Real-time Expert System Applied to Mold Bath Level Control of Continuous Caster

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Fluctuation of the mold bath level of continuous caster greatly influences the surface quality of cast slabs or billets. It is difficult to maintain an optimal bath level by a PID controller and a slide gate vibration controller with fixed parameters, because the characteristics of casting condition fluctuate during operation. To solve this problem, an expert system method has been applied to the mold bath level control system. In this expert system operator know-how regarding control parameter adjustment is represented in the form of a knowledge base, and that knowledge base is driven by inference engine when a significant fluctuation of the mold bath level occurs. This system has been applied to a continuous round caster, and has effectively regulated the mold bath level fluctuation by adjusting the controlling parameters to optimize the state of operation when the fluctuation occurred.

KEY WORDS: expert system; inference engine; operators' know-how; knowledge base; continuous round caster; mold bath level fluctuation; mold bath level control; PID controller; slide gate vibrator.

1. Introduction

Modern computer-assisted process control technology can be divided into two areas:

- i) Computer control based on knowledge obtained under actual operating conditions.
- ii) Computer control based on modern control theories.

These advanced types of control are important in order to follow the changes during operation and to produce high quality products with today's sophisticated equipment.

Modern control theories are applied to the mold bath level control systems for continuous casters, where such systems greatly affect the surface quality of cast slabs or billets, but only a few applications¹⁾ have been successful. In Wakayama Steel Works, Sumitomo Metal Industries, Ltd., it is recognized that operators of the continuous round caster have accumulated know-how regarding how to regulate the fluctuation of mold bath level. In addition an expert system building tool for process control has been developed in Sumitomo Metal Industries, Ltd. (SMI). Therefore an expert system, a computer control system based on knowledge obtained under actual operating conditions, has been attached to the conventional mold bath level control system of the continuous round caster. This expert system can work in conjunction with the conventional control system and can infer at a very high speed in real-time use.

The improved control system not only has conventional PID control and slide gate vibration control, but also has three other control functions. These

are

- i) optimization of control parameters (proportional gain, integral action time, derivative action time, and amplitude and cycle of vibration);
- ii) assessment of the cause of mold bath level fluctuation; and
- iii) assessment of operational state.

The system has been used on-line effectively to regulate the fluctuation of bath level.

In this paper, we first outline the mold bath level control system of the continuous round caster in Wakayama Steel Works, and then describe the conventional way to improve the mold bath level control. After that, we present an outline of an improved control system and the effect on bath level fluctuation. Finally we give a general evaluation of the expert system in on-line use through an experiment.

2. Experimental

2.1. Outline of the Continuous Round Caster

The continuous round caster in Wakayama Steel Works provides round billets for seamless tubes and pipes. Table 1 shows the main specifications of the continuous round caster.

Fig. 1 shows the main control items in the continuous caster. The mold bath level is one of the most important control items and must be strictly controlled, because fluctuation of the bath level greatly influences the surface quality of cast slabs or billets. Fig. 2 shows the relation between the amplitude of the mold bath level fluctuation and surface quality of tubes and pipes.

Table 1. Main specifications of round caster.

Item	Specification
Type	S-type continuous straightening
Mold size (mm ϕ)	187/197/213/231/261/282/292/335
Number of strands	Two twin strands
Casting radius	10 m
Max. casting speed	3.2 m/min.

Fig. 1. Main control items in continuous caster.

Fig. 2. Influence of mold bath level fluctuation on surface quality of pipes: defect frequency below 2 represents satisfactory surface quality.

Fig. 3 shows the configuration of a conventional mold bath level control system. A microcomputer is used as a controller. The controller is equipped with PID control function to calculate the control signal of the slide gate, and with a slide gate vibration function to compensate for the delay in the motion of the slide gate. In the operation, operators set the control parameters according to the state of operation. Fig. 4 shows the relation between the cross-sectional area of the mold and the fluctuation cycle of the mold bath level. In the continuous round caster, the cross-sectional area of the mold is about 1/4 to 1/6 of the slab caster and the fluctuation cycle is about 1/2. Because of the smaller section the fluctuation tends to continue in a short cycle once it occurs, and the disturbance to the bath level control system is greater than in the continuous slab caster. Generally, in a continuous round caster it is difficult to maintain an optimal bath level throughout the whole operation.

Fig. 3. Schematic diagram of conventional mold bath level control system.

Fig. 4. Influence of mold cross-sectional area on cycle time of mold bath level fluctuation.

2.2. Conventional Approach to Improving Controllability

The following adaptive control methods were introduced or examined before introduction of the expert system:

i) Introduction of vibro method²⁾ and related automatic tuning³⁾:

Fluctuation of the mold bath level occurs because of a delay in the movement of the slide gate caused by adhesion of solidified steel. Therefore a vibratory signal is added to the control signal of the slide gate to ease for smooth movement. In addition, to maintain the smooth movement of the slide gate, an automatic tuning device estimates the delay from the stroke signal of the slide gate and adjusts the amplitude and/or cycle of the added vibratory signal.

ii) Introduction of automatic PID parameters tuning method:

Fluctuation of the mold bath level occurs when the state of operation changes and the PID parameters become unsuitable. Therefore, an automatic PID parameters tuning device is attached to the conventional PID controller. When fluctuation occurs, this device samples the mold bath level signal for 10 or

15 s and calculates specific characteristics of the wave form. Then the device compares this calculated wave form with the originally calculated wave form (determined through simulation under the condition of unsuitable PID parameters) and adjusts the parameters.

iii) Examination of Model Reference Adaptive Control (MRAC):

MRAC is based on the adaptive control theory, one of modern control theories. The idea is to identify the transfer function parameters of the real control system through comparison of the reaction of the system to a control signal with the reaction of a reference model (an ideal model realized in computer) to the same control signal, and then to adjust the parameters of the controller automatically to compensate for the deviation. A change of flow characteristics due to a clogged or fused slide gate, and non-linear relation between control command to slide gate and flowing area are compensated for by a change of flow gain.

Table 2 compares the applicability of each method to on-line use. The automatic vibro tuning method is effective when there is a delay in the movement of the slide gate, but not effective when the slide gate and/or nozzle turn out to be clogged or fused. In some cases, although it functions sufficiently to compensate for the delay, the excessive amplitude of the vibratory signal causes fluctuation in the mold bath level. The automatic PID parameters tuning method functions effectively when the fluctuation is caused by the changes in the flow characteristics of molten steel. Such change is caused by the changes of the state of operation such as casting speed, temperature, clogged or fused slide gate and/or nozzle, and so on. However, it adjusts unnecessarily when a delay in the movement of the slide gate causes the fluctuation. In a simulation model, MRAC is recognized to be much more effective in regulating fluctuation than conventional PID control. However it was not available for on-line use at the time of this examination, because it involves changing the control signal of the slide gate excessively in identifying transfer function parameters of real control system. As previously

mentioned, many causes of mold bath level fluctuation exist in a real control system and influence fluctuation because of the small cross-sectional area of the mold. Therefore the conventional adaptive control methods alone cannot further improve the mold level controllability.

On the other hand, operators judge the state of operation from all available data (not only the stroke signal of the slide gate and the mold bath level signal but also the temperature, casting speed, heats per tundish, and so on). They assess the cause of fluctuation and decide the action of the controller. Through experience, operator know-how related to regulating mold level fluctuation has been accumulated.

3. Outline of the Improved Control System

3.1. Introduction of the Expert System

It has been shown that it is difficult to maintain an optimal mold bath level using a conventional controller equipped with PID control function, slide gate vibration function and automatic tuning functions. A more effective control system, which could estimate the cause of mold bath level fluctuation and regulate the control parameters when the fluctuation occurred, was needed. We therefore looked to the accumulated know-how of our operators. An expert system building tool had already been developed for the present purpose. The decision to introduce an expert system was made and the function of operator know-how was introduced to the mold bath level control system. In the experiment, MARKS^{4,5)} (Multi Access Real-time Knowledge System) was used as a building tool. This building tool has the following features:

- (i) The operators' know-how can be represented in the form of a knowledge base in Japanese.
- (ii) The knowledge base can be modified through learning in experiments.
- (iii) It can work in conjunction with conventional control systems.
- (iv) It can infer at high speed in real-time use.

3.2. Functions of the Improved Control System

Fig. 5 shows the configuration of the improved control system, which combines the expert system with the conventional control system. The functions of each system are as follows:

i) Conventional control system:

The conventional control system mainly operates controls such as automatic casting start, mold bath level control, slide gate vibration; it checks the level fluctuation and then activates the expert system.

ii) Expert system:

The expert system mainly diagnoses the condition of the mold level control and edits referable data for inference. This diagnosis, based on know-how of operators who are experts, in other words experts' know-how, is represented in the knowledge base which is divided into three parts. Fig. 6 shows the connection between these three parts. The function of each

Table 2. Applicability and effectiveness in on-line use.

Cause	Method		
	Auto-tuning of slide gate	Auto-tuning of PID parameter	MRAC
Changes in slide gate movement	○	△	△
Changes in flow characteristics	●	○	○
Applicability	Good	Good	Poor
Notes	Effective to delay in slide gate movement	Excessive reaction to fluctuation by slide gate	Excessive change of control signal in identifying

Ex. ○ △ ●
 ← →
 Effective Ineffective

Fig. 5. Configuration of improved control system.

part is as follows.

a) Assessment of state:

This part is activated at a fixed interval and estimates the state from sensory data such as casting speed, mold level, stroke of slide gate, tundish weight, and so on. This data is processed to represent the characteristics of each sensory signal. The results of the inference are informed through the AI station. The inferred items are the state of the slide gate (clogged, fused, or normal), the state of mold level detector's sensitivity, etc.

b) Assessment of cause:

This part is activated only when the fluctuation of the mold bath level occurs, and estimates the cause of level fluctuation based on the inferred operational state, characteristics of stroke signal of the slide gate, and mold level signal. Those characteristics are processed from the most recently sampled data.

c) Assessment of effective parameter:

This part is switched on simultaneously with the 'Assessment of cause' part, and determines which parameter can affect the reduction of fluctuation and determines the required adjustment. The results are transmitted to the control system for immediate adjustments.

3.3. Effects of the Improved Control System

Fig. 7 shows examples of the control parameter adjustment. In each example the level fluctuation check works at point A. In these examples level fluctuation is judged to occur when the deviation from the set value is more than 5 mm. In example 1, after the fluctuation is detected, the stroke signal of the slide gate and the mold level signal are sampled at 0.1 s pitch for 10 s. Then the average amplitude and cycle of each signal are calculated. In this example, since irregularity in the cycle of the slide gate stroke is detected, the cause of fluctuation is considered to be due to insufficient slide gate vibration. Finally the amplitude of the vibratory signal added to the control signal of the slide gate increases,

Fig. 6. Outline of inference flow.

Fig. 7. Example of control parameters adjustment.

and the fluctuation is gradually reduced. In example 2, the average amplitude and cycle of each signal are calculated as in example 1. In this example, the cycle of the slide gate stroke is regular, but the peak points of the slide gate stroke signal and the mold bath level signal occur almost simultaneously and the

Fig. 8. Attained reduction of bath level fluctuation by improved system: the excessive fluctuation represents fluctuations of bath level more than 5 mm.

cycle time of the mold level fluctuation is short. In this case, slide gate vibration is moderate and the cause of fluctuation is determined to be that the proportional gain is too sensitive. The proportional gain is therefore reduced. These examples show the expert function based on operator know-how working effectively.

As previously mentioned, the expert system functions effectively at the moment of fluctuation. Fig. 8 shows the effect of the improved system on the reduction of mold level fluctuation. As a result the frequency of casting in which mold level fluctuation is more than 5 mm has been reduced to 60 % of the conventional system.

4. Evaluation of the Expert System

Some aspects of the expert system were evaluated through an experiment.

4.1. High Speed Inference

During the experiment we concentrated on securing high speed inference in real-time use. Therefore some measures were introduced in the system construction and have achieved high speed inference. These include:

i) Choice of building tool

The expert system building tool used here has the following characteristics which ensure high speed inference:

- (a) It is compatible with conventional control system.
- (b) It has modularity of knowledge base.
- (c) It implements a high speed inference algorithm (our original version of Rete algorithm.⁵⁾ The Rete (network) match is an algorithm for efficiently determining which rules can be satisfied by the contents of working memory on each recognize-act cycle).

ii) Division of functions

Two microcomputers are used. One responsible for the main control of procedural program and the other responsible for the newly added expert function. These were connected by a multibus.

The microcomputer responsible for the expert function is further divided into two parts. One part is the knowledge base (with operator know-how divided

into three functional parts), and the other the procedural program, responsible for calculating and editing the data referable in knowledge base.

4.2. System Construction

In the case of an expert system, the system construction process is divided into two parts. One part is the process of collecting the know-how from the experts, arranging it in the form of a knowledge base and then constructing the prototype; the other is checking and modifying the function of the knowledge base during on-line experiments. In our experiment, it took 2 months for the former process and after the prototype construction, on-line examinations and modifications were repeated for 3 months. In these on-line experiments, it was confirmed that an expert system can produce positive results soon after application. In other words, unlike conventional systems, the expert system can function effectively from the beginning. As the system becomes more and more complete, through on-line test and modification of the knowledge base, the system becomes more and more effective.

4.3. Knowledge Base Construction

The key to a successful expert system is knowing how to extract the expert know-how and how to arrange it into a knowledge base. Unfortunately a method is not yet established and knowledge engineers must arrange knowledge bases by trial and error. In this experiment, we first chose a key man and interviewed him about his general knowledge of the subject and then his more specific know-how. Next a knowledge engineer arranged the collected know-how in the form of a table (the table represents the relation between causes and effects of phenomena). Then each piece of information was checked in operation. Only confirmed know-how was included in the knowledge base. In future a system for know-how arrangement must be established and the number of skilled knowledge engineers must increase in order to further develop and expand the expert system.

4.4. Suitable Area for Expert System

The expert system will work best in an area where there is a recognized body of expert know-how and where there exist disturbances to the system that are not currently detectable. It is further desirable that operators have a strong will to improve their plant. Such operator's possess know-how that they do not realize they have. In such an area, an expert system based approach to improving controllability can be superior to a conventional theory based approach. In our experiment, it was shown that the expert system could work effectively from the beginning. As new know-how was produced (by combining the operators' experience-based knowledge and the knowledge engineer's control theory-based knowledge) during on-line experiments, the system became more and more effective. This is another advantage of the expert system.

4.5. Languages for Description of Knowledge Base

Recently, almost all newly developed expert system building tools implement the language geared for the description of a knowledge base. These languages are said to be easy to describe, to read and to modify. But through experiment, we found that though they are friendlier than LISP or PROLOG, they are far from ideal. It is important to say that the process of knowledge base construction is just the same as conventional programming. Therefore construction of the knowledge base requires skilled knowledge engineers and cannot be maintained by experts alone.

4.6. Future Problems

There are specific points still to be studied and developed. Areas suitable for application of an expert system will be limited. The scale of the knowledge base maintainable seems to be about two or three hundred rules at most, and too many rules will reduce the possibility of easy modification. Therefore specific conditions necessary to make an expert system successful must be examined. It is especially important to establish a method for arranging know-how, and we intend to investigate possible methods in further applications.

5. Conclusion

We described the outline for the application of an

expert system to the mold bath level control in the continuous round caster and confirmed that an expert system can be an effective tool in improving conventional systems. We made every effort to ensure high speed inference for real-time application. The speed of inference is mainly influenced by the implemented inference algorithm, but the description of the knowledge base and the division of functions between knowledge base and procedural programs, are also very important. In this application, a division of functions was made and the expert system worked at high speed in on-line use. As a result, the ratio of billet casting whose level fluctuation is more than 5 mm has been reduced to 60 % of that using the conventional control systems.

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