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Development of Intelligent Multivariable Optimal Control for No. 4 Skin Pass Mill in Fukuyama District, West Japan Works

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Abstract:

To enhance the quality of hot coils, JFE Steel Corp., constructed No. 4 skin pass mill (4SKP) in Fukuyama district, West Japan Works in 2015. Together with the construction of the mill, we developed intelligent multivariable optimal control of the flatness, elongation and walking of the strip during high speed rolling. The characteristic of this control is to utilize the operational data of the hot strip mill and control range of the elongation of the strip by improving the control performance. Application of this automatic control technology has improved the quality of the products at the mill speed of 800 m/min, which is the world fastest in hot skin pass rolling. As a result, we have achieved high productivity in 4SKP.

1. Introduction

JFE Steel constructed and began commercial operation of a hot skin pass mill (hereinafter, 4SKP) in the Fukuyama District of its West Japan Works in 2015 in order to respond to customers' requests for further improvement in the product quality of hot-rolled mill scale steel. Together with the construction of the new 4SKP, state-of-the-art control technologies for various controlled variables, i.e., the operational indexes of flatness, elongation, thickness and lateral walking, were developed based on the concept of the "Cyber Physical System"[1)] by a fusion of optimization and simulation techniques utilizing IT technology and various types of sensor data. This technology was named "Intelligent Multivariable Control," as it has features that do not exist in conventional technologies, particularly improved controllability by utilization of the operational data of the hot-rolling process, which is preceding process, and the elongation control range. Application of this technology enables highly accurate automatic control at the world's highest line speed of 800 m/min in a hot skin pass mill, thereby contributing to both improvement of product quality and improvement of productivity. This paper presents an outline of the skin pass mill, and then introduces the developed technology and describes its validation by examples of numerical simulation and actual mill tests.

2. Outline of Skin Pass Mill

2.1 Role of Skin Pass Rolling and 4SKP

The skin pass mill is an important rolling equipment for building quality into products, and has the role of improving the shape (flatness) of steel sheet products and the role of adjusting the mechanical properties of the material, namely, eliminating yield point elongation and adjusting the material hardness. These roles are realized by adjustment of the work roll bending force, leveling (one-side screwdown position), rolling force (two-side screwdown position), and strip tension before and after the rolling mill.

As shown in **Fig. 1**, 4SKP consists of work rolls and backup rolls, which are arranged vertically, and is an

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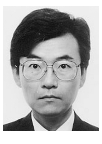

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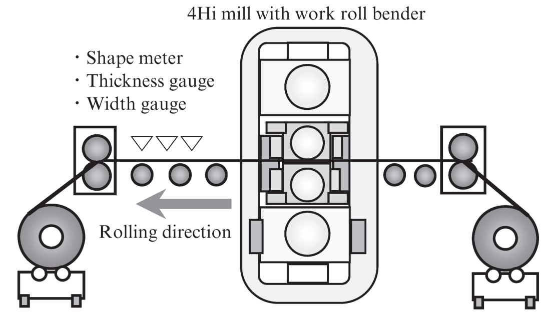

Fig. 1 Skin Pass Mill

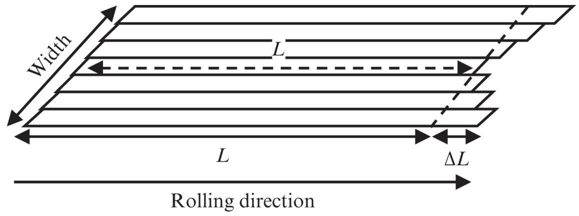

Fig. 2 Flatness of the strip

original type of 4Hi skin pass mill with an increase bender and a decrease bender. The mill is equipped with a shape meter, thickness gauge and width gauge, which are used in quality control and control of the various controlled variables (flatness, elongation, thickness and lateral walking).

2.2 Operational Indexes

The operational indexes for steel strips are the relative difference in elongation, which expresses the flatness of a steel strip, and elongation, which is a determining factor for mechanical properties.

The relative difference in elongation expresses the nonuniformity of elongation in the rolling direction in the strip width direction. As shown in **Fig. 2**, "relative difference in elongation" is defined by the ratio ($\Delta L/L$) of the difference (ΔL) in the elongation at an arbitrary strip width position other than the center of width position and the elongation at the center of width position, when the elongation (L) in the rolling direction at the center of width position is assumed as a reference. The value obtained by multiplying this ratio by 10^5 ($\Delta L/L\times 10^5$) is generally used in quality control and flatness control as a unit called the I-unit. The typical forms of flatness defects are edge wave and body wave. In edge wave, the distribution of the relative difference in elongation in the strip wide direction takes a convex form, whereas in body wave, the distribution of the relative difference in elongation in the width direction is convex upward. As other flatness defects, the widthwise distribution of the relative difference in elongation displays a W shape or an M shape; these modes are termed composited elongation. Although it is possible to grasp all of these flatness modes by the distribution of the relative difference in elongation in the strip width direction, for a quantitative evaluation of the mode components that comprise flatness and their sizes, it is necessary to approximate the distribution of the relative difference in elongation in the width direction by a linear combination of orthonormal functions[2].

Elongation (e) is defined by Eq. (1), as shown below, by using the entry side velocity (V_1) and exit side velocity (V_2) of a steel strip, and is expressed as a % unit. The target value and control range of mechanical properties, the allowable range of variation within one coil and other values are specified from the viewpoint of the mechanical properties that should be achieved in each rolled material. In skin pass rolling, this is generally set in the range of approximately 0.5 % to 2.0 % in many cases.

$$e=\frac{V_2-V_1}{V_1}\times 100 \quad \text{(1)}$$

Another operational index is lateral walking, meaning the deviation between the strip being rolled and the mill center position. To prevent treading problems, it is necessary to minimize lateral walking.

3. Intelligent Multivariable Control

As mentioned in section 2.2, multiple controlled variables exist in a skin pass mill. The developed technique comprised three control functions for controlling these variables (① Calculation of the actuator settings based on a highly accurate flatness prediction model using information on the actual operational results of the hot-rolling process, ② Optimal feedback/feedforward control of flatness and elongation and ③ Optimal lateral walking control). Among these control functions, ① and ② achieve the necessary flatness and elongation. Of these functions, this paper introduces ② Feedback/feedforward control.

3.1 Conventional Techniques and Their Problems

The manipulated variables for controlling flatness are generally the amount of leveling and the work roll bender force, and the manipulated variables for controlling elongation are the rolling force and strip tension before/after of the rolling mill (entry side/exit side tension). The conventional flatness control technique[3] is feedback control based on actual flatness values. In this technique, flatness indexes comprising indexes (Λ_1 and Λ_3) expressing the symmetrical components of flatness and indexes (Λ_2 and Λ_4) expressing the asymmetrical components are calculated from the shape

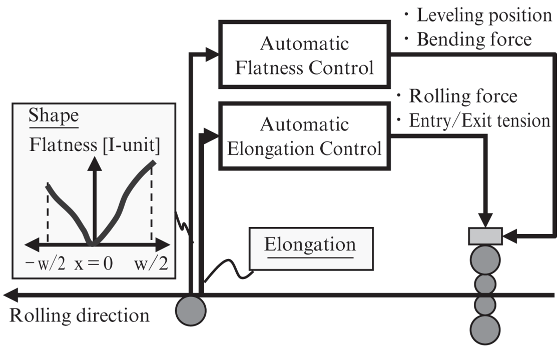

Fig. 3 System configuration of the conventional control

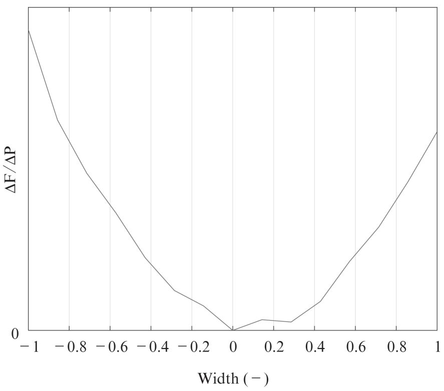

Fig. 4 Influence coefficient ($\Delta F/\Delta P$)

meter output in each control cycle (for N channels, corresponding to positions in the strip width direction), and the amount of leveling and the work roll bender force are set so that the flatness index achieves the target value, based on influence coefficients expressing the amount of change in the flatness indexes (Λ_1, Λ_2, Λ_3, Λ_4) relative to the amount of change in leveling and work roll bender force.

As conventional techniques for elongation control, feedback control[4] and dynamic setup control[5] are used. In these methods, the elongation calculated from the strip speed before and after the mill is controlled to a uniform target value over the full length of the strip by adjusting the rolling force. In feedback control, the rolling force is adjusted by PID, etc. so as to minimize the control error (deviation) between the actual value and the target value of elongation. Dynamic setup control is a technique in which the plasticity coefficient and entry side thickness of the material being rolled are estimated sequentially from the actual values of the initial rolling force, screwdown position and elongation, and the rolling force command value is corrected so as to achieve the target value of elongation in order to shorten the length of material with nonconforming elongation caused by error in the initial rolling force setting.

These conventional techniques[3–5], as shown in **Fig. 3**, are configured with individual controllers. With this configuration, the rolling force operation and tension operation by elongation control influence the condition of roll deflection, and that influence causes interference, as it influences flatness. As a problem of these techniques, this interference means there is a limit on the achievable flatness. As one example of interference, **Fig. 4** shows the actual value of the influence coefficient ($\Delta F/\Delta P$), which expresses the amount of change in flatness (ΔF) relative to the amount of change in the rolling force (ΔP). Here, the strip width position has been normalized in the range from −1 to +1. From this distribution of the influence coefficient in the strip width direction, when rolling force is increased, the relative difference in elongation at the edges becomes large and the mode changes to the edge wave.

3.2 Proposed Technique

The target value of elongation and its control range (range between the upper and lower limits), etc. are set for each rolled material. However, with some rolled materials, product quality can be secured if elongation satisfies the control range, without strictly conforming to the target value. Because the conventional methods attempted to control elongation to a certain target value, interference with flatness was a problem, but if the control range can be relaxed, it is thought that the rolling force and entry/exit strip tension, which are the actuators generally used in elongation control, can be set considering the influence on flatness, and as a result, interference with flatness can be minimized. Therefore, this paper proposes a control technique that minimizes interference between shape control and elongation control, and thereby improves flatness controllability, by utilizing the elongation control range.

The control object is a multiple input/multiple output (MIMO) system, in which the manipulated variables (inputs) are five variables, namely, the work roll bender force, leveling, rolling force, strip tension at the entry side of the mill and the strip tension at the exit side of the mill, and the controlled variables (outputs) are N+1 variables consisting of flatness (N channels corresponding to strip width positions) and elongation. Although research and development on control techniques for MIMO systems has been carried out previously, the proposed technique was developed referring to model based predictive control[6], which is an optimal control technique under constraint conditions.

First, as shown in **Fig. 5**, the control object is modeled by a transfer function matrix having primary delay transfer functions as its elements. Here, the variables T_i (i=1, 2,... 5) in the figure are time constants, $g_{j,i}$ (i=1, 2,... 5, j = 1, 2,... N) are gain with respect to flatness and h_i (i = 1, 2,... 5) are gain with respect to elongation.

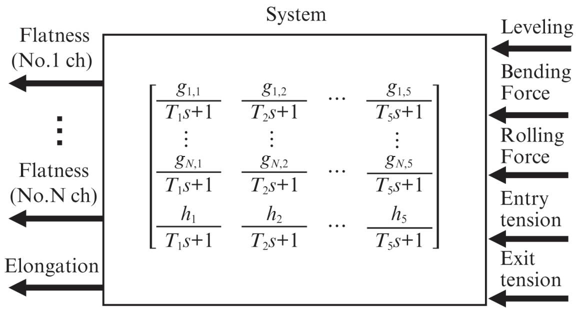

Fig. 5 Transfer function matrix of the system

The variables i ($1 \le i \le 5$) indicate leveling, bender force, rolling force, entry tension and exit tension in that order, and s is a Laplacian operator. Since an adequately long control cycle for this control object was adopted considering the dynamic characteristics of the control object, if constant values are assigned to the control inputs within the control cycle, the system output at the end of the control cycle can be regarded as representing the values of the control inputs multiplied by the above-mentioned gains. Thus, in this case, it is possible to predict flatness and elongation by using the control inputs and gains. This was used as the flatness prediction model and elongation prediction model in the following calculations.

In the proposed technique, the control inputs are obtained by solving an optimization problem which minimizes the evaluation function f (Eq. (2)), comprising the evaluation value of flatness and the evaluation value of elongation under the constraints described below, for each control cycle.

$$f = \sum_{i=1}^{N} q(i)\big(r(i) - y(i)\big)^2 + q(N+1)\big(r(N+1) - y(N+1)\big)^2 \quad \cdots\cdots\cdots\cdots\cdots (2)$$

where, $r(i)$, i=1, 2,... N is the target flatness corresponding to the strip width position, r $(N+1)$ is the target elongation, $y(i)$, i=1, 2,... N is the predicted value of flatness corresponding to the strip width position and y $(N+1)$ is the predicted value of elongation. In addition, $q(i)$, i=1, 2,... N are weights for flatness corresponding to the width position, and q $(N+1)$ is a weight for elongation. Both of these weight values are adjustable parameters that are set to a value of 0 or larger.

Deviation of operational constraints is avoided by setting the following constraints for this optimization problem.

· Operational range of actuators (upper/lower limits)
· Operational speed range of actuators (upper/lower limits)
· Upper/lower limits of strip thickness tolerance
· Control range of elongation (upper/lower limits)
· Flatness prediction model
· Elongation prediction model

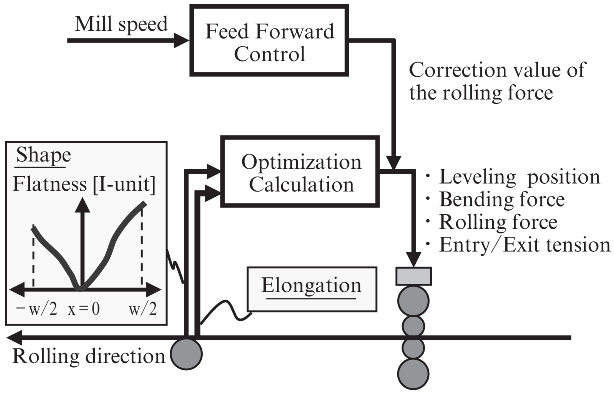

Fig. 6 Proposed control system

Finally, feedback control in which flatness and elongation are controlled simultaneously under the various operational constraints is realized by giving the results of this optimization calculation to the rolling mill control system as commands. It may be noted that the weights in the evaluation functions in this control technique have the role of eliminating the influence of differences between the unit systems of the two controlled variables (i.e., flatness and elongation), and determining the priority for control of flatness and elongation. It is possible to set the method of elongation control by setting $q(N+1)$ to a large value for rolled materials that require control of elongation to a certain target value, and setting $q(N+1)$ to a small value of 0 or larger when the target value of elongation is not critical and it is only necessary to satisfy the control range.

In actual operation, the mill speed undergoes a transition in the order of the initial strip threading speed region (low speed), acceleration from the initial strip threading speed region to the top speed region (high speed), rolling in the top speed region, deceleration from the top speed region to the tail end speed region (low speed) and the tail end speed region. Elongation changes in the acceleration and deceleration speed regions because the strip thickness at the mill exit side changes over time due to the strain rate dependency of strip deformation resistance. Therefore, in order to suppress these changes, JFE Steel developed a feedforward control technology which corrects rolling force commands by using the relationship between the rolling speed and acceleration rate, which are factors in elongation changes, and the strain rate dependency of the deformation resistance of the steel strip.

By combining the aforementioned feedback control and the developed feedforward control as shown in **Fig. 6**, appropriate control of flatness and elongation changes has become possible, even in high speed rolling with large acceleration/deceleration.

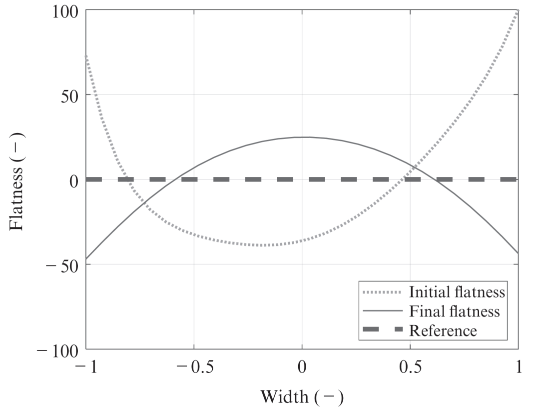

Fig. 7 Simulation results of the flatness by the conventional method

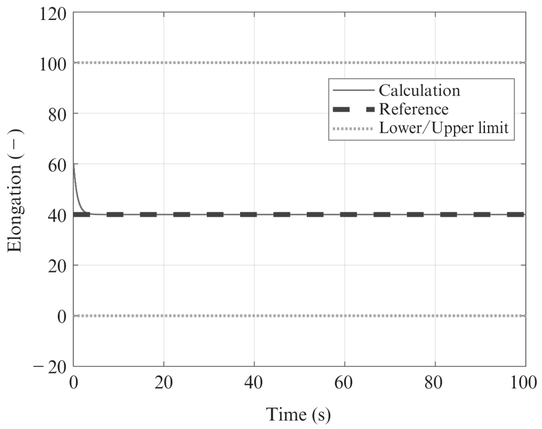

Fig. 8 Simulation results of the elongation by the conventional method

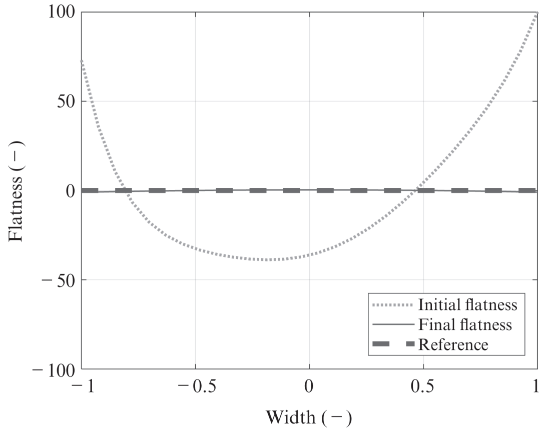

Fig. 9 Simulation results of the flatness by the proposed method

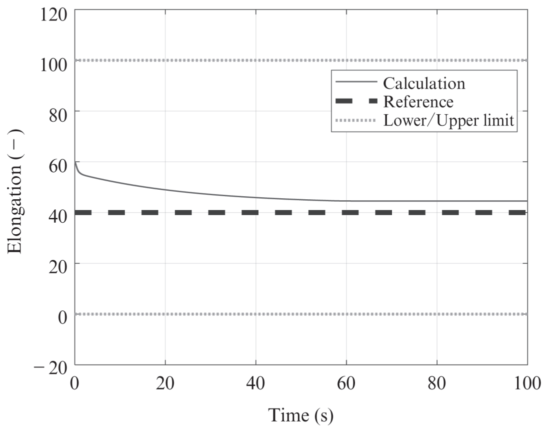

Fig. 10 Simulation results of the elongation by the proposed method

4. Validation of Improvement of Flatness Control by Simulation

In this chapter, the flatness control improvement effect of the proposed method is validated by simulation. Although the proposed method is compared with the conventional method, in order to validate the improvement effect, the same operational conditions are assumed in the two methods. (These conditions comprise the flatness target value, elongation target value, operational range and operational speed range of actuators, upper/lower limits of strip thickness, control range of elongation, rolling speed.) As a point of difference between the two methods, in the conventional method, control is performed by the elongation controller so that the actual value of elongation coincides with the target value, but in the proposed method, the weight for the elongation target value, which is included in the evaluation function f, is set small because trackability of the elongation target value is not required, and control is performed so that elongation is kept within the control range. The values of the parameters (gains and time constants) of the control object model used here were identified by an advance experiment.

The flatness control results with the conventional method and the proposed method are shown in **Fig. 7** and **Fig. 9**, respectively. Here, the abscissa of the figures represents the strip width position (normalized), and the ordinate represents flatness (normalized). In the figure symbols, “Initial Flatness” is flatness after rolling the head end of the steel strip, “Final Flatness” is the flatness after rolling the tail end of the strip and “Reference” is the target flatness. The results of elongation control by the conventional method and the proposed method are shown in **Fig. 8** and **Fig. 10**. In these figures, the unit of the abscissa is time, and the ordinate represents elongation (normalized). In the figure symbols, “Calculation” means the simulation results, “Reference” is the target value and “Upper/Lower Limit” shows the upper and lower limits of the control range.

Comparing the results of flatness control (Fig. 7 and Fig. 9), the proposed method enables control close to the target value. If the results of elongation control are compared at this time, the conventional method controls elongation to the target value. In contrast,

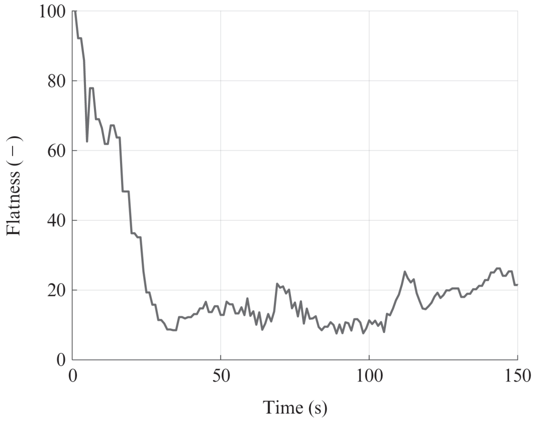

Fig. 11 Experimental results of the flatness

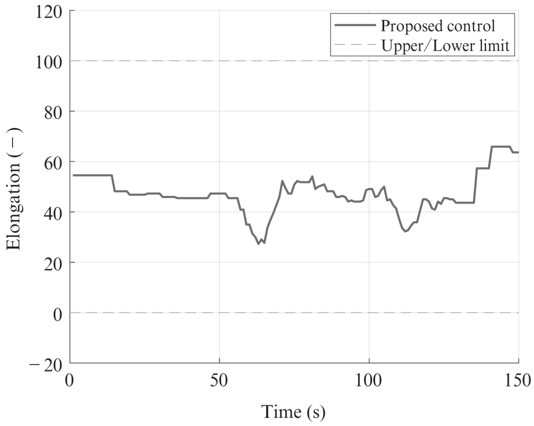

Fig. 12 Experimental results of the elongation

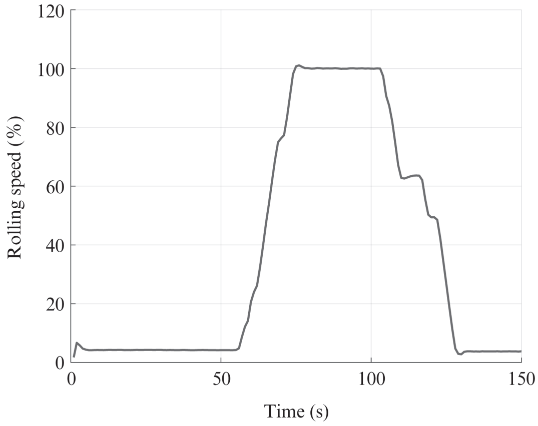

Fig. 13 Experimental results of the rolling speed

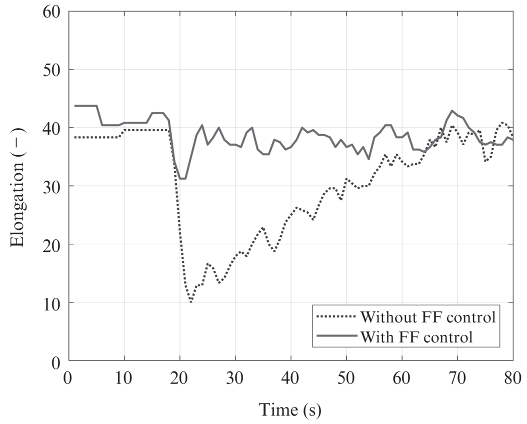

Fig. 14 Experimental results of the elongation (For validation of the FF control)

with the proposed method, elongation is within the control range but the values are different from the target value.

With the proposed method, interference with flatness can be minimized because the elongation is controlled considering the influence on flatness. This simulation confirmed the flatness control improvement effect of the proposed method.

5. Validation by Actual Machine Experiment

The validity of the proposed technique was verified by an actual machine experiment. The target values of flatness set in this experiment were all 0 (I-unit) in the width position.

The experimental results of flatness, elongation and rolling speed are shown in **Fig. 11**, **Fig. 12** and **Fig. 13**, respectively. The unit of the abscissa in these figures is time, and the ordinate shows the respective physical quantities normalized by fixed parameters. Among these, for flatness, the maximum value of the actual values of N channels obtained in each control cycle was normalized. Because the actual value of flatness approaches the target value of flatness, as shown in Fig. 11, it can be understood that the proposed method is effective for improvement of flatness. Furthermore, as the actual values of elongation are kept within the control range, the product quality of the rolled material is satisfactory.

Next, the validity of feedforward control will be verified. Because the purpose of this control is to reduce variations in elongation during mill speed changes, the results of control with and without the feedforward control function were compared under the operational condition of acceleration. The experimental results for elongation, rolling force and rolling speed are shown in **Fig. 14**, **Fig. 15** and **Fig. 16**, respectively. Here, the symbols “Without FF Control” and “With FF Control” correspond to the case without feedforward (FF) control and the case in which FF control was enabled, respectively. In the case without FF control, elongation decreased greatly during acceleration. This is due to the delay in corrective action for the rolling force when using only feedback control. In contrast to this, in the case in which FF control was enabled, rolling force correction was performed promptly and

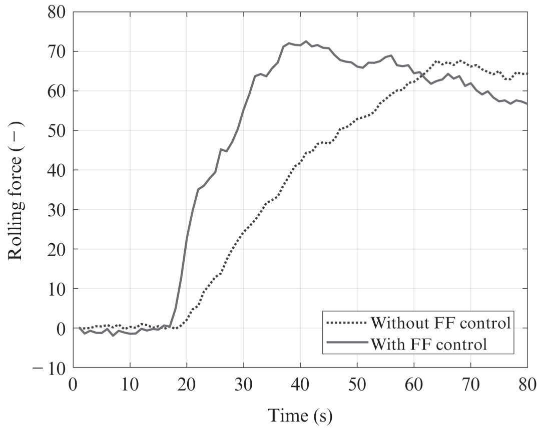

Fig. 15 Experimental results of the rolling force (For validation of the FF control)

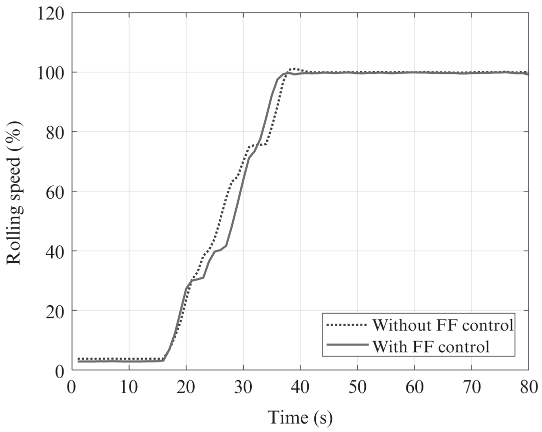

Fig. 16 Experimental results of the rolling speed (For validation of the FF control)

the variation in elongation was small. Accordingly, variations in elongation during rolling speed changes can be reduced by applying this control.

Next, the flatness after rolling of a large number of materials rolled with another mill at JFE Steel and 4SKP materials was compared. As a result, when indexed to the flatness of the materials rolled on the other mill (average value of relative difference in elongation in the rolling direction), a flatness improvement effect of 48 % was achieved with the 4SKP materials.

6. Conclusion

JFE Steel constructed a new No. 4 Skin Pass Mill (4SKP) at Fukuyama District, West Japan Works in order to further improve the product quality of mill scale steel. The multivariable control technology (Intelligent Multivariable Control) developed for that purpose enables highly accurate control of various types of controlled variables under high speed rolling. As described in this paper, the validity of the developed control technology was verified by simulations and actual machine experiments.

Application of the developed technology has enabled highly accurate automatic control of various controlled variables in rolling at the world's highest line speed in a hot skin pass mill, and is contributing to improvement of both product quality and productivity.

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