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CONTROL STRUCTURE FOR THE REDUCTION OF DEFECTS IN CONTINUOUS CASTING

F.R. Camisani-Calzolari * **I.K. Craig** **
P.C. Pistorius ***

* *Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria, 0002, South Africa. Tel. +27 12 420 2166 Fax. +27 12 362 5000 email:cami-fr@suntiger.ee.up.ac.za*
** *Corresponding Author. Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria, 0002, South Africa. Tel. +27 12 420 2172 Fax. +27 12 362 5000 email:icraig@postino.up.ac.za*
*** *Department of Materials Science and Metallurgical Engineering, University of Pretoria, Pretoria, 0002, South Africa. Tel. +27 12 420 3922 Fax. +27 12 362 5304 email:pistori@postino.up.ac.za*

Abstract: The causes for surface defects in the continuous casting process must be understood so that surface defects can be eradicated. The defects which were considered are presented and an approach to eliminate many of the influencing variables using statistical hypothesis testing is presented. These methods show that only the thermocouple temperature readings within the mould are necessary to accurately predict the occurance of defects. The use of ARX modeling is then presented for a predictor which uses thermocouple temperatures as inputs and defects as outputs. A mould model can be determined in the same way using controlled variables as inputs and the thermocouples as outputs. Optimal control and feedback control can be used to diminish the defects.

Keywords: steel industry, continuous casting, defect, hot charging, direct rolling, CAQC, control system, statistical tests, system identification

1. INTRODUCTION

The continuous casting of near ideal product and subsequent direct charging (Holleis *et al.*, 1985) allows more product to be generated because one stage in the process, known as "grinding", falls away. With grinding, the surface defects which arise in the system are ground away before rolling takes place. Elimination of the grinding stage will allow throughput of product to increase, generating more revenue in the long run (Hague and Parlington, 1988).

This paper is intended to show an approach that can be followed for the eradication of defects so that the plant can deliver higher quality steel to the rolling mills. Similar approaches using neural networks have been presented by Hatanaka *et al.* (1993). This work makes use of ARX methods so that proper control systems analysis and design can be applied to the system.

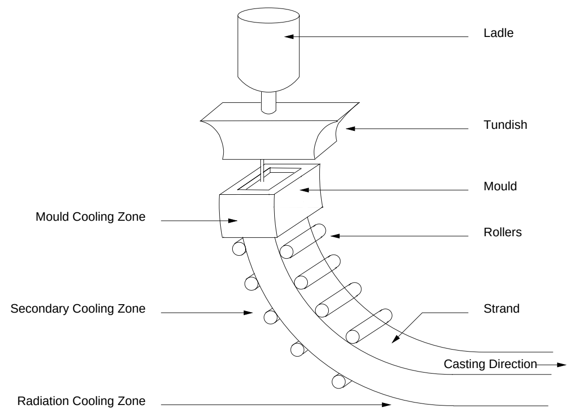

Fig. 1. Bow-type continuous caster.

The most common surface defects in continuous casting are presented, and the influence of mould variables are scrutinized to determine which variables can be used to predict the occurance of surface defects. The use of statistical tools are presented for the purpose of variable elimination. ARX modeling which can be used as predictors/estimators of the defects is presented and finally, a control approach for the eradication of the defects is given.

2. PROCESS

The most commonly used continuous caster found in industry today is the bow or arc type continuous caster. See Fig. 1. Molten steel is transported to the continuous casting machine in a ladle. The ladle feeds a reservoir known as the tundish. The tundish in turn feeds the mould where primary cooling takes place. The mould is open-ended and steel is withdrawn from the bottom of the mould at the casting speed. On exit from the mould, the steel enters the secondary cooling zone where heat is extracted by means of water sprays. On exit from the secondary cooling zone, the strand enters the radiation zone where cooling takes place in air. The steel strand is then cut and sent for further processing such as a rolling mill.

3. DEFECTS

The following discussion deals with the defects which were considered in this study. Examples of the surface defects are given in Fig.2.

Transversal cracking occurs during bending below the mould and straightening of the curved strand at low *temperatures* and is most prevalent in the secondary cooling zone (Mintz *et al.*, 1991) though it initializes in the mould.

Longitudinal cracking is caused by *rapid cooling* near the meniscus[1] (Brimacombe *et al.*, 1979), improper sulphur and carbon content (Kim *et al.*, 1996), improper spray patterns in the secondary cooling zone (Moiseev *et al.*, 1986) and increased heat flux on the wide face of the mould (Nakajima *et al.*, 1994).

[1] the level of molten steel at the top of the mould

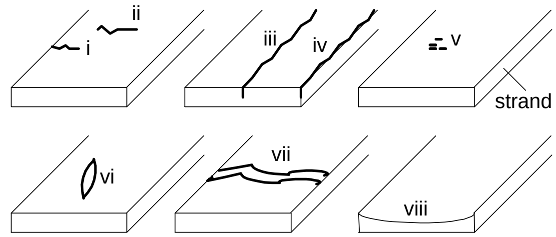

Fig. 2. Surface defects. i.) Transversal corner crack. ii.) Transversal center crack. iii.) Longitudinal center crack. iv.) Longitudinal off-corner crack. v.) Inclusions. vi.) Bleeder. vii.) Oscillation marks. viii.) Longitudinal depression.

Inclusions form at the surface of the steel-slag interface due to precipitation of solid or liquid particles in the mould (Bouris and Bergeles, 1998).

Bleeders form due to *high temperature* regions on the surface of the strand during casting within the mould (Kumar *et al.*, 1995; Hiebler, 1992). The strand ruptures and the molten metal leaks from the tear at the strand surface. If re-solidification is possible before the bottom of the mould is reached, the bleeder heals—leaving only a surface scar—but, if the bleeder continuous beyond the bottom of the mould, the strand surface may be too thin to contain the molten mass, resulting in a break-out of liquid steel (Mills *et al.*, 1991; Blazek and Saucedo, 1990).

Oscillation marks form due to varying flux pressure at the surface of the strand (King *et al.*, 1993) due to improper mould oscillation operation (Spaccarotella *et al.*, 1985) and/or improper mould lubrication (Brendzy *et al.*, 1993) resulting in periodic deviations in shell *thickness* along the strand.

Stopmarks form when the casting speed is lowered or even stopped such that *rapid cooling* occurs within the mould causing a thicker shell to form. This again has an adverse effect on the rolling operation of the steel (BISRA, 1967).

Depressions form as either transversal or longitudinal depressions and usually preempt longitudinal and transversal cracks. These depressions form during bulging below the mould as a result of inadequate *heat flow* within the mould(Thomas *et al.*, 1995). The transversal depressions form at the meniscus of the mould and move down the mould. The gap between the strand at the depressed area is filled with flux (Thomas *et al.*, 1997).

When developing a soft-sensor to predict the occurance of defects, all the defects can be detected by monitoring the thermal properties of the steel as it travels down the mould. This is prevalent in the above discussion where it is evident that the temperature of the strand is influential in the genesis and evolution of the defects. This information is very valuable, especially when developing the soft sensor for prediction of the defects, since many variables may be eliminated for the structure of the soft sensor. Furthermore, the defects almost always originate in the mould.

4. CAUSES

The controlled variables or manipulated variables (MV's) for the specific plant that was used in this study are the flow-rate of steel into the mould, mould oscillation frequency, mould water flow-rates, casting speed and mould mensicus level. Typical input disturbances or uncontrolled variables (UV's) include the superheat [2] and mould powder inclusion at the mensicus for lubrication of the mould. The superheat depends on the temperature at which the steel is when it arrives at the casting machine and mould powder is added manually so that human intervention is unreliable.

The output variables (OV's) in the control hierarchy are the specific defects. The defects are grouped into the 9 defects as discussed in §3. Each of the defects occur at the surface or near-surface of the strand. Furthermore, the defects are classified to occur in one of one-thirds the width of the strand conveniently named left, center and right. The result is that there are a total of 108 outputs.

Thermocouples are used near the mould-strand face to record temperatures. These temperature variables can not be controlled directly and they do not form part of the outputs. Because of their significance in the detection of defects they cannot, however, be excluded from the model. They are therefore called intermediate variables (IV's). Fig. 3 graphically shows the point of view.

5. STATISTICAL ANALYSIS

To find out which (input) variables truly influence the formation of defects and which inputs carry duplicate information, a statistical approach was used. This was necessary to try to reduce the dimension of the predictor. Two approaches were used to eliminate repetitive information. The first makes use of correlation to determine linear relations between inputs and inputs as well as inputs and outputs. An example is the linear relationship between casting speed and mould oscillation frequency. The correlation coefficient was 0.99 in this case. This means that either one of the two variables may be omitted in the generation of a defect predictor.

The second method is to determine whether there are *significant* differences between the inputs of slabs that exhibit a particular defect and those which do not exhibit the particular defect. This is done in terms of the mean and variances of the inputs of the system. The reasoning behind this is that a change of input variables from the regular mean value indicates a change in the equilibrium of the system. The same can be said about the effect of variance of a particular input variable on the scatter from the equilibrium. The frequency distributions of inputs of good slabs (slabs without defects) and bad slabs (slabs with defects) are then compared using goodness-of-fit tests (D'Agostino and Stephens, 1986). These tests are hypothesis tests which compare two distributions. The outcome of the tests determine whether the distributions are the same or not. Two types of tests were used in this study. The Kolmogorov-Smirnov test is given by Massey Jr. (1951) as

$$D = max\left|F_n(x) - F(x)\right|, \quad \forall x; \qquad (1)$$

that is, it is the maximum difference (evaluated at all points of x) of the theoretical and empirical cumulative distributions. The null hypothesis (H_0) states that the empirical observations belong to the theoretical distribution. The alternative hypothesis (H_1) states that the two distributions do not belong to the same distribution, *i.e.* they are different.

The Kolmogorov-Smirnov test has weak power (Johnson, 1994). It does not have a great ability to detect situations when there is a significant difference between the empirical and theoretical distributions. Furthermore, this deficit is usually found in the tails of a Normal or near-Normal probability distribution. Another test emerged as a counter to this problem, and though well documented, is not as well known. The test is known as the Anderson-Darling test for goodness-of-fit (Anderson and Darling, 1952; Johnson, 1994).

The test statistic is a normalized version of the Kolmogorov-Smirnov test and can be computed by

$$A^2 = -\frac{\sum_{i=1}^{n}(2i-1)[\ln \mathrm{u}_i + \ln(1-\mathrm{u}_{n+1-i})]}{n} - n, \qquad (2)$$

where $\mathrm{u}_i = F(x_{(i)})$ is the value of the theoretical cumulative distribution at the i-th largest empirical observation.

[2] temperature of steel above the liquidus temperature

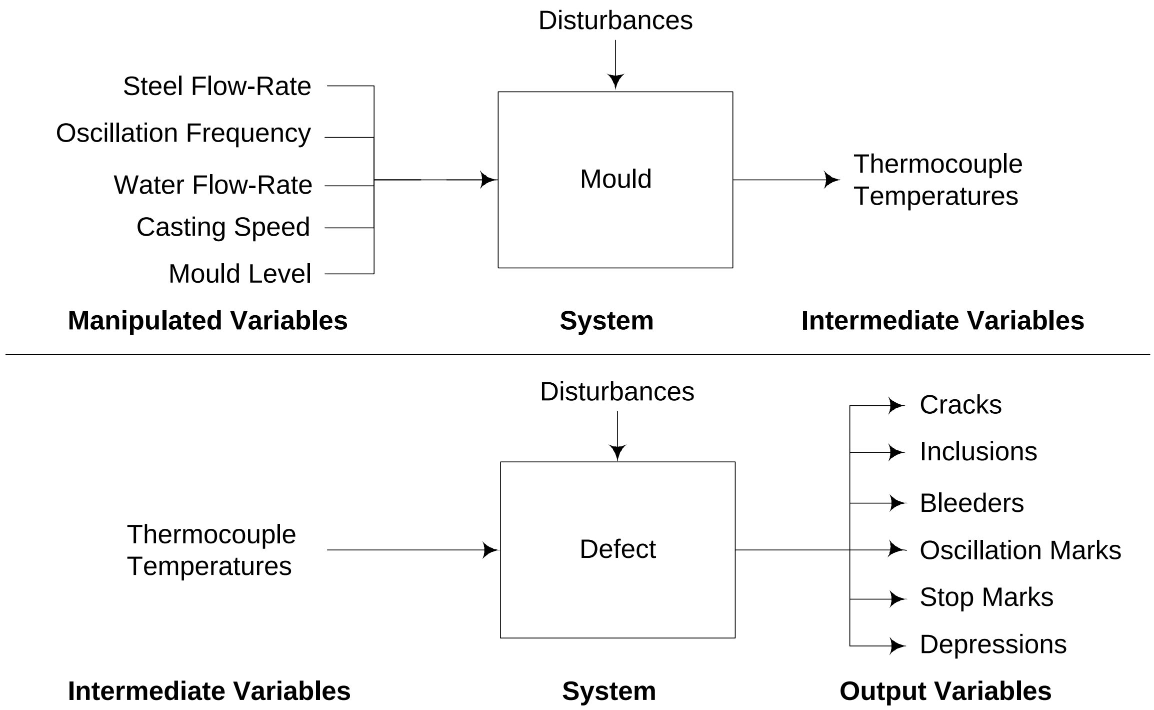

Fig. 3. Philosophy behind the implementation of the prediction control system.

Table 1. Extract of Anderson-Darling hypothesis tests for deep oscillation marks. 8 bad slabs and 354 good slabs were used. Critical value = 2.492.

Variable	Mean	Variance
Casting Speed	0.921	0.973
Mould level	0.908	0.998
Water Inlet Temperature	0.376	0.431
in1	1.230	4.311
in2	1.340	1.981
in3	0.889	4.152
in4	1.130	2.011
in5	0.409	2.988
in6	0.610	3.092
in7	1.080	2.431
in8	0.407	2.171

The null hypothesis is the same as with the Kolmogorov-Smirnov test. The null hypothesis will be rejected when the statistic is larger than a critical value in the upper-tailed test. This value is reported as $a_c^2 = 2.492$ (Johnson, 1994) with confidence $\mathscr{C} = 0.95$. This means that we reject the null hypothesis when $A^2 > 2.492$ to strongly conclude that the empirical distribution is not from the theoretical distribution.

An example of the usage of the Anderson-Darling test is given in Table 1 for deep oscillation marks and some of the input variables. Good slab means and variances are used as the theoretical distributions because enough data was available (between 80 and 400 slabs, depending on the defect in question). The empirical distributions are based on means and variances of slabs with specific defects (ranging between 1 and 109, depending on the defect).

The input variables include the difference between the upper and lower thermocouples on the inner wide face of the mould. For example, "in4" indicates the difference between a thermocouple roughly in the centre of the mould and a thermocouple 15cm below it.

The first column shows the specific input variable, the second shows the Anderson-Darling (Anderson and Darling, 1952; Johnson, 1994) test statistic value for the mean of the variables and the third shows the variance test statistic value. If any of the values in the mean and variance columns are greater than a critical value of 2.492, the null hypothesis is rejected and the distributions of good or bad slabs differ. This implies then that the variable is influential in the occurance of deep oscillation marks. If both values are smaller, then the input has no contribution. In this case it is seen that casting speed, mould level, and inlet temperatures have no significant effect on the output and the (temperature) related thermocouple readings in1, in2, etc. do almost all have an influence. Therefore, the thermocouples have an influence on the origin or detection of the defect. These ideas can be extended to all the other defects mentioned previously and it was found that the most significant defect detection could be done by only monitoring thermocouple temperatures.

6. SYSTEM IDENTIFICATION

Knowing that the predictor can be modeled using only the thermocouple temperature measurements as input variables allows us to further ex-

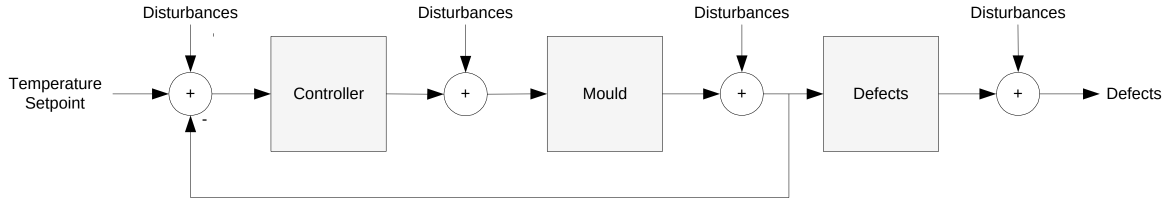

Fig. 4. Control system implementation.

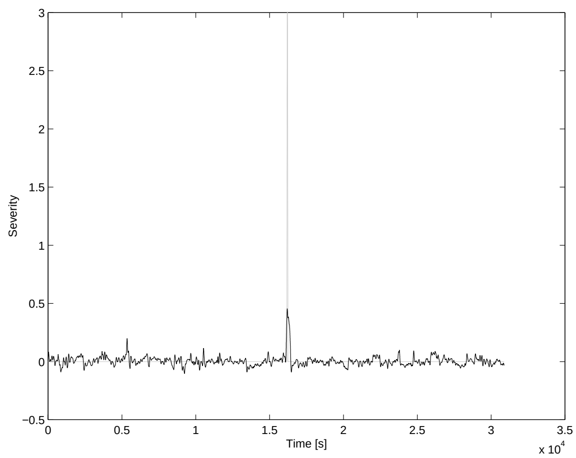

Fig. 5. Comparison of the defect prediction algorithm and actual defect for other inclusions.

amine the structure of the system depicted in Fig. 3. The system can now be expanded to include the manipulated variables as inputs and the intermediate variables as outputs for the first (mould) system and thermocouples as inputs and defects as outputs for the second (defect) system. A block diagram of the total system will make the concept clear (Fig.4). Finding the mould model and defect model can be done using ARX techniques when assuming that the system is linear in the region of operation. The ARX model is given by

$$\hat{\mathbf{y}}_{LS}[nT] = \hat{\mathbf{\Theta}}^T \boldsymbol{\psi}^*[nT], \quad (3)$$

where $\boldsymbol{\psi}^*[nT]$ is the input consisting of the past predicted outputs and the past and present inputs, $\hat{\mathbf{\Theta}}$ is the familiar Theta model (Ljung, 1987) and $\hat{\mathbf{y}}_{LS}[nT]$ are the outputs. The model is too large to present here, but results of the predictor for other inclusions are given in Fig.5. The dark line represents the output of the predictor for other inclusions and the feint line represents the true defect. A threshold can be implemented to minimize the occurance of a false alarm or failure to detect the defect. These thresholds are computed using the predicted defects and the true defect data; and determining the level at which less than 5% of an error is made in the prediction. For the current example, this threshold was computed at 0.3581 which implies an accuracy of 99.98% over time.

7. CONTROL

The development of a control system can involve the following two steps.

(1) Using optimal control theory and the defect prediction algorithm, one can design the ideal temperature set-points for the system.
(2) Using a feedback controller, one can design the controller to maintain the desired temperature set-points.

The optimal control scheme requires knowledge of the defect model to compute the ideal temperature values for the intermediate variables, so that no defects occur. The feedback controller requires knowledge of the mould model, i.e. the relation between the manipulated variables and the output variables.

8. CONCLUSION

Current research involves the training of ARX models based on plant data for the mould model. Preliminary results on the thermocouple models are very promising with high correlation with occurring defects. The predictor is currently being tested in practice. The completion of the defect and mould models will yield models to use to design controllers for the eradication of the defects.

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