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Automatic Rolling Scheduling for Synchronized Operation of Casting and Hot Rolling

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Abstract:

In the synchronized operation of casting and hot rolling, rolling schedule is determined manually considering multiple complex constraints due to wear of mill roll surface. It causes loss of an opportunity of hot direct rolling and increases fuel cost. Therefore, JFE Steel developed a new automatic system, which calculates rolling schedule including hot direct rolling. The parsing method is introduced to this system in order to check the satisfaction in the scheduling constraints in real time. Finally, the proposed technique is applied to Chiba No.3 Hot Strip Mill in JFE Steel and its availability has been confirmed.

1. Introduction

The majority of slabs cast by continuous casting in the steelmaking process are transported once to the slab yard for temporary holding, and then transferred to the hot strip mill for rolling to the desired dimensions. Before rolling, the slabs are charged into the reheating furnace and reheated for several hours to a temperature at which rolling is possible. On the other hand, in synchronized operation of the casting and rolling processes, heat loss is reduced by transporting the high-temperature slabs after casting directly to the hot strip mill without temporary holding in the yard. This process, called hot direct rolling, improves fuel consumption by shortening the slab residence time in the reheating furnace.

However, because the order of materials to be rolled in a rolling mill is subject to complex empirical constraints (rolling constraints, as described later), it is not possible to roll all slabs by hot direct rolling of slabs, and whether hot direct rolling is possible or not is left to the judgment of the operator. That is, a rolling schedule consisting mainly of slabs transported from the yard (yard slabs) is planned, and each time hot direct rolling slabs conveyed directly from the steelmaking shop arrive, the operator judges whether they satisfy the constraints or not, and inserts them into the schedule if possible.

As a result, many opportunities for hot direct rolling are lost because this is a manual process, and even if a hot direct rolling opportunity is not lost, suddenly inserting an arriving slab into the rolling schedule will prolong the residence time of the following slabs in the reheating furnace, and may lead to overheating.

To solve this problem, JFE Steel developed an automatic rolling scheduling system which takes rolling constraints into account[1)]. This system has achieved automatic real-time calculation of rolling schedules that satisfy rolling constraints, while implementing the system in a form that allows easy adjustment of complex empirical rolling constraints by using the parsing method. By planning rolling schedules that include hot direct rolling slabs in advance, this system has reduced both missed opportunities for hot direct rolling and overheating due to unscheduled receiving of direct-rolling slabs, contributing to improvement of fuel consumption. This system has been introduced at No. 3 hot strip mill (3HOT) at JFE Steel's East Japan Works (Chiba District), and its effectiveness has been verified[2)].

2. Background

2.1 Overview of Equipment

Figure 1 shows an overview of the typical facilities of the casting process and hot rolling process that enable synchronized operation of casting and hot rolling.

Yard slabs, which comprise the majority of slabs

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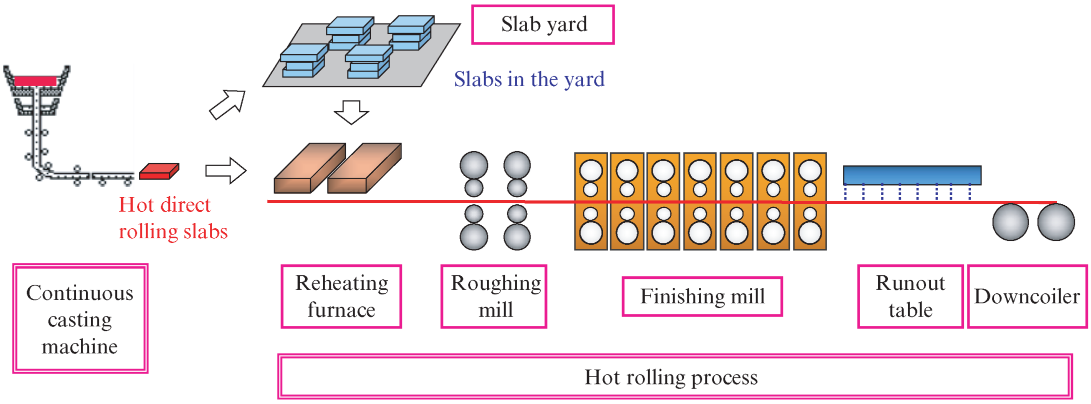


Fig. 1 Overview of casting and hot rolling process

arriving from the continuous casting machine, are transported once to the slab yard, and are then transferred to the reheating furnace for reheating. On the other hand, hot direct rolling slabs are transported directly to the hot rolling process while still at high temperature, and are heated for a short time in the reheating furnace.

The slabs are extracted from the reheating furnace after heating to a sufficient temperature for rolling, and are then rolled in the roughing mill and finishing mill in that order. The roughing mill reduces the slab thickness to about 1/10 of its original thickness, and the finishing mill rolls the material to the target thickness of the hot strip mill (either the product thickness or the required thickness in the following process). After cooling on the runout table, the strips are coiled by the downcoiler.

2.2 Rolling Constraints

Rolling constraints are constraints related to the rolling schedule of materials to be rolled by the above-mentioned hot rolling process, and are set empirically to secure the quality of the product surface and threading stability in the rolling mill. Concretely, rolling constraints include the same width condition, where slabs of the same width are rolled continuously, the width connection condition, where the width difference between the preceding material and following material is controlled, and the composition condition, where slabs with different compositions are restricted in sequence. Many conditions are set for the slab composition and product dimensions.

One reason for setting constraints is roll wear of the rolling mill rolls. The mechanism of finishing mill work roll wear is shown in **Fig. 2**. In this mill, 4-high rolling mills are generally used, comprising the two work rolls above and below the steel strip, which are in direct contact with the strip, and two backup rolls that support the work rolls from the outer side. As rolling proceeds, these rolls, and particularly the work rolls of the finishing mill, undergo step-like wear. For example, if slab A is rolled first, the profile of the work roll surface will be worn out by the same width as slab A. Then, if the slab to be rolled next is wider than A, as in the case of slab B, the uneven part of the roll caused by slab A will be in contact with the surface of B, causing deterioration of the surface shape of B. To prevent this, the next slab to be rolled should preferably be narrower than A. If slab C, which has a narrower width than A, is rolled next, and the slab is perfectly straight when it enters the rolling mill, it can be rolled by the flat surface between the step-like marks on the roll and hence the quality of strip surface is secured. This becomes a constraint on the rolling schedule, as the following material should be narrower than the preceding material.

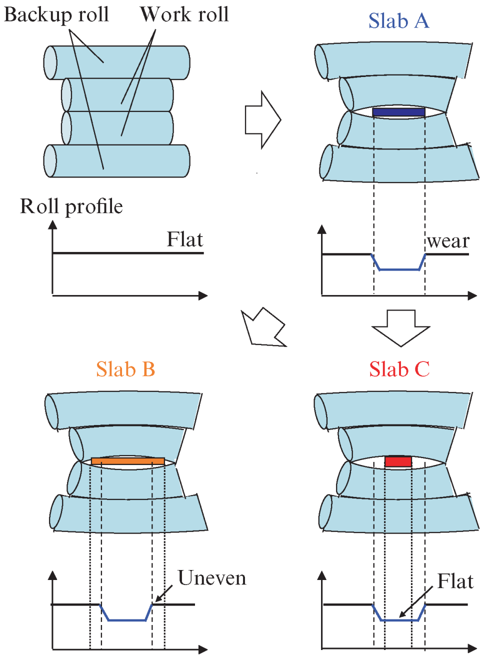


Fig. 2 Finishing mill work roll wear

In hot strip mills, these kinds of constraints are set

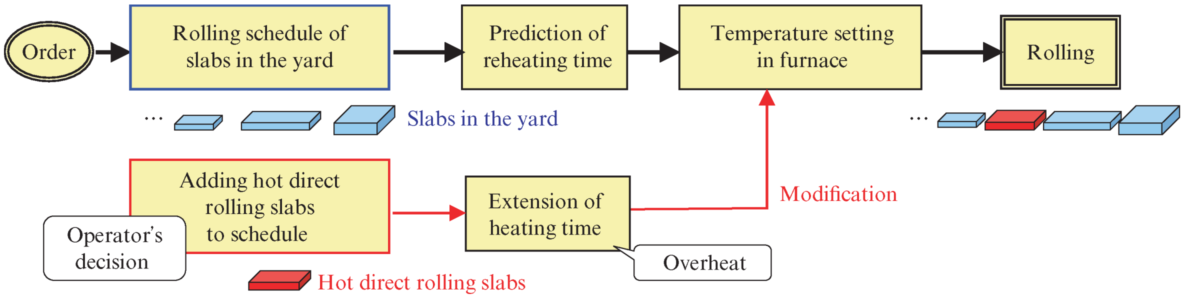


Fig. 3 Traditional flow of rolling scheduling

in diverse ways based on the experience of the operators. Although rolls can be changed when wear becomes remarkable as a result of extended rolling, care is necessary so as not to violate these constraints when planning the rolling schedule during rolling with the same rolls.

2.3 Traditional Flow of Rolling Scheduling and Scheduling Problems

The flow of rolling scheduling and setting the temperature of the reheating furnace is shown in **Fig. 3**. As mentioned previously, first, the rolling schedule is decided for yard slabs. Because the residence time of each slab in the reheating furnace can be predicted when the slabs are charged and extracted from the reheating furnace according to this rolling schedule, the temperature is set so that the slab can be heated up to the temperature necessary for rolling within that time. However, each time a hot direct rolling slab arrives, the operator judges the rolling constraints and inserts suitable slabs in the rolling schedule.

Since slabs are inserted in the rolling schedule manually based on the operator's judgment in this process, radiant heat loss may occur due to missed rolling opportunities, while on the other hand, the rolling schedule of the following yard slab may be delayed if a hot direct rolling slab is inserted in the schedule immediately preceding that slab, and in this case, the temperature may exceed the necessary temperature (overheating) due to the prolonged heating time. In other words, sudden insertion of hot direct rolling slabs in the rolling schedule makes it impossible to optimize the furnace temperature, causing deterioration of the fuel cost of the reheating furnace as a whole.

2.4 Direction for Improvement

To solve the issues described above, JFE Steel developed an automatic planning function for rolling scheduling which includes hot direct rolling slabs in advance. Since it was necessary to implement this in a form that allows easy adjustment of rolling constraints set on the basis of experience, in this development, this function is realized by introducing the parsing method. This function is expected to improve fuel consumption by suppressing overheating.

3. Automatic Rolling Scheduling System

3.1 Overview of Functions

The calculation flow of the automatic rolling scheduling system is shown in **Fig. 4**. In this system, information on both yard slabs and hot direct rolling slabs is necessary. Information on yard slabs includes the slab dimensions, rolling time and target heating temperature, and the rolling schedule consisting of only yard slabs. On the other hand, the latter includes not only the dimensions and other information concerning the hot direct rolling slabs, but also their scheduled arrival time from the continuous caster and the predicted temperature upon arrival.

Using this information, first, the system adds the

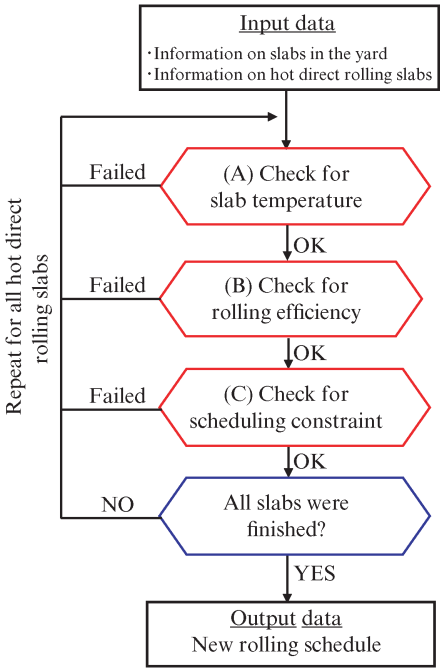


Fig. 4 Calculation flow of proposed system

hot direct rolling slab expected to arrive earliest to the front of the yard slab schedule, and makes the following three checks:

(A) Check for slab temperature

To avoid delays in the rolling of yard slabs due to waiting to heat up hot direct rolling slabs, the system checks to determine whether the time when the hot direct rolling slab reaches the target heating temperature is earlier than the extraction time of the yard slab immediately after the hot direct rolling slab insertion time or not. The time when the hot direct rolling slab reaches the target temperature is estimated using the following thermal conduction equation:

$$\rho c \frac{\partial \theta(x,t)}{\partial t} = \lambda \frac{\partial^2 \theta(x,t)}{\partial x^2} \quad \text{..........................} \ (1)$$

where, θ $(x,\ t)$ indicates the thickness-direction temperature distribution at time t. The initial value is given by the predicted arrival temperature from the continuous caster. ρ is density, c is specific heat and δ is thermal conductivity.

(B) Check for rolling efficiency

Here, the system judges whether the rolling time of the hot direct rolling slab makes it possible to complete rolling during the time interval before extraction of the yard slab immediately following the insertion position. If rolling cannot be completed in this interval, rolling of the yard slab will be delayed due to congestion on the hot rolling process line.

(C) Check for scheduling constraint

The system confirms that the new rolling schedule after insertion of the hot direct rolling slab satisfies the rolling scheduling constraint. As the parsing method is used, the details are described below.

If the hot direct rolling slab passes all of these checks, its insertion position is confirmed. Following this, the arriving hot direct rolling slab is checked. If the slab fails any of these checks, the system searches for a position that satisfies the checks, while shifting the insertion position of that slab to positions later in the yard slab schedule. These calculations are performed for all hot direct rolling slabs in order to determine their insertion positions, and the rolling schedule is output. Hot direct rolling slabs for which no acceptable insertion position can be found in this series of judgments are transferred to the slab yard.

3.2 Parsing Method

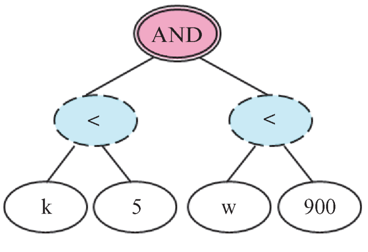
Although rolling constraints are complex conditions that span a diverse range of items such as material quality, dimensions and other parameters, the system must be implemented in a form that allows easy maintenance to allow empirical adjustments. Furthermore, in order to calculate the most recent rolling schedule at all times based on the constantly-changing conditions of the continuous casting equipment and the slab yard, it is also necessary to execute checks for constraints, always using the most recent constraints. To meet these requirements, the parsing method was introduced in this study.

Parsing analysis is a technology in which a computer recognizes input sentences (strings of symbols) described by predefined operators[3]. Parsing is generally used in compilers that recognize the source code described in a programming language, and in machine translation systems where a computer automatically translates text written in a certain natural language. However, in this study, we used the parsing method to recognize and describe rolling constraints.

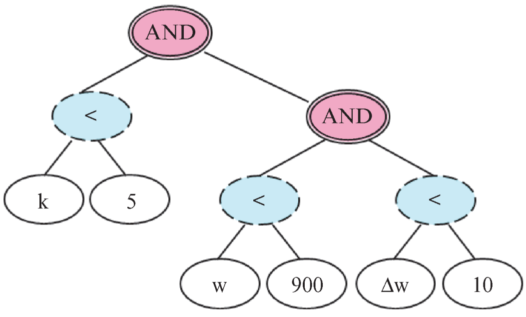
First, the expressions necessary to describe rolling constraints, such as “upper limit k of the number of continuous slabs of the same width,” “finishing width w,” “difference from the width of the previous slab Δw” etc. are defined as operators. Symbols such as “=”, “ < ” and “ > ” are used as relational operators, and “AND” and “OR” are used as logical operators. This makes it possible to express diverse rolling constraints by operator equations, for example, as shown below, by using only these operators and arbitrary numerical values.

$$k < 5 \quad \text{AND} \quad w < 900 \text{..........................} \ (2)$$

Next, a parse tree structure like that shown in **Fig. 5**



(a) Equation (2)



(b) Equation (3)

Fig. 5 Tree structures in the parsing method: upper is based on equation (2) , lower is based on (3)

(a) is constructed in this system. Parse tree structures are constructed by identifying the logical operators in the given operator equation, parsing the operator equation into multiple expressions before and after the logical operator, and then parsing those expressions into operators and numerical values at the point of their relational operators. This method of defining operator equations and constructing a parse tree is carried out before rolling based on the empirically determined rolling constraints.

When the automatic rolling scheduling system is launched, it judges whether the tentative rolling schedule which includes hot direct rolling slabs satisfies the rolling constraints by using this type of parse tree structure during the check for rolling constraints. At this time, judgment begins from the terminal nodes (leaf nodes) of the tree, and all the branches are checked while searching upward through the tree structure. Even where complex rolling constraints must be considered, real-time judgment is possible by this method if the rolling constraints are described by operator equations.

If it becomes necessary to modify the rolling constraints based on empirical knowledge, Eq. (2) is changed, for example, to Eq. (3), and the tree structure is also reconstructed as shown in Fig. 5 (b).

$$k < 5 \quad \text{AND} \ (w < 900 \quad \text{AND} \quad \Delta w < 10) \quad \ldots (3)$$

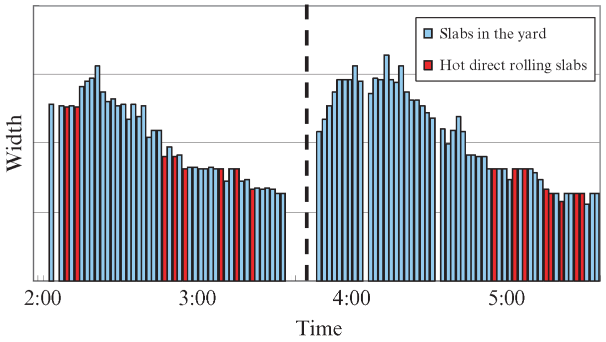
At this time, the user only revises the operator equation information stored in the computer, and it is not necessary to modify the program of the system itself. In other words, simply by editing the operator equations, the system can always recognize the most recent rolling constraints, and reflect those constraints in the rolling schedule.

4. Application Example

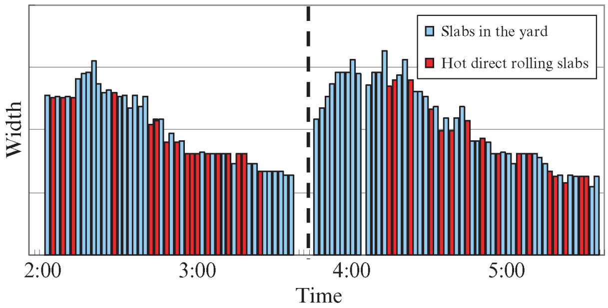
This chapter describes the results of a simulation and application to an actual production line, which were carried out to verify the effectiveness of the automatic rolling scheduling system.

4.1 Results of Simulation

The automatic rolling scheduling system was implemented on the process computer of the standby system at 3HOT. A rolling simulation was planned based on the same slab information as in the process computer of the active system, and was compared with the schedule of the actual rolling line planned manually by the operator. The results are shown in **Fig. 6**. The upper row shows the rolling schedule prepared by the operator using the active system, and the lower row shows the schedule prepared by the proposed system. The abscissa shows time, and the ordinate shows the product width.



(a) Manual

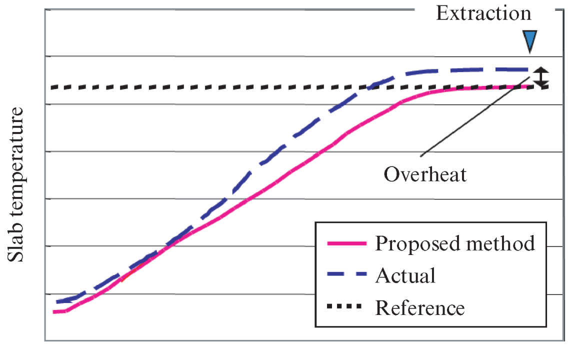


(b) Using proposed method

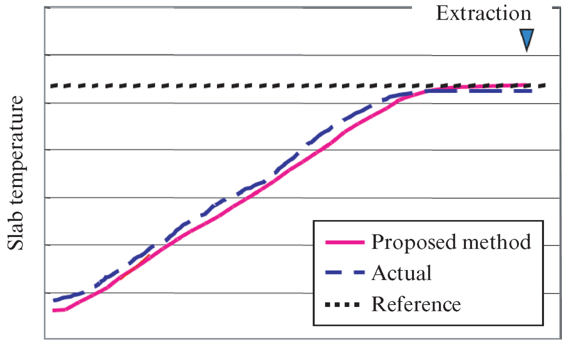
Fig. 6 Comparison of schedules: upper is scheduled manually, lower is scheduled by proposed method

From Fig. 6, it can be understood that the automatic rolling scheduling system plans receiving of a larger number of hot direct rolling slabs than the operator, indicating that is it possible to reduce the radiant heat loss due to missed rolling opportunities for hot direct rolling slabs. Since this system also plans the future rolling schedule in advance, which contributes to suppression of overheating due to sudden unplanned insertion of hot direct rolling slabs, a fuel cost reduction effect can be expected. These results demonstrated that the rolling schedules provided by this system satisfy rolling constraints. In Fig. 6, the broken lines indicate the timing of a finishing work roll change. From this figure, it can be confirmed that the product width gradually becomes narrower in both rolling schedules before and after the work roll change, that is, during rolling with the same rolls, thereby satisfying the rolling constraint described in section 2.2.

Next, to verify the overheating suppression effect of the system in greater detail, the slab heating pattern in the reheating furnace was calculated. This simulation was performed for yard slabs immediately after and immediately before insertion of the hot direct rolling slab, and the result was compared with the actual heating pattern. The results are shown in **Fig. 7**. The upper



(a) Following slab



(b) Previous slab

Fig. 7 Comparison of slab temperature: upper is next of the added slab, lower is previous of the added slab

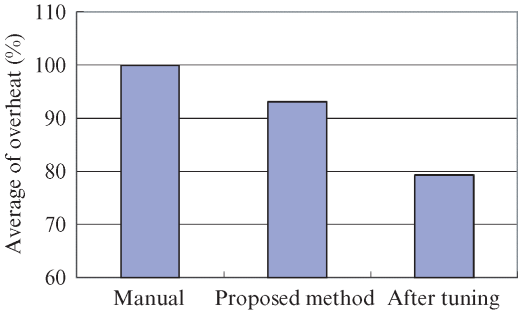


Fig. 8 Comparison of the average overheat

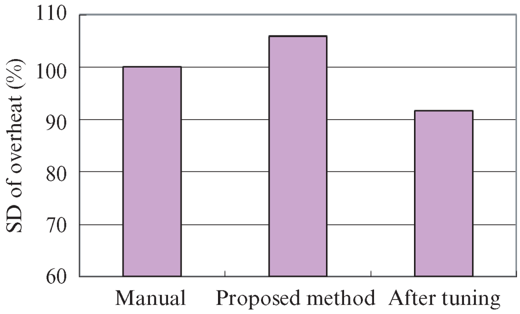


Fig. 9 Comparison of the standard deviation of overheat

and lower rows show the patterns of the yard slabs immediately after and immediately before the hot direct rolling slab, respectively. The abscissa shows the heating time, and the ordinate shows the slab temperature.

From Fig. 7 (a), it can be observed that the slab temperature reaches the target heating temperature earlier when the proposed system is not used. This is because the reheating furnace residence time of the following slab is extended due to the sudden insertion of the hot direct rolling slab after heating to the target temperature is already been completed, and this results in overheating corresponding the delay in the reheating furnace slab extraction time. On the other hand, in the heating pattern using the proposed system, it is possible to adjust heating corresponding to this extended heating time because insertion of the hot direct rolling slab is planned in advance, and as a result, overheating is slight. On the other hand, as shown in Fig 7 (b), overheating of the previous slab is minimal, regardless of whether the proposed system is used or not.

Summarizing these results, this system is considered to be effective for suppressing overheating of slabs when the rolling schedule is delayed due to sudden insertion of hot direct rolling slabs, and it can contribute to reducing fuel costs by optimization of the furnace temperature settings considering extensions of the reheating furnace heating time.

4.2 Results of Evaluation in Actual Production Line

Finally, the results of applying the automatic rolling scheduling system to actual operation at 3HOT will be described.

Trial operation was carried out by incorporating this function in the process computer of the active system at 3HOT, and the system was put into on-line operation approximately 1 month later, after adjustment of the rolling constraint operation equations, computational parameters, etc. To assess the effects of the system, the deviation between the actual temperatures when slabs were extracted from the reheating furnace and the target heating temperature was defined as overheat, and the average values and standard deviations before and after online implementation of the function were compared. The average value and standard deviation of overheat are shown in **Fig. 8** and **Fig. 9**, respectively. In both figures, the results are shown as percentages, where overheat before the system went online is defined as 100%.

From Fig. 8, an overheat suppression effect of about 20% by this system can be confirmed. It can also be understood that parameter tuning was indispensable for maximizing this effect. Since the number of hot direct rolling slabs that fail the constraint check will increase if an excessive number of constraint operator equations is added, the constraints must be adjusted carefully in order to reduce the number of slabs inserted. Looking at Fig. 9, the standard deviation of overheat could be reduced by roughly 10%. Conventionally, decisions concerning the rolling schedule depended on the operator's judgment, and overheat tended to increase due to individual differences in the abilities of operators. In this study, this problem was substantially reduced by automating the decision process, contributing to minimization of fuel costs.

5. Conclusion

In conventional operation at 3HOT, decisions on rolling schedules including hot direct rolling slabs depended on the judgment of operators, resulting in missed opportunities for hot direct rolling and overheating due to sudden insertion of hot direct rolling slabs in the rolling schedule. Therefore, an automatic rolling scheduling system was developed to reduce these problems, and online operation was started. Although judgments of rolling constraints had conventionally been made by operators, automation of the judgment process was achieved by introduction of the parsing method.

As the results of a simulation and application of the proposed system to the actual hot rolling line, a fuel unit consumption improvement effect was confirmed, as overheating in the reheating furnace was reduced by approximately 20%. This system is currently in standard operation at 3HOT at East Japan Works (Chiba).

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This paper reproduces the paper listed as reference 4), which was written by the same lead author, with revisions of some expressions.