approach to modelling will be used. Artificial intelligence (AI) techniques such as artificial neural networks (ANN) have previously been used to predict defects [18], and will thus not be considered in this work as a modelling tool, except to compare published results and results of this work. The aim of this work is then to use system identification on practical data as the modelling technique.

1.4 Approach

The approach followed in this work is to find a model describing the effect of mould variables (inputs) on the formation of defects (outputs) using data from an industrial continuous caster in South Africa. The mould variables are obtained from the level 2 system of the continuous caster, and the defects are obtained by plant personnel inspecting the slabs off-line. The defect data are read into a computer for analysis and model training. A reduction of the number of mould variables (inputs) is carried out using statistical hypothesis testing and correlation analysis. From this data, it also becomes clear that the mould/defect data can be split into two models, one describing the effect of casting speed, mould level and inlet temperature on thermocouple temperatures and another describing the effect of thermocouple temperatures on defects. The outcome of the model split is that the continuous measurement of thermocouples makes it possible to apply feedback control. The thermocouple temperature set-points are then determined such that no defects will occur due to mould temperature; and the casting speed as manipulated variable is used to maintain these thermocouple temperatures in a feedback fashion. The models are derived and validated using ARX (auto regressive with exogenous input) methods together with plant data. Three controllers are designed and compared to show the improvement for thermocouple temperature set-point tracking. These controllers are not tested on the plant, but in simulation.

1.5 Contribution

Several contributions are made in this work. Firstly, the thesis shows that it is feasible to split the model for defect prediction into two models, one that relates the manipulated variable (casting speed) to intermediate variables (thermocouple temperatures) and another to relate the intermediate variables to outputs (defects). The advantage of the split is that feedback control can be used by measuring thermocouple temperatures, instead of defects which are difficult to measure and have a long time delay before they can be measured. The model split also implies that the thermocouples are the only variables to be measured to predict the defects; and thus act as a soft sensor of defects.

The second contribution is that both models can be trained (and verified) from real plant data using ARX methods, as is demonstrated in this work. The model is also motivated from defect literature.

Thirdly, the model relating the thermocouple temperatures and defects is used to determine the optimal set-points for the thermocouple temperatures such that few or no defects occur due to mould temperature variation.

Fourthly, it is shown how controllers can be designed to improve the set-point tracking of thermocouple temperatures using casting speed as a manipulated variable. Three different controllers are designed and compared in this work.

The literature contributions of this thesis can be found in one published [20] and three submitted journal articles [21–23]. Further literature contributions can be found in six conference proceedings [24–29] and one submitted conference article [30].

1.6 Outline

Chapter 2 describes the background needed for this thesis and includes an overview of the process and the predominant defects that are present in continuous casting. A description of the Kolmogorov-Smirnov and Anderson-Darling goodness-of-fit tests and correlation analysis is also given. ARX as the system identification technique to model the system is described. Lastly, a single-input, multiple-output (SIMO) controller in the form of a steady-state linear quadratic tracker will be described.

Chapter 3 deals with modelling aspects. The different variables that are found in the mould are explained. The defect data and the data gathering from cast slabs by humans are also explained. The extraction of data from the level 2 system of the plant, based on auxiliary data and time-position reconciliation, is described. A statistical analysis, using the goodness-of-fit tests and correlation to reduce the number of variables and to show that the model can be split into two models, is also given. The use of ARX as a modelling tool to find models for the manipulated to intermediate variable model and intermediate to output variable model is then perused. The models are shown to be accurate using training and validation sets. The intermediate to output variables are thresholded to ensure that a defect occurs only when the output variable passes a certain value. The intermediate to output variable model is used to determine set-points for the thermocouple temperatures (intermediate variables) such that no defects occur due to mould temperature.

Chapter 4 shows the application of control to reduce variation in thermocouple temperature within the mould, thus reducing the occurrence of defects. Three controllers are compared.

The first is SIMO and called a linear quadratic tracker at steady-state (LQTSS). The second is a single-input, single-output (SISO) controller which uses one thermocouple output to reduce the variation in temperature and is called a single output controller (SOC). The third is called a worst-case controller (WCC) and uses the worst performing temperature error together with bump-less transfer to control the variation in temperature.

Chapter 5 gives an assessment of the study and recommendations for future work.