1988

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EDRC-06-45-88

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Longitudinal Surface Cracking In Continuous Casting

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Abstract

Defect prediction, using the knowledge based system approach, is being developed for the case of longitudinal surface cracks. Knowledge about longitudinal cracking is in the form of databases, mathematical models and qualitative information. Much of this comes from the technical literature on related topics, but is supplemented by plant experience, as well. Knowledge based systems provide the facility for handling such types of knowledge, with control particulars left up to the system builder The current implementation is forward chaining and uses the OPS5 inference engine. The system involves the use of all three types of knowledge, but more mathematical models are being sought.

Introduction

Hot charging has made defect awareness and detection in the continuous casting of steel a more important problem than in the past. If slabs coming off the caster are inspected, thermal units will be lost, and if slabs are passed, unchecked, the risk is higher that finished product quality will be unacceptable to the customer and higher costs will be incurred. It would seem clear that the best approach to the situation is an accurate predictive tool that provides for the confidence that only high quality slabs are passed to the hot rolling mill.

The current practice consists of 'setting the controls', according to established practice for the particular grade (or application) being cast, i.e. a table lookup of recommended operating regions for different grades. This has a number of drawbacks. First of all, the acceptance of established procedure may be too conservative under certain conditions. For example, there may be heats which can be cast faster, or sprayed differently than the recommended amounts, in order to hold more heat for the rolling operation, or to increase productivity. Secondly, there are a number of 'response' variables which can significantly affect various defect formations, which are not immediately selectable by the operator, such as variations in casting speed or mold level. Thirdly, table lookups only account for one variable at a time. In addition, tables provide no guidelines or predictions for dispositioning of slabs.

This paper will present some of the basic types of information relating to longitudinal cracks that may be used in a knowledge based system. This modelling approach will be defined and contrasted with the more traditional algorithmic approaches. In addition, the framework developed for predicting longitudinal surface cracking will be outlined.

Information on Longitudinal Surface Cracking

The difficulty is that, while certain problems in casting, such as shell thickness determination (mathematically), are relatively straightforward and dependable, reliable defect prediction methods are not readily available. This is a consequence of the uncertainty with which defects form. In the gase of longitudinal surface cracking, it is obvious from the literature[1,2] that the problem is related to irregularity in the mold cooling, both transverse and longitudinal. Irregular heat fluxes will give rise to irregularities in the solid shell thickness and, hence, in the solid shell strength, as well. In this situation, it is easy to envision a thicker portion of the shell pulling away from the wall, while a neighboring thinner area is pushed back against the wall by ferrostatic pressure, leading to a crack, or worse, a breakout. The key issues, then, are thermal and mechanical ones. How large is the difference in neighboring shell thicknesses? How much transverse stress is the shell experiencing, and how does a particular steel respond to these stresses?

Methods are described in the literature which attempt to make predictions about cracking, based on finite element stress/strain analysis[3,4]. These have primarily been with reference to internal cracks, i.e. further down the caster, but have even been attempted for the case of longitudinal cracking[5]. Such approaches cannot account for the large amount of uncertainty involved, or for various operating features, such as mold level fluctuations. In addition, important qualitative considerations cannot be integrated.

The primary sources of knowledge for defect formation, in general, are databases, mathematical models and qualitative considerations. Database information is of two types, relating to properties or phenomenology. Property databases simply consist of tables or plots of various mold, strand and powder properties showing, for example, dependence on temperature. Phenomenological databases cover all of the information in the literature (and elsewhere) which speaks to either the defect, itself, or some important aspect of the defect. For example, peritectic steels (carbon in the range 0.08 to 0.16 %) are expected to exhibit longitudinal surface cracking greater than other grades,[6-9] as shown in Figure 1. This is related to the shrinking attendent to the peritectic transformation[10-11], as well as microsegregation effects[12]. Similar results can be found for a host of variables :

- Chemistry
- Operating variables (speed, pouring temperature, spray practice, etc.)
- Mold powder characteristics (viscosity, softening temperature, etc.)
- strand dimensions
- 'Response' variables (variations in speed, mold level, etc.)

Other chemistry effects include the Mn/S ratio, which is directly related to ductility considerations. In this case, 'database' refers to the knowledge which has been compiled on the high temperature strength and ductility of steels, as a function of composition[13*14]. Casting speed (v), and mold powder viscosity (TJ) have been shown to have the same kind of effects[15*16] (see Figure 2), since both will be involved in the even flow of molten flux down the side of the strand. It has even been suggested that a parameter of interest would be TI*V[17]. strand dimension effects have mainly been in the form of width to thickness ratios for slabs, higher ratios leading to more cracking[18]. 'Response variable' effects have been shown to be strong, particularly with mold level variations[19]-[20].

These variables are obviously important, but what about quantities such as the steepest temperature gradient at the midface (at various positions in the mold and just below), the temperature rebound below the mold, etc.? These quantities are of considerable importance, and should be integrated as well. This will lead to greater specificity of the independent variable space. For example, the (average) casting speed will greatly affect the temperature distribution, but will have separate effects, as well. These kinds of information are afforded by the vast work done on modelling in continuous casting. Heat flow modelling has been done on the strand[21"23], in the mold[24], and in the flux layer[25], as well. This is usually done in the following form (in the strand) :

dx V dx) dy v By ' V p dt J

In addition, modelling work has been done in the area of stress and strain determination[3]-[26]-[27]. This is a difficult undertaking in the mold, where mesh sizes must be extremely fine for finite element strain analysis (on solid shells only 1 or 2 cm thick), but has been done with reasonable results[27]-[28].

The final source of knowledge about cracking is in the form of qualitative considerations. These are often in the form of heuristics, or rules of thumb, which don't necessarily have any basis in theory, but are found to be true, nonetheless. For example, tube changes have been suggested to have a negative effect on cracking[29]. Also, it has been suggested that longitudinal cracks often happen in bunches[30].

Knowledge Based Systems

BACKGROUND

The problem of defect prediction is being approached in the present study, in two different ways, for the particular defect of longitudinal surface cracking. One approach is to take a statistical approach to partitioning the independent variable space, and assessing probabilities for cracking in each sub-space, using the package, 'Entropy Minimax'[31]-[32]. This is a data specific method which not only attempts to partition the variables, based on the data, but includes facilities for inserting models such as heat flow, as well. This is primarily a numerical process, however, and is not ne9ft?§3£\'yQbased on an understanding of what causes longitudinal surface cracking. The Ottiyf^l)fra^^i^lpfVs the focus of this paper, is to use the knowledge based system implementSft8N.E^£'^^QY»v^ \ j \ 15213

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Knowledge based systems can take a number of forms depending on the architecture and

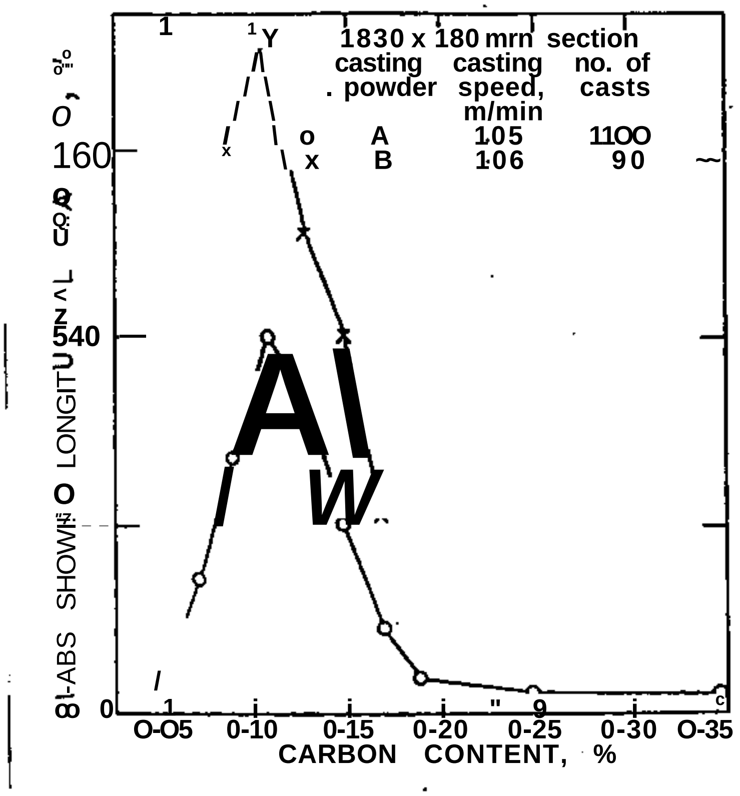

Figure 1. Effect of carbon on longitudinal cracking (after Gray et al[9])

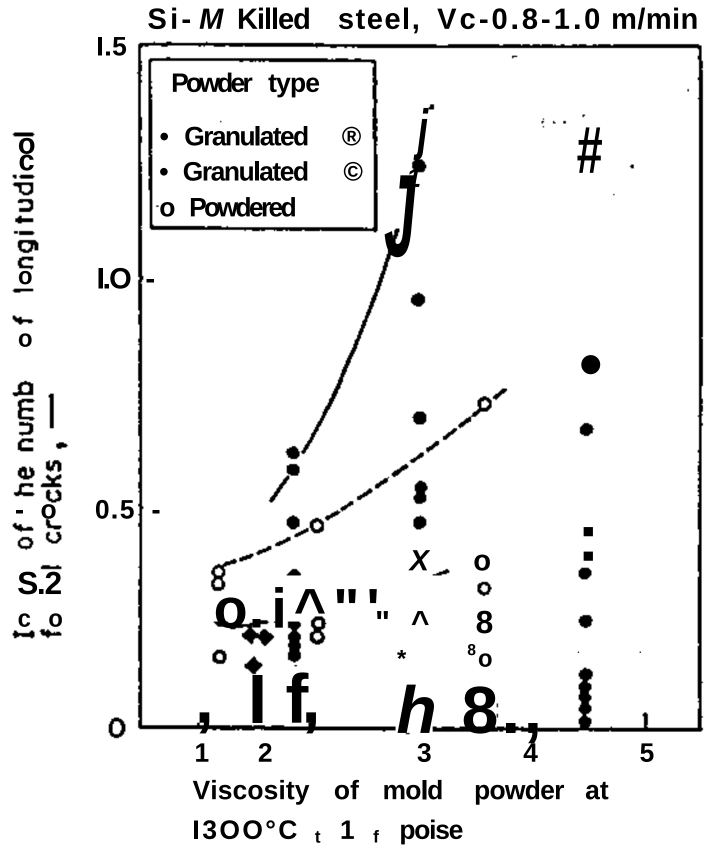

Figure 2. Effect of flux viscosity on longitudinal cracking (after Suzuki et al[2])

control structure used, but are characterized, in general, by a separation of the domain knowledge (i.e. information about cracking) from the controlling mechanism of the system[33]. This is contrasted with a typical algorithmic application (e.g. in Fortran), where a majority of the coding is concerned with controlling the execution of the program. In addition, knowledge based systems are characterized by an attempt to reason through some process. For example, cracking could be thought of as depending on strain levels, which could be thought of as depending on stress levels, which could be thought of as depending on temperature gradients, strand/mold wall friction, etc., and so on.

Reasoning, as used here, can be in three different directions. Using the terms of logical formalism, these are deduction, induction and abduction. These are characterized by which of the general system components, p (input data), p =*> q (rules or information) and q (results), is being sought, i.e.

- Deduction: p, (p => q) —> q
- Induction: p, q —> (p ⟹ q)
- Abduction: (p=s>q), q — > p

Deduction is the most straightforward and, accordingly, the most common in knowledge based systems. Deduction is central to defect prediction problems. Induction is the process of making large statements about the process, based on experience, i.e. learning. In the context of a computer environment, this is a difficult thing to do. Obviously, induction, in the human environment, must be done before any deduction can be done. Abduction is of intermediate difficulty, and may be concerned with problems such as determining what things caused cracking in the past.

The particular knowledge based system implementation that is put into place is largely determined by the architecture and control structure that are used. Architecture, here, is used to refer to software particulars. In the present study, a package known as OPS5[34] is being used, within the framework of a larger development tool, Knowledge Craft™. OPS5 is a production system, consisting, entirely, of IF/THEN rules, which are cyclically checked for candidates whose conditions are all true, as shown in Figure 3. Control structure is used here to refer to the particulars of how one goes about doing the particular tasks involved in the system. The first question in determining control structure is the direction that reasoning will proceed, i.e. forward versus backward chaining. In forward chaining, or data driven systems, reasoning proceeds from the input data to the conclusions which are desired. In backward chaining, or goal driven systems, reasoning proceeds from the conclusion of interest to the data, in order to test the conclusion's validity. Further control structure issues involve the depth of rules or information to be used.

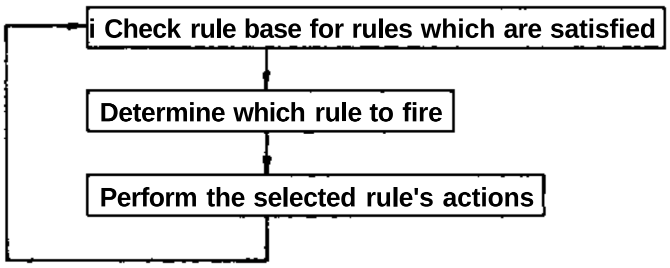

Figure 3. Production System Cycle

FORMULATION

The problem of determining whether longitudinal surface cracking will occur is being structured as shown in Figure 4, below. In this forward chaining approach, a small number of rules are written, called control rules, which insure that this sequence is stepped through each time a prediction about cracking is made. Making an inference about cracking amounts to literally stepping through what is expected to be the progression of the crack's formation. Each task in the sequence given below contains a number of rules used to make the necessary determination. For example, the first task contains rules whose actions are simply to say how smooth the heat flux is around the shell perimeter, the second contains rules to estimate the transverse regularity of the solid shell, and so on.

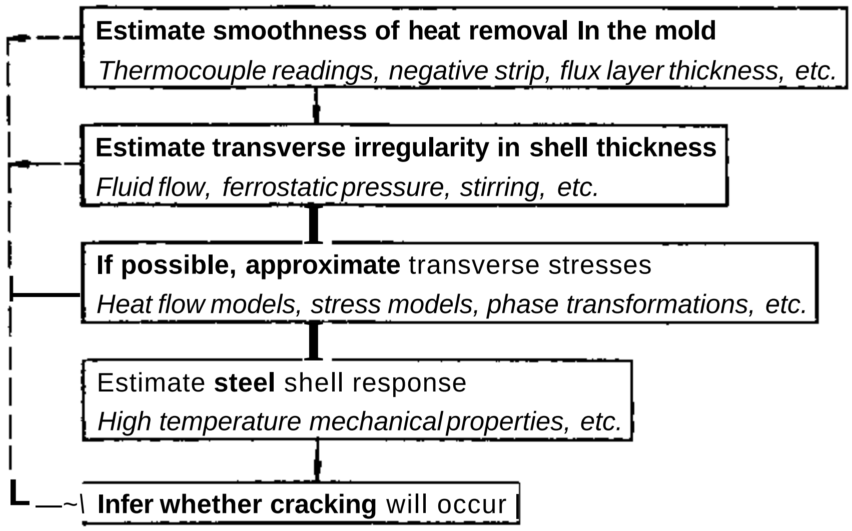

Figure 4. Structure of longitudinal surface crack prediction problem

By performing **a** number of tasks, in series, uncertainty is being propagated down through the problem. How this uncertainty is handled is entirely up to the system builder. Much has been written on fuzzy systems[35], uncertainty factors[36], prior odds, and so on, but there is no accepted means for keeping track of uncertainty. Shell irregularity can be assigned a number, for example, from 0 to 1, or from -5 to 5. Similarly, irregularity can be assigned a qualitative tag, such as 'slight' or 'high'.

An important feature of the current structure is that 'routes' out of the problem are available at any level. For example, rules in the first task (smoothness of heat flux) can deal with the case where there are thermocouple readings in the mold. Under certain conditions of these readings a direct inference about cracking can be made. That is, some rules in this task (and in each task) have the following form :

```
IF the current goal is to check for irregular heat flux
AND condition 1
AND condition 2, etc.
THEN infer that cracking Is ...
AND step down to writing output and halting the system
```

It's clear from the formulation of the above rule that considerable flexibility is afforded by the production system architecture. Right hand sides of rules (the actions, or THEN parts) can do whatever the software and hardware configurations will allow. This includes writing output, interacting with the user, and, importantly, running external mathematical codes, written in a suitable programming language, such as Fortran. This last capability is of extreme importance, because it allows the integration of accepted modeling techniques, such as heat flow, stress and strain analysis, etc. into the problem. The insertion of models (with our configuration) is trivial, and once a model has been called, the results can themselves be conditions for further rules to act on. In addition, long-winded models may not always be necessary. The rules can be written so that the models are only run under certain conditions, and only down (along the caster) to the point of interest. Furthermore, the rules can be written so that, for particularly uncertain conditions, analyses can be run which arrive at predictions about cracking from purely mathematical criteria.

It is easy to see that the knowledge base can be, at the very least, a locust for knowledge about continuous casting, in the form of databases, models and qualitative information. In addition, the flexibility inherent in knowledge based systems affords straightforward user interfaces which can include such things as explanations of why a particular thing is being sought, references for where a particular piece of information came from, caster diagrams, showing where interest is being focused, and plots of model results.

Implementation

In the current approach to knowledge based system prediction of longitudinal surface cracking, a forward chaining OPS implementation is being used, with the control structure given above. The hardware being used is a MicroVax II, with 16 Megabytes of memory and 220 Megabytes of disk storage. The software being used is Vax Lisp (version 2.1), Vax Fortran, and Knowledge Craft™, a system development tool containing the OPS inference engine. Currently, callouts are done only for heat flow computation[37], but stress/strain models are being sought for integration, as well. The dependent variable, longitudinal surface cracking, is being considered as a ternary output variable. That is, three output values are possible, cracking, uncertain, and no cracking. This is hoped to mirror the actual choice made in dispositioning, where a strand may face scarfing (cracking), or inspection (uncertain), or may be passed to the rolling mill (no cracking). The only possible further refinement is the division of •uncertain* to include two grades of uncertainty, one being more likely to show cracking, in order to represent the decision between hot and cold inspection. This may be a non-trivial distinction, since cold inspection can be of considerable cost.

Uncertainties are handled, implicitly, by assigning qualitative tags to various parameters. For example, ductility is assumed to be either 'Good' or 'Poor'. Shell irregularity is assumed to be 'Little', 'Slight', 'Moderate* or 'High*, and so on. Cracking is based on these qualitative tags, and is checked for at various points down the mold. Points below the sprays are not considered, and only midface temperature gradients are considered. Paths out of the system are provided at each task level. When wide enough variations in mold thermocouple readings are logged, then direct statements about cracking are made. Also, when stresses are being considered, and the heat flow model is called, gradients severe enough, along with other conditions (chemistry, etc.) cause direct statements to be made, as well.

Information for the various tasks to be performed has been taken from the literature available on longitudinal surface cracking and related topics. At this point, no attempt is made to reconcile conflicting information. That is, only one point of view has been inserted for a particular piece of information. For example, if an estimate is required for the (average) thickness of molten flux between the strand and mold wall, a relationship is used from a particular source on mold powders[15]. However, it is envisioned that other approximations for such quantities will be introduced shortly, with provisions for weighting or blending these different approaches.

Summary

The literature clearly indicates that longitudinal surface cracking is closely related to the interaction of thermal and mechanical features of continuous casting. The effects of carbon, manganese, sulfur, phosphorous, casting rate, flux viscosity, mold level fluctuation and strand dimensions can all be considered in this light. In order to reason through crack formation, then, these interactions need to be accounted for. This is done with an emphasis on the problem of irregularity in mold cooling. This irregularity is assumed to have an important influence in determining the variations in solid shell thickness and, in turn, solid shell strength.

Reasoning through longitudinal crack formation in this manner can be done in a knowledge based system environment. Knowledge based systems provide not only the framework for reasoning through the process, but for collecting the primary sources of information on cracking, namely databases (experimental data, property information, etc.), mathematical models and qualitative considerations, as well. In addition, the flexibility of this approach allows for providing a number of alternative paths to the conclusion of interest. That is, the main path down through the problem, including the running of models, can be circumvented under appropriate conditions. Such conditions include, for example, wide variations in mold thermocouple readings.

The current implementation of longitudinal surface crack prediction deals in a ternary output variable, with possible values of cracking, uncertain and no cracking. Inferences are based on estimates of derived quantities (shell irregularity, temperaure gradients, strains, etc.), input quantities (chemistry, operating variables, etc.) and observations (recency of tube changes, etc.).

Acknowledgements

The authors would like to acknowledge USX Corp. for financial support.

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