1. Introduction

In a hot rolling plant, various technologies are applied to achieve higher quality, higher productivity, and lower costs over many years. In mill set-up to meet the strip specifications such as thickness, crown, and etc., a lot of techniques are studied especially for automation and improvement of the rolling accuracy. These techniques are based on rolling theory, i.e., the physical approach to clarify the rolling mechanism. Though these approaches are quite important and effective for basically seeking better operation, the phenomena of the real world is complicated and is sometimes difficult to represent as a physical formulation. For these reasons, several factors remain which are difficult to express as a quantitative model, which often lead to undesirable operation. Of these, a major factor in the mill set-up system, “rolling balance” is necessary for stable operation.

When the rolling balance is mismatched, deformation of the sheet is occurs or scale defects are generated due to damage to the rolls. Miss rolling also happens according to the imbalance of the rolling condition. In order to avoid these undesirable situations, skilled operators manually modify the set-up calculated by the computer set-up system, based on their expertise. Our motivation of this study is to realize perfect automatic operation by modeling the operator’s manual intervention to the set-up system and constructing a new set-up system.

As a technique to computerize such expertise of skilled operators, the Expert System approach has been applied to various processes. For a mill set-up system, the expert system was proposed for informing the operator of the rolling balance as the mill set-up guidance. Though this approach is effective in the point that various fragmental “know-how” can be handled and utilized in the system, it must be pointed out that it is difficult for the system to correspond to some change such as facility change, as generalization of the reasoning results is difficult and complicated.

In this paper, a new mill set-up method is proposed, which integrates a process model and operator expertise. We represent the operator’s expertise in terms of the constraints on roll gap differences between neighboring stands to avoid excessive loads that may lead to unstable rolling. The problem is formulated as that of minimizing deviation between the know-how-based roll gap difference pattern and the actual one. In order to realize such mill set-up considering the roll gap differences in actual plant, in which the computational time is strictly restricted, an estimation method of the Jacobian matrix for solving the problem is proposed. The efficiency and validity of the method are discussed, based on the linear system theory and case study results of simulations. The method is found to have valid computational properties for applying to the actual set-up of the process. Applying the system to the actual plant, it was found that operator intervention has been markedly reduced compared with the conventional set-up method. Furthermore the stability of operation, i.e., a decrease in the frequency of defective rolls, is also achieved.

KEY WORDS: mill-set-up; hot strip mill; roll gap differences; automation.

2. Mill-set-up for Hot Finishing Mill

Figure 1 shows the hot strip mill in the iron and steel making industry. The steel strip, preheated and rolled at a rougher mill, is rolled through this finishing plant and coiled as products which are about 1 mm thick. The plant is
composed of 7 tandem stands of finishing mill. Each product has specifications on strip thickness, strength, and surface shape. In order to meet such specifications and to maintain stable rolling, each set-up condition, i.e., roll gap and speed, should be appropriately set-up before starting rolling. A flow chart of the mill-setup calculation is shown in Fig. 2.

Traditionally, this setup is done based on the “power-curve method,” in which the power that each stand can consume in rolling is assigned, based on a predetermined proportion. Then the draft schedule which specifies the thickness of a strip at the exit of each stand, i.e., “delivery thickness,” is generated. The load of each stand is predicted using a process model, then the roll gap and speed are calculated. The traditional setup method cannot use knowledge about preventing deformations of operation, e.g., scale defects caused by the rough surface of the roll through production, or some other trouble. The operators are used to manually modify the computer setup based on their expertise to avoid these problems.

3. New Mill-setup System

3.1. Operator Expertise

Through interviews with operators and data analysis, we found that they modify the setup using a conventional computer system based on roll gap differences between neighboring rolling stands. They acquire knowledge about the pattern of roll gap differences through the experience of running the plant.

The main objectives of the modification knowledge are as follows:

- To prevent the scale defects caused by rough surface rolls that result from excessive loads at the upper stands.
- To prevent the deformation of the strip shape that originates in excessive loads at the lower stands.

The roll gap differences are expected to quantitatively represent operators’ knowledge about rolling balance. An example of roll gap differences is shown in Fig. 3. As seen from Fig. 3, the roll gap difference between the first and second stands is as large as 7 mm. In contrast, the difference between the sixth and seventh stand is negative. This reflects the expertise that the reduction of thickness should be mainly done at the beginning stands and the rolling load at the last stand should be minimum, from the view point of sheet shape. Our basic concept of a new set-up system is to calculate the set-up to meet the operator expertise about rolling balance, expressed as the roll gap difference pattern based on the rolling process model.
3.2. Integration of a Process Model and Expertise Based on the Roll Gap Difference Pattern

The problem is to calculate a set-up that realizes the above roll gap difference pattern subject to the constraints on desirable thickness of the strip. This problem can be formulated as the minimization of:

\[
E = (\mathbf{ds}^* - \mathbf{ds})^T (\mathbf{ds}^* - \mathbf{ds}) \tag{1}
\]

where \( \mathbf{ds}^* \) is a target vector of the roll gap differences representing the operators' expertise and \( \mathbf{ds} \) is a vector of calculated roll gap differences based on the mathematical set-up model represented as \( \begin{bmatrix} s_1 - s_2, s_2 - s_3, \cdots, s_6 - s_7 \end{bmatrix}^T \). Where \( s_i \) denotes the roll gap of the \( i \)-th stand.

According to the set-up model, \( \mathbf{ds} \) is a function of \( \mathbf{h} \), which delivers a thickness quantity function expressed as \( [h_1, h_2, \cdots, h_7]^T \), where \( h_i \) denotes the delivery thickness of the \( i \)-th stand. \( \mathbf{ds} \) is approximated by a Taylor expansion around the thickness \( \mathbf{h}_0 \):

\[
\mathbf{ds} = \mathbf{ds}(\mathbf{h}_0) + J\Delta \mathbf{h} \tag{2}
\]

where \( \mathbf{ds}(\mathbf{h}_0) \) is a vector of the roll gap differences at the thickness \( \mathbf{h}_0 \), \( J = \frac{\partial \mathbf{ds}}{\partial \mathbf{h}} \) is a Jacobian matrix, and \( \Delta \mathbf{h} \) is a variation vector of the delivery thickness of the stands.

\( E \) in Eq. (1) is minimized when \( \frac{\partial E}{\partial \Delta \mathbf{h}} = 0 \) is satisfied. Because the Jacobian matrix is regular (as shown below), and from Eq. (2), we can derive:

\[
\Delta \mathbf{h} = J^{-1}(\mathbf{ds}^* - \mathbf{ds}(\mathbf{h}_0)) = J^{-1}\Delta \mathbf{ds} \tag{3}
\]

where \( \Delta \mathbf{ds} \) is an error vector between the reference pattern and the calculated pattern of roll gap differences. From Eq. (3), because \( \Delta \mathbf{h} = \mathbf{h}_{n+1} - \mathbf{h}_n \), an iterative update formula to minimize the above objective function \( E \) in Eq. (1) is obtained as follows:

\[
\mathbf{h}_{n+1} = \mathbf{h}_n + J^{-1}\Delta \mathbf{ds}_n \tag{4}
\]

where \( n \) denotes the \( n \)-th repetition.

In order to apply this method to the actual plant, computational time and numerical stability are quite important. We describe how we deal with these issues. \( J \) should be appropriately estimated through the calculation. According to the mathematical model of the process, the relationship between the delivery thickness and roll gap is formulated for each stand as:

\[
h_i = s_i + \frac{p_i}{M_i} \quad (i = 1, 2, \ldots, 7) \tag{5}
\]

where \( p_i \) denotes the rolling load of the \( i \)-th stand, and \( M_i \) denotes a mill modulus of the \( i \)-th stand which is predefined before setup calculation. From this equation, we have the following relationships:

\[
\frac{\partial s_i}{\partial h_i} = \left(1 - \frac{1}{M_i} \frac{\partial p_i}{\partial h_i} \right) \\
\frac{\partial s_i}{\partial h_{i-1}} = \frac{1}{M_i} \frac{\partial p_i}{\partial h_{i-1}} \quad (i = 2, 3, \ldots, 7) \tag{6}
\]

\[
\frac{\partial s_i}{\partial h_i} = 0 \quad \text{if} \quad j \neq i, j \neq i - 1 \tag{7}
\]

From Eq. (3) and Eqs. (6)–(8), \( J \) is given by

\[
J = \begin{bmatrix}
(b_i + a_i - b_2 & b_2 & \cdots & b_n & b_2 & \cdots & b_n \\
- a_2 & b_2 + a_3 & \cdots & b_n & - a_3 & \cdots & b_n \\
0 & - a_3 & \cdots & b_n & - a_4 & \cdots & b_n \\
0 & 0 & \cdots & - a_4 & b_2 + a_5 & \cdots & b_n \\
0 & 0 & \cdots & 0 & - a_5 & b_5 + a_6 & - b_5 \\
0 & 0 & \cdots & 0 & 0 & - a_5 & \cdots & b_5 + a_6 \\
\end{bmatrix}
\tag{9}
\]

where,

\[
a_i = \frac{1}{M_i} \frac{\partial p_i}{\partial h_i} \tag{10}
\]

\[
b_i = 1 - \frac{1}{M_i} \frac{\partial p_i}{\partial h_i} \tag{11}
\]

From the characteristics of rolling, i.e. the physical relationship between rolling loads and delivery strip thickness, \( a_i > 0, b_i > 0 \) is guaranteed.

The determinant of \( J \) in Eq. (9) is given by

\[
\det J = b_1 b_2 b_3 b_4 b_5 b_6 + b_2 b_3 b_4 b_5 a_1 + b_2 b_3 b_5 a_2 + b_2 b_3 b_4 a_1 a_2 + b_2 b_4 a_1 a_2 a_3 + b_2 b_3 a_1 a_2 a_3 a_4 + a_1 a_2 a_3 a_4 a_5 \tag{12}
\]

Because \( a_i > 0, b_i > 0, \det J \) is always positive. This guarantees the regularity of \( J \). Thus, \( J^{-1} \) always exists and numerical instability is avoided. It is also noted that the degree of freedom of the delivery thickness is 6 because the rougher thickness and the targeted thickness are measured and given constants. So the dimension of delivery thickness to decide through the set-up calculation is equal to that of the roll gap difference pattern. From this regularity, it can also be said that the operators' knowledge about the roll gap difference is valid in the sense of system theory.

In addition, partial differential coefficients, i.e. \( \frac{\partial p_i}{\partial h_{i-1}} \) and \( \frac{\partial p_i}{\partial h_i} \), are estimated numerically from the load models as described below. The load models are generally written as:

\[
P_i = F(h_{i-1}, h, \sigma_{i-1}, \sigma_i, R_i, w_i, \theta_i, \ldots) \tag{13}
\]

where \( i \) denotes the number of stands, \( F(\ ) \) denotes the model function that predicts the loads, \( h_{i-1} \) denotes the \( i \)-th input thickness, \( \sigma_{i-1} \) denotes the \( i-1 \)-th delivery thickness of the stand, \( \sigma_i \) denotes the \( i \)-th output tension force of the stand, \( R_i \) denotes the \( i \)-th roll diameter, \( w_i \) denotes the \( i \)-th strip width, and \( \theta_i \) denotes the \( i \)-th strip temperature. The partial derivatives can be calculated numerically as follows:

\[
\frac{\partial P_i}{\partial h_{i-1}} = \frac{-F(h_{i-1}, h, \sigma_{i-1}, \sigma_i, R_i, w_i, \theta_i, \ldots)}{\partial h_{i-1}} \tag{14}
\]

\[
\frac{\partial P_i}{\partial h_i} = \frac{-F(h_{i-1}, h, \sigma_{i-1}, \sigma_i, R_i, w_i, \theta_i, \ldots)}{\partial h_i} \tag{15}
\]
where $\Delta h_i$ is the deviation of the $i$-th delivery thickness of the stand, $\Delta h_{i-1}$ is the deviation of the $i-1$th delivery thickness.

From the iterative update calculation by using Eq. (4) based on the estimation through Eqs. (6)–(11), (14) and (15), the targeted roll gap difference pattern is expected to be realized through the set-up calculation.

3.3. Estimation Robustness of Jacobian Matrix

In order to confirm the basic performance of proposed methods, a numerical analysis of Jacobian matrix is done by using nominal setup data. It is assumed that the operational range of the total setup system remains within linear characteristics and the characteristics do not change over time. Specifically, Jacobian matrix $J^*$, which is calculated by total setup model using draft schedule and screw down results, is assumed to be a true value and not to vary through the iterations. From Eq. (9), $J^*$ is calculated for satisfying the constraints of roll gap differences. In selected nominal data, these matrices, i.e. $J^*$ and $J^*$, are generally different in actual value. In such a condition, how the error of Eq. (1) is decreased through the iterations will be discussed below.

The error is represented based on the above assumption as:

$$\varepsilon_{n+1} = \varepsilon_n - J^* \Delta h_n$$

where $\varepsilon_n$ denotes an error vector between the reference pattern and the calculated pattern of roll gap differences in the $n$-th iteration. The modifying manipulation of the delivery thickness vector is calculated from measured error vector as:

$$\Delta h_n = J^*^{-1} \varepsilon_n$$

From Eq. (16) and Eq. (17), the error transition is represented as follows:

$$\varepsilon_{n+1} = A \varepsilon_n$$

$$A = I - J^* J^*^{-1}$$

By applying typical data, eigen values of $A$ in Eq. (19) are calculated and the results are shown in Fig. 4. From the results, the system as expressed in Eq. (18) is stable, as the absolute eigen values of $A$ are within 1. Every value is within a circle with the radius of 0.083 as shown in Fig. 4. Furthermore, the matrix $A$ can be handled approximately as a "nilpotent matrix", because the eigen values are quite small. In such an assumption, it is well known that the iterations for seeking the error vector to be completely 0, are less than 6. From the analysis, the method is considered to be valid and robust under the empirically measured differences of the Jacobian matrix. More detailed results of practical computed case studies are shown in the next section.

4. Case Study Results of Proposed Methods

4.1. System Configuration

The block diagram of the setup system described above is shown in Fig. 5. The initial delivery thickness of each stand is defined from the conventional setup system, i.e. “power-curve method.” The patterns of roll gap differences, categorized by steel type, targeted thickness, and target width, are stored as a reference table.

4.2. Case Study Results

The set-up computation should be carried out on-line in a short period of time, i.e. after the strip comes out from the rougher mill and before it goes into the finishing mill. In order to check whether our method satisfies the constraint on computational time and to evaluate the convergence characteristics, off-line simulations using process data are carried out.

In the case when 1.63 mm is required as the specification of targeted thickness, a targeted pattern of roll gap differences is shown as well as the initial pattern by conventional methods in Fig. 6. After several iterations of our methods, the targeted pattern is achieved. The results are shown in Figs. 7–9. Corresponding to each stand, the delivery thickness is shown in Fig. 7, the roll gap in Fig. 8, and the rolling force in Fig. 9. From these results, the setup is shifted to have more rolling loads in the lower stands according to the optimization calculation. In this case, through this calculation, the scale defects are expected to be prevented by operator’s expertise represented as a roll gap difference pattern that the more rolling loads are appropriate in the
lower stands.

Another example is simulated in the case when 1.66 mm as target thickness is required in order to evaluate the convergence performance of the system. The target pattern is shown in Fig. 10. The error transition between the target pattern and calculated pattern corresponding to each neighboring stand is shown in Fig. 11. Figure 12 shows two evaluation values of error transition through the iterations. One is the square sum of errors in each neighboring stand, i.e. objective function value in Eq. (1), and the other is the
maximum value among each value of the error vector at each iteration, which is shown in Fig. 11. It should be noted that the first iteration is equivalent to the conventional methods. As seen from these results, they are converged to the desirable roll gap differences at the 4th repetition through the optimization.

About 4000 cases are simulated, in order to evaluate the convergence performance corresponding to many and more varied specifications, i.e. target thickness, temperature, constituent, and so on. The result is shown in Fig. 13. The average value of maximum error between the target pattern and computed pattern of roll gap differences, i.e. the average value of depicted value as "Maximum error" in Fig. 12, is shown in Fig. 13 over the number of repetition. It is noted that the maximum error is decreased to 0.05 mm by the third repetition and under 0.01 mm by the fourth repetition. This result convinced us that our method satisfies the required constraint on computational time. The method has valid computational properties for application to the actual set-up of the process.

Next, simulations are done under the same rolling condition except FDT, i.e. the specification on the temperature at the exit of the finishing mill. Results are shown in Fig. 14. Our new method reduces the variation of the rolling load in comparison with the conventional method. In the conventional set-up method, the draft schedule is fixed and the rolling load is varied according to the variation of specified temperature. Conversely, in our method, the variation of the temperature is reflected to both the draft schedule and rolling loads. As the variation of the rolling loads leads to the deformation of strip shape empirically, this robust property of our method could contribute to the improvement of the strip shape and the achievement of stable operation.

5. Experimental Results in the Actual Plant

In order to apply the system to the actual plant, variation of the thickness in the exit of the rougher mill should also be handled appropriately. Though the setup system based on the roll gap difference pattern has proper characteristics under the variation of temperature as described above, the balance of rolling load is shifted according to the variation of the thickness in the exit of rougher mill, i.e. the inlet thickness to the finishing mill. Setup calculation examples are shown in Figs. 15–17, in which the rougher thickness is changed to 34.5 mm from 29.5 mm. In this example, the
target pattern of roll gap differences is prepared for the specification of 29.5 mm in rougher thickness. The draft schedule is shown in Fig. 15, the roll gap in Fig. 16, and the rolling force in Fig. 17, respectively, after the optimization calculation. From these results, it can be seen that required rolling load modification caused by the rougher thickness change is assigned, especially at the F1 stand. This behavior is not desirable in the sense of operation balance.

In order to prevent the system from such unbalance operation, two manners can be considered. First, the target pattern can be prepared for each rougher thickness. Although, the number of target patterns is increased enormously and the table representation is complicated. As this leads to a low maintainability, another method is developed. The method is the same as the operation manner of skilled operators. It is realized as the target pattern modification from the variation of rougher thickness as follows:

\[
ds^* = ds^0 + \alpha (Hr - Hr^0) + \beta \ ...
\]

(20)

where \(ds^*\) denotes the modified target pattern, \(ds^0\) denotes the prepared target pattern corresponding to the predetermined rougher thickness \(Hr^0\), \(Hr\) is the measured rougher thickness, and \(\alpha \) and \(\beta \) are parameter vectors. These parameters are decided by the operator’s expertise about this operation, and the relationship in Eq. (3) considering the power curve redistribution. Simulation results of this method are shown in Figs. 18-20. The draft schedule is shown in Fig. 18, the roll gap in Fig. 19, and the rolling force in Fig. 20, respectively, after the optimization calculation. From these results, the concentration of rolling loads at F1 stand is distributed in the upper stands.

After these implementations, we did experiments by the proposed system at the actual plant over several months. The results are shown in Fig. 21. In the results, the frequency of operator’s intervention to the computational setup is decreased by 80% compared with the conventional set-up.
method through the adjustment of the roll gap difference pattern table. Furthermore the stability of operation, *i.e.* a decrease in the frequency of defective rolls, is achieved. As another merit, the complicated and fidgety operation entailed by manual intervention is reduced markedly as a result of new computational setup. The main reason why manual intervention still remains, is thought to be the restricted accuracy of process models, *i.e.* the load model and temperature model. In order to extend the system for more automated operation, improvement of the process models is necessary as well as improvement of the system.

6. Conclusion

We described a new mill-setup system for hot strip finishing mill based on operator’s expertise expressed as the pattern of roll gap differences. It is shown that the new setup system has good performance in terms of computational time and accuracy through the simulation case studies. The experimental results also show that the operator’s intervention is drastically decreased applying this architecture. This contributes the improvement of automatic operation of the plant. Furthermore the stability of operation, *i.e.* a decrease in the frequency of defective rolls, is achieved.

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