Chapter 5

Conclusion

THIS chapter presents a summary of the work, some conclusions, and recommendations for future work. A brief assessment of the work will be given, highlighting the main contributions. Future research that can follow from this work is considered.

5.1 Summary

Chapter 1 presented an introduction to the thesis. Some background on the process was given with a brief explanation of the continuous casting process and its merits over traditional ingot casting. The motivation for the research work was given, noting that direct rolling and hot charging are technologies that most steel-making companies strive for. These technologies can only be implemented once post-casting defect treatment in the form of grinding can be eliminated. The use of a predictor to determine when defects will occur is advantageous since slabs that do not have defects can be directly rolled or hot charged. Controlling the occurrence of defects can lead to all slabs being directly rolled or hot charged. The thesis focused on the application of the methods on a continuous casting plant in South Africa.

Chapter 2 gave an overview of the process and an account of the most useful literature for the thesis. The defects that were studied in this thesis were perused so that a thorough understanding of the variables which are instrumental in defect formation was obtained. Goodness-of-fit tests known as the Kolmogorov-Smirnov and Anderson-Darling tests were explained. These tests determine whether an empirical statistical distribution forms part of a given theoretical distribution. Correlation analysis was also explained and is used to test cross-correlation between inputs. Time-series modelling in the form of ARX was explained, and is the modelling scheme used in this thesis. A linear quadratic tracker operating at steady-state was chosen as an adequate method for controlling the SIMO plant. The theory behind the LQTSS was given.

Chapter 3 dealt with modelling aspects. The data that was available from the level 2 system of the plant was described. The data was divided into three sections, namely mould data, defect data and auxiliary data. The mould data was used as inputs to the model and the defect data was used as the outputs. Defect data was gathered by the human measurement system. Each operator of the HMS marked a slab inspection report to indicate the position, type, severity and location of a specific defect when it occurred. This data was digitised and used to generate the output data. The auxiliary data aids in the extraction of data form the plant databases. The relation between position and time was reconciled by integrating the casting speed with respect to time. This was necessary because defect data has a position dimension and mould data has a time dimension. The statistical goodness-of-fit tests exploit the stationarity of the process to determine which mould variables significantly differ between slabs with- and slabs without defects. When the good and bad slabs were statistically different for a specific input variable based on mean and standard deviation, that variable was considered to be influential in the occurrence of a defect or could aid in the detection of a defect. These results were used in conjunction with correlation values between inputs to make sure that information in inputs are not repeated *i.e.* inputs are not cross-correlated. The result was that casting speed, mould level, inlet temperature and the thermocouple temperatures were influential in– or could detect– the occurrence of defects. Casting speed, thermocouple temperature and mould level were correlated with the thermocouple temperatures. Casting speed acted as a manipulated variable and mould level and inlet temperature acted as measured disturbances.

The fact that the temperatures were mostly rejected in the goodness-of-fit tests when defects occur implies that the model could be reduced to two models. The first is a MV to IV model and relates the effect of casting speed, mould level and inlet temperature to the thermocouple temperatures. The second is the IV to OV model and relates the thermocouple temperatures to the defects. This implies that the thermocouple temperatures can be used to detect the defects, and not that the thermocouple temperatures necessarily cause the defects. The models were trained using plant data. Both the MVIV and IVOV models gave good results in mimicking the plant data and this was emphasized by the testing with validation data. Comparison to published predictors could only be made for the longitudinal cracking defect, as results for other defects could not be found. For longitudinal cracks, sensitivity and specificity are 2.1% and 18.5% respectively better than the published result of the artificial neural network of Hunter *et al.* [18]. A threshold was applied to the IVOV model to reduce the number of false alarms while still detecting the defects accurately. The IVOV model was then used to determine optimal set-points for the thermocouple temperatures such that no defects occur. This was done using an inversion of the IVOV model.

Chapter 4 presented control techniques to maintain the thermocouple temperature at the desired thermocouple temperature set-points. These methods were not implemented in practice but three controllers were implemented in simulation. The LQTSS controller was ideal to handle the SIMO system, since it has an averaging effect on the outputs and thereby reduces the average tracking error. The second controller was the single output controller which used one output for control. This output was selected after designing SISO control loops for each output and selecting the one which gave the best overall performance for the system. The third controller used bump-less transfer to control that output which is performing the worst at a specific point in time by switching to that loop in a bump-less fashion. This controller is known as the worst case controller. The LQTSS gave the best improvement in overall set-point tracking over all slab widths, with the SOC controller coming in second best. The WCC controller had the worst response.

5.2 Assessment of study

It was found that the model describing the effect of mould variables on the formation of surface defects can be broken down into two separate cascaded models. The first sub-model describes the effect of casting speed, mould level and water inlet temperature on the thermocouple temperatures (MVIV). The second sub-model describes the effect of thermocouple temperatures on the formation of defects (IVOV). The IVOV model is used as a predictor of defects and this implies that thermocouple temperatures can be used to infer the formation of defects. The MVIV model is used to control the formation of defects which result from mould temperature variation. The model separation is a significant contribution because it allows feedback control to be used. The delay between the formation and measurement of defects is moved outside the loop by using the (defect inferring) thermocouple temperatures as the output variables.

The ARX modelling technique was shown to be a valid approach for the MVIV and IVOV models. The ARX technique is simple and can be used for analysis and design using standard control system techniques. This is a significant reduction in modelling complexity over techniques such as artificial neural networks and expert systems; and allows first principles to be worked into the model. The MVIV model output is influenced by disturbances, but follows the thermocouple temperatures well. The IVOV model is a good predictor of defects. The uncertainty in the accuracy of the HMS is overshadowed by good validation results for the IVOV model. Threshold values on the outputs of the IVOV model are used to indicate whether a specific defect will occur at a particular position and location. The MVIV and IVOV models were trained and validated on different sets of data to show the robustness of the models.

The IVOV model was also used to determine ideal thermocouple temperature distributions in the mould. Since the thermocouple temperatures infer defects, (constant) thermocouple temperatures must exist in a sub-space where no defects occur due to mould temperature variation. The calculation of these temperatures was done by determining the thermocouple temperatures that will not cause any defects.

The fourth contribution is that control can be used to reduce the variation in thermocouple temperatures. Three controllers were compared to illustrate the effectiveness of control. Though improvements of temperature variations over the uncontrolled case can be as high as 30%, the reduction of actual defects is difficult to estimate because the controllers could not be tested on a real plant.

The research publications that originate from this work have been given in §1.5.

The work deals with the application of the techniques on practical data. Therefore the models in this thesis cannot be presumed to work on any plant, but rather that the techniques can be applied by process engineers to determine models for their plant. Similarly, the optimal thermocouple temperatures that were found using the IVOV model also only account for the plant in question. They are optimal for this scenario only. The methods prove to work well, even when *e.g.* the IVOV model was only validated on data obtained three years after model training. Naturally, as is the case with any model, further tuning of the model will result in even better results.

Though many defects did arise, not all locations on the slabs necessarily had all the defects. This implies that the predictor cannot detect defects when the defects actually occur at locations where the predictor was not trained to look for defects. This can be overcome by training with more data.

5.3 Recommendations for future work

An improvement for this system is to eliminate the noise of the defect measurement system (HMS) used. Three people were used to gather defect data. Between them, inconsistent measurements already add a measure of noise to the system. One operator may have given a severity of 4 to a defect and thought it was casting powder entrapment while another person would have given a severity of 3 and said that the defect was some other inclusion. Another problem is that defects may have gone unnoticed, or may even have been disregarded. This leads to false results and is probably why some defects are predicted but not actually seen. The improvement would be remarkable if some unbiased measurement system such as a laser profilometer or electronic imaging system could have been used to measure the surface profile. Such systems are usually costly, and are in essence not used after casting but after rolling, because end-product is assumed to be more important than intermediate stages of the process. The use of electronic measurement of surface profile also means that data can be gathered for more slabs, thus having more data to work with. This could also improve the model response and the predictor accuracy. If an electronic measurement system is not available, studies can be undertaken to determine the accuracy of the HMS.

Several problems exist with the measurement of temperature in the mould, which fall outside the practical reach of the author. The thermocouples are usually fed from the backing plate, through the water chamber into the copper sheath. A small hole (3mm to 5mm in diameter) is drilled in the copper sheath and the thermocouple point is meant to intrude into that hole. The first problem is that the thermocouple does not necessarily enter into the hole. This causes no contact of copper and the thermocouple point so that a very high thermal resistance (air) is present. The second problem is that some thermocouples do enter the hole but are deformed (possibly from too much pressure during insertion) so that contact of the sides of some thermocouples are made to the side of the hole that was drilled. This results in a higher thermal conductance than other thermocouples. The third problem is that the rigorous motion of the mould can cause the thermocouple to get dislodged or break contact with the copper so that the thermal resistance is increased. Usually a high conductivity paste is used to decrease the thermal resistance between the copper and thermocouple point. This paste can also get dislodged so that the thermal resistance is increased. These problems can possibly be solved by using a spring-loaded system for each thermocouple, so that the thermocouple always makes contact with the copper.

The result of inadequate measurements is that the model is not necessarily an exact reflection of the plant, and that the control results are not as good as they could be. The IVOV model does however predict the defects, because the variability of the measurement system is worked into the IVOV model due to the large amount of data that was used. The control systems do improve the tracking of the thermocouple set-points, though the MVIV model includes the dynamic effect of the thermocouples.

An increase in the number of thermocouples would also improve the accuracy of the predictor and controller. When few thermocouples are used, not all areas of the slabs are measured (see *e.g.* Fig. 2.2 and Fig. 3.2), implying that the mould is essentially under-sampled. Another problem is the spacing between thermocouples. Some defects which are localised such as casting powder entrapment, other inclusions and bleeders may move between two thermocouples, thus causing the predictor to "miss" the defects and not signal an alarm. Mahapatra *et al.* [160] report using 114 thermocouples arranged in as many as 17 rows along the length of the mould compared to the industrial partner who uses only 40 spaced in two rows 15 cm apart. (Hunter *et al.* [18] use 39 thermocouples in each wide face). Defects which form lower in the mould will probably not be detected.

Based on this work, the control of the temperature in the mould seems to be a fundamental problem. Note that the models derived in this thesis have two functions: firstly, to predict when defects will occur based on thermocouple measurements and secondly, to design controllers to control the thermocouple temperatures. Controlling the temperature will not necessarily ensure that a defect will be removed. This is especially true in the case of inclusions. An increase in the temperature of the surface may cause the inclusion to entrain back into the liquid pool, after which it may propagate back to the meniscus. The main problem with temperature control is the number of manipulated variables that are available. Usually only casting speed is a manipulated variable. In this thesis, 38 temperatures had to be controlled using only one manipulated variable which is fundamentally an uncontrollable system. Even when lumping the thermocouples into single values such as bottom and top rows, reducing the 38 intermediate variables to 19 and reducing thermocouple pairs with similar responses into groups of say, 3 to 4, leaves 5 intermediate variables. This still then remains a fundamentally uncontrollable system, because one manipulated variable is available and 5 intermediate variables have to be controlled.

A solution to the above problem is to redesign the mould so that water flow in the mould itself can be controlled in several chambers between the backing plate and copper face. The approach is similar to zone water flow-rate control in the secondary cooling zone [35]. Currently water is circulated at the maximum constant flow-rate possible. The addition of the water flow- rate control together with casting speed as manipulated variables allows different sections of the mould to be cooled individually and as a whole, thus making temperature control more feasible. Care should be taken in this approach to ensure that the flow-rates for each chamber are adequate to extract enough heat so that solidification of the liquid pool can take place.

With the above comments taken into consideration, direct rolling and hot charging are technologies that will probably take a while before they can be fully implemented in a real continuous casting plant, without any post-casting inspection or treatment.