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Improvement of Accuracy for Gauge and Elongation Control by Dynamic Process Control Simulator

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Abstract

We have developed many dynamic-process-control-simulators with dynamic-properties as same as the real plant for a part of process-control-solution. By these simulators, we have been able to diagnose the control and examine the improved control method. For example, we have made the simulators of automatic-gauge-control for single cold strip mill and elongation-control for skin pass mill based on our simulator for tandem cold strip mill, and we have been able to examine the size-control for various mill types. Especially for continuous galvanizing line, with the control method improved by using the simulator of elongation control, we could have much improved the yield of elongation in front and behind of welding point at high speed of mill in the delivery section of furnace.

1. Preface

Nippon Steel Corporation has developed many dynamic-process-control-simulators with dynamic-properties as same as the real plant for a part of process-control-solution, and applied them to the diagnosis of process control systems and development of new control techniques for the production facilities of integrated steel-making processes (see **Fig. 1**).

With respect to the thickness control of sheet products, an automatic gauge control (AGC) simulator for a tandem cold mill was developed at the time of the construction of New Cold Rolling Mill Plant of Yawata Works, Nippon Steel Corporation for the development studies of a new AGC system. Then, application of the AGC simulator was expanded to the AGC for a single-stand cold rolling mill and the automatic elongation control (AEC) for a skin pass mill, and these applications led to studies of product dimension control (thickness and elongation) for various other sheet rolling mills of the company.

As a result of the studies, a technique to automatically identify simulator parameters, which had conventionally been calculated manually by trial and error, was worked out and thanks to this, accuracy of simulators has been significantly improved and the efficiency of development of simulators enhanced. The automatic parameter identification technique is a method whereby parameters for a mill control simulator such as the friction coefficient of rolled material and controller parameters of existing AGC systems are automatically identified by the non-linear least-squares method (see **Fig. 2**). Measurement of controller parameters of existing AGC systems was difficult, especially in the cases of analogue control systems of old production facilities, because of a great amount of manpower required conventionally for on-line multi-point measurement on control system wiring and picking up of noise during the measurement. The technique that was developed solved the problem and it became possible to automatically identify controller parameters through measurement at a minimum number of measuring points. As a result, it has been made possible to simulate sheet thickness very closely to real thickness, diagnose existing thickness control systems and efficiently study their improvement measures (see **Fig. 3**).

In addition, utilization of the dynamic process simulators has facilitated development of new dimension control techniques for sheet products. As an example of such developments, this paper presents the development of a new AEC technique for an in-line skin pass mill of a continuous hot dip galvanizing line (CGL).

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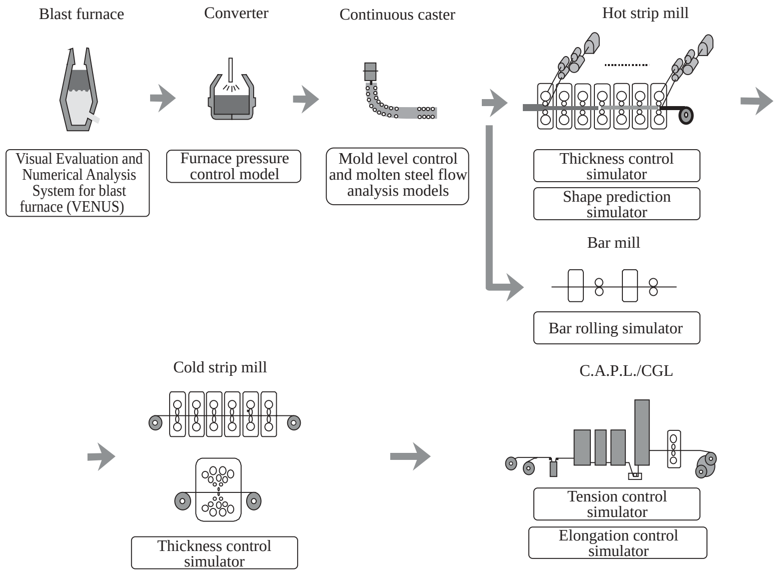


Fig. 1 Dynamic process control simulator map

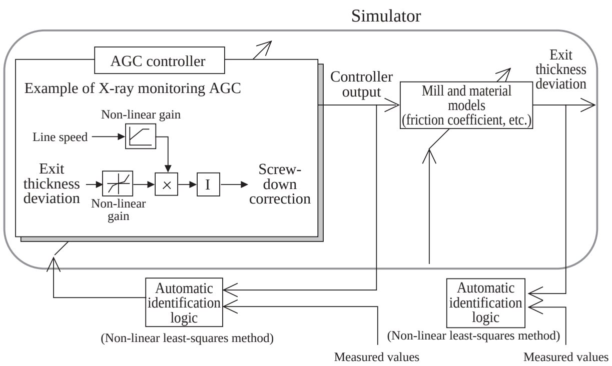
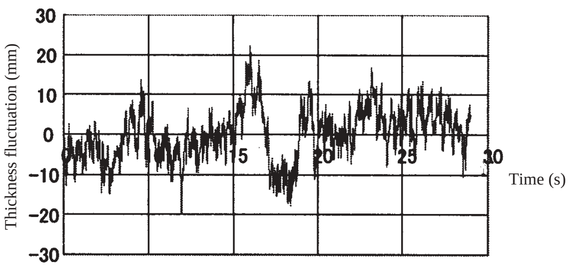
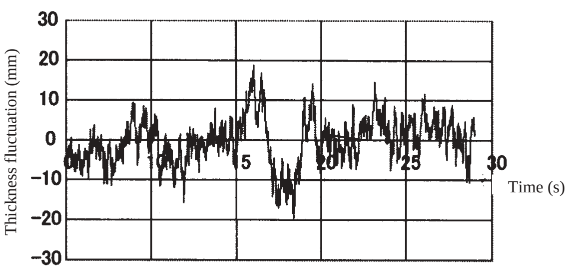


Fig. 2 Automatic identification of simulator parameters



(a) Actual thickness fluctuation



(b) Simulation

Fig. 3 Example of sheet thickness at single-stand cold rolling mill (simulating test rolling)

2. Development of New AEC Technique Using AEC Simulator

2.1 Introduction

From the viewpoint of enhancing product quality and productivity, high accuracy is essential for the AEC function for an in-line skin pass mill of a continuous processing line.

What is described in this section is a technique regarding the AEC of an in-line skin pass mill of a CGL to reduce the strip length in which elongation falls outside a desired range that occurs immediately after a change of mill setting such as a change of strip materials. The technique makes it possible to improve the prime yield of a CGL and thus enhance its productivity.

In applying the developed AEC technique to a real in-line skin pass mill, a high-precision skin pass mill simulator was used for quantitatively evaluating, off-line and prior to the event, the deterioration of mill control functions that often occurred because of errors and disturbances at the introduction of a new control technique. The control logic of the new technique was improved based on the results of the evaluation using the simulator. As a result, the time required for tuning the control system of the real mill was significantly shortened, and expected performance was fully and quickly realized. The dynamic skin pass mill simulator that was utilized in the above verification is also explained below.

2.2 In-line skin pass mill of continuous processing line

Fig. 4 shows an example of the equipment of an in-line skin pass mill of a continuous processing line such as a CGL to which the developed AEC technique is applied. Here, the drive motor speeds of the entry and exit bridle rolls are controlled independently from each other to establish desired tension values at the entry and exit sides of the mill. Under the tension conditions established by the above control systems, a desired elongation is realized by controlling the rolling force of the mill by a hydraulic screw-down control system.

2.3 AEC for skin pass mill of continuous processing line

2.3.1 Conventional AEC methods and their problems

In most cases, an in-line skin pass mill of a CGL is installed at its center section (furnace section) and for this reason it is difficult to slow down the line speed when strip-welding-point(WP) passes

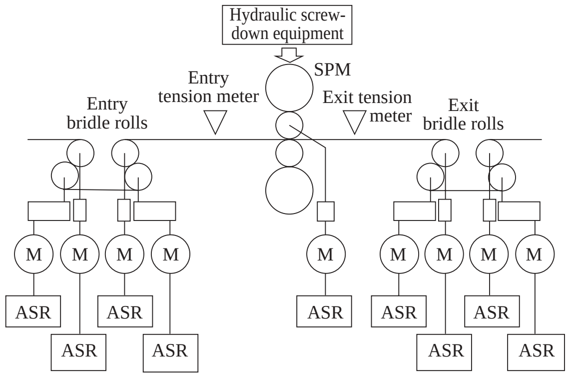


Fig. 4 In-line skin pass mill equipment (In the figure, M describes motor and ASR describes automatic speed regulator.)

through the mill. The following measures are usually taken to cope with the problem related to AEC at the mill setting change in relation with WP:

(1) When WP comes close to a skin pass mill, its rolling load is reduced in order to prevent the work roll surfaces from damaging by WP.
(2) An optimum rolling load value calculated by a selected method is set as an initial pre-set value for the strip after WP.
(3) After WP has passed through the mill, the rolling load is controlled by the hydraulic screw-down system so as to attain the initial pre-set rolling load value.
(4) After the initial pre-set rolling load value has been attained, a desired elongation value is achieved by the AEC function based on controlling the hydraulic screw-down system by actual elongation value.

In step (2) above, the mill screw-down is changed quickly until the pre-set rolling load value is attained and as a consequence, elongation changes also quickly. If there is no difference between the pre-set rolling load value and the rolling load value to realize the desired elongation, the desired elongation is achieved within a very short time after the actuation of the AEC through the hydraulic screw-down in step (4) above. Aiming at realizing this situation, accurate definition of the pre-set rolling load value has been sought through measures such as off-line learning and sophistication of rolling load models.

In actual practice, however, line operating conditions such as the furnace annealing condition, strip material characteristics and the roughness of the work roll surfaces change from time to time and for this reason, even with the above improvement measures, there always remains a deviation of a pre-set rolling load value from the ideal rolling load value to realize a desired elongation. This means that a target elongation value cannot be accurately met even when the mill screw-down is adjusted to a pre-set rolling load value. Although the elongation deviation remaining after the initial pre-set rolling load value has been achieved is fed back to the mill screw-down system to correct the deviation by the above conventional elongation feed-back control method, if the above difference between the two rolling load values is large, the strip length in which elongation falls outside a target range becomes long and the yield of prime products is decreased.

2.3.2 Dynamic skin pass mill set-up method

By the developed method, which is called the dynamic skin pass mill set-up method, the optimum rolling load for the AEC of an in-line skin pass mill to realize a desired elongation is quickly attained, the strip length in which elongation does not meet a target range is significantly shortened and the prime product yield improved, even if the pre-set rolling load value for the strip after WP contains a large error and a desired elongation is not obtained after the pre-set value is established. This is realized by correcting the initial pre-set rolling load value in real time based on the rolling operation data at the screw-down after the passage of WP.

The correction method and the calculation method of the amount of correction according to the developed dynamic skin pass mill set-up method are specifically explained below.

When the strip thickness at the mill entry is H_1, its entry speed is V_1, the strip speed at the mill exit V_2 is equal to the speed V_2^{ref} to realize a target elongation e^{ref}, and the strip thickness at the mill exit H_2 is equal to a target exit thickness H_2^{ref}, then equations (1) hold true according to the law of constant mass flow.

$$H_1V_1 = H_2^{ref}V_2^{ref}$$
$$\therefore H_2^{ref} = \frac{H_1V_1}{V_2^{ref}} \tag{1}$$

Further, V_2^{ref} can be expressed, using the target elongation e^{ref}, as

$$e^{ref} = \frac{V_2^{ref} - V_1}{V_1}$$
$$\therefore V_2^{ref} = V_1(e^{ref} + 1) \tag{2}$$

Therefore, from equations (1) and (2), the target exit strip thickness H_2^{ref} can be expressed as

$$H_2^{ref} = \frac{H_1}{e^{ref} + 1} \tag{3}$$

When the actual elongation is expressed as e, its deviation from the target elongation as Δe, and the exit strip speed V_2 as per equation (4) using its deviation ΔV from the target exit speed V_2^{ref} and its deviation ΔV_2,

$$V_2 = V_2^{ref} - \Delta V_2 \tag{4}$$

then, the actual elongation e can be expressed as

$$e = \frac{V_2 - V_1}{V_1}$$
$$= \frac{V_2^{ref} - V_1}{V_1} - \frac{\Delta V_2}{V_1} = e^{ref} - \Delta e \tag{5}$$

From the above, it follows that the exit strip speed V_2 can be expressed as follows using the deviation of elongation Δe:

$$V_2 = V_2^{ref} - \Delta e V_1 \tag{6}$$

Here, in relation with the exit strip thickness H_2,

$$H_1V_1 = H_2V_2 \tag{7}$$

holds true according to the law of constant mass flow and as a consequence, from equations (2), (6) and (7), the exit strip thickness H_2 can be expressed as

$$H_2 = \frac{H_1}{e^{ref} - \Delta e + 1} = \frac{H_1}{e + 1} \tag{8}$$

Accordingly, it follows that the deviation of exit strip thickness ΔH_2 when the deviation of elongation is Δe is expressed as

$$\Delta H_2 = H_2^{ref} - H_2$$
$$= \left(\frac{1}{e^{ref} + 1} - \frac{1}{e + 1}\right) \cdot H_1 \tag{9}$$

If it is intended here to eliminate the deviation of exit strip thickness ΔH_2 by screwing down the mill by ΔS, it is accomplished by controlling the mill screw-down so as to satisfy

$$\Delta H_2 = -\frac{M}{M+Q}\Delta S \tag{10}$$

where M is a mill constant, and Q a plasticity coefficient. As a conclusion, the incremental screw-down amount ΔS to eliminate the deviation of exit strip thickness ΔH_2 is, from equations (9) and (10), expressed as per equation (11).

$$\Delta S = -\frac{M+Q}{M}\left(\frac{1}{e^{ref}+1} - \frac{1}{e+1}\right)H_1 \tag{11}$$

Further, the incremental rolling load ΔP to bring about the incremental screw-down amount ΔS defined by equation (11) is given as

$$\begin{aligned}\Delta P &= \frac{MQ}{M+Q}(-\Delta S) \\ &= Q \cdot H_1 \cdot \left(\frac{1}{e^{ref}+1} - \frac{1}{e+1}\right)\end{aligned} \tag{12}$$

Therefore, in order to eliminate the deviation of elongation Δe, it is necessary to increase the rolling load by the value of ΔP defined by equation (12). That is to say, a desired elongation is achieved more quickly than by the feed-back control if the deviation of elongation at the time when the initial pre-set rolling load is established is measured, the value of ΔP defined by equation (12) (set-up load correcting amount P_{adj}) is added to the pre-set rolling load, and the sum is set as a new pre-set rolling load.

On the other hand, in order to calculate equation (12), it is necessary to estimate the values of the plasticity coefficient Q and the entry strip thickness H_1 in consideration of the thickness deviation from a reference thickness. In the same manner as the above, these two can be estimated using the following equations, respectively:

$$Q = \frac{P_b - P_a}{\frac{1}{M}(P_b - P_a) + (S_b - S_a)} \tag{13}$$

$$H_1 = H_{1a} = \frac{P_b - P_a}{Q\left(\frac{1}{e_b+1} - \frac{1}{e_a+1}\right)} \tag{14}$$

where P_a, P_b, e_a, and e_b are the rolling load and actual elongation values when the screw-down position is S_a and S_b, respectively.

2.4 Off-line verification of developed elongation control method using high-accuracy skin pass mill simulator

As stated earlier, Nippon Steel has developed various kinds of simulators for the control of steel production processes and the simulators are effectively utilized for providing solutions to efficiently and effectively enhance process control accuracy in response to clients' requirements for better product quality. Before applying the above new dynamic elongation control technique to a real skin pass mill, its function was verified off-line using a dynamic skin pass mill simulator.

2.4.1 High-accuracy dynamic skin pass mill simulator

An outline of the dynamic skin pass mill simulator used for the above verification is briefly explained below.

As seen in **Fig. 5**, the simulator outputs the values of exit strip thickness, elongation, rolling load, tension, etc. based on input data such as entry thickness and various control parameters. Its model section (plant section) contains detail models of rolling theories, elasto-plastic characteristics of strip materials, dynamic characteristics of actuators, discrete time motion of controllers and so forth. The simulator also has a function to automatically identify unknown parameters contained in the calculation of a friction coefficient, deformation resistance or the like based on data obtained through real operation.

Fig. 6 shows a comparison of actual rolling operation data at test rolling of the skin pass mill of a processing line with the simulation results obtained by the simulator under the same operation conditions. It is seen in the figure that the simulator can very accurately reproduce real rolling conditions.

2.4.2 Improvement of control logic based on simulation studies

The authors verified the function of the dynamic set-up logic explained in 2.3.2 using an AEC simulator as described in 2.4.1. As a result, it was found out that the dynamic set-up method might yield a set-up rolling load value containing an error, depending on conditions, because of the influences of elements such as: the non-linear factor of the mill constant M in a light screw-down range; change of the plasticity coefficient Q due to the strain velocity-induced factor of the effective average deformation resistance of a steel strip and fluctuation of tension; sensor noise; and delay in the operation of a control actuator. At this finding, in order to mitigate the influence of the error and secure stable functioning of the elongation control logic explained in 2.3.2 at its actual application, the authors modified the

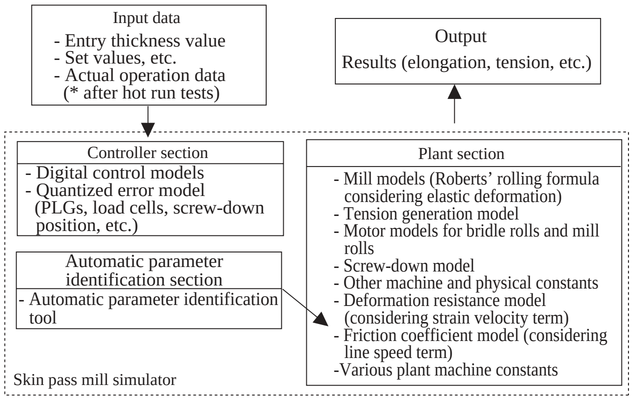
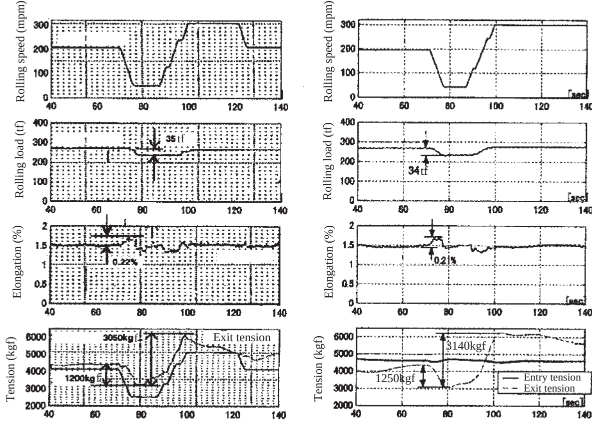


Fig. 5 Dynamic skin pass mill simulator



(a) Charts of actual rolling (test run) (b) Simulation

Fig. 6 Accuracy verification of dynamic skin pass mill simulator

control logic as shown in the flow diagram of **Fig. 7**. Note that the values of the control parameters in the flow diagram can be calculated using the dynamic simulator, which is capable of accurately reproducing real process behaviors, and the values thus calculated can be used for a real mill without modifications. Therefore, by carrying out tuning off-line using the dynamic simulator, the time of tuning the control systems of a real production facility can be reduced significantly.

Fig. 8 shows the simulation results of the dynamic set-up logic modified as per Fig. 7. The simulation condition was as follows: the error of the initial pre-set rolling load (240 tf) was −30% with respect to the optimum rolling load (345 tf) to obtain a desired elongation of 1.0%; and the mill screw-down toward the optimum rolling load was commenced at the time point of 30 s. The responses of rolling load and elongation with and without the application of the modified dynamic set-up logic are compared in the figure.

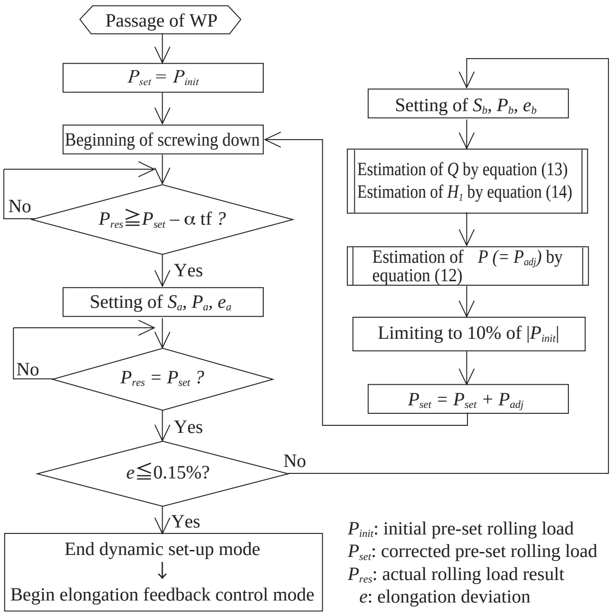
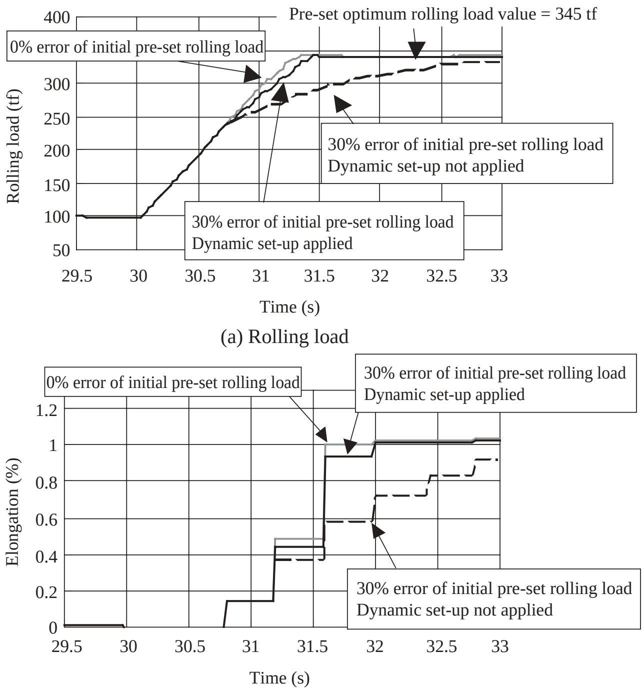


Fig. 7 Dynamic set-up logic of skin pass mill



(a) Rolling load

(b) Actual elongation results (target elongation = 1.0%)

Fig. 8 Verification of developed technique by simulation

It is seen from the figure that, despite the −30% error in the initial pre-set rolling load, a rolling load response as quick as in the case of a 0% error was realized thanks to the accurate correction calculation by the modified dynamic set-up logic, and as a result, the target elongation was quickly attained without overshooting.

2.5 Results of actual application of new elongation control technique

2.5.1 Performance of new elongation control technique

Fig. 9 shows an example of the results obtained through the application of the developed elongation control technique to a commercially operated skin pass mill. The case shown here is that two steel strips of different steel grades were welded at WP and the strip size changed from 1.015 mm × 1,618 mm to 1.008 mm × 1,707 mm and that the error in the initial pre-set rolling load was −40% with respect to the optimum rolling load to obtain a desired elongation with the new strip. It is seen here that, like in the simulation results shown in Fig. 8, the rolling load was corrected to the optimum value in real time thanks to the application of the developed dynamic set-up logic and as a consequence, the target elongation was quickly attained. Note that the line was operated at a rated high seed and the line speed was not altered at the time of WP passage through the mill.

The operation conditions of the above example were fed to the dynamic skin pass mill simulator for the purpose of simulating a case where the developed dynamic set-up logic was not applied. **Table 1** compares the strip length in which the elongation was inadequate by the simulation with that in the above example of real operation applying the developed dynamic set-up logic. Here, the portion with inadequate elongation means the portion where the deviation of actual elongation from the target elongation was outside the

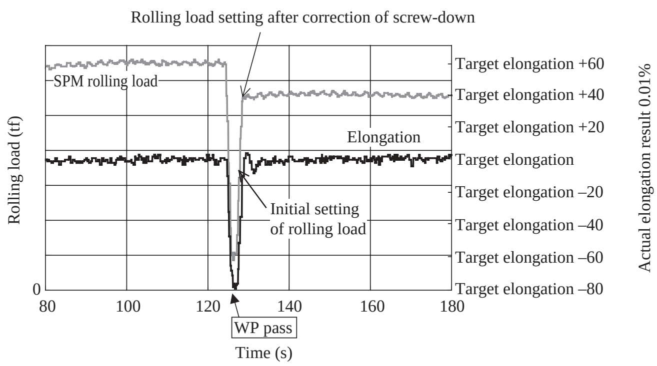


Fig. 9 Result of AEC on real mill (setting change from 1.02 mm × 1,618 mm to 1.00 mm × 1,707 mm)

Table 1 Reduction of strip length with inadequate elongation by application of developed technique

	Strip length with inadequate elongation
Developed dynamic set-up logic applied	2.6 m
Developed dynamic set-up logic not applied	8.5 m *1

*1: estimation from simulation under identical conditions range from –0.1% to +0.1%. It is clear from the table that, as a result of application of the developed dynamic set-up logic, the strip length with inadequate elongation after the passage of WP through the mill was greatly reduced even when a pre-set rolling load value contained an error, and the product yield was enhanced as a consequence.

2.5.2 Reduction of test run period

As stated in 2.4.2, sufficient preliminary verification of the developed dynamic set-up method was done utilizing the high-accuracy skin pass mill simulator. As a result, the test run period of the new set-up method on the real skin pass mill was significantly reduced as shown in **Table 2**.

Table 2 Test run period of new set-up method on real mill (including time period for adjusting control gain)

	Test run period
Conventional test run method	14 days
Test run after preliminary verification using simulator (developed method)	2 days

2.6 Closing

Development of a new automatic elongation control (AEC) method for the in-line skin pass mill of a continuous hot-dip galvanizing line (CGL) has been reported herein as an example of a new development method of control techniques utilizing a dynamic process control simulator. The developed AEC technique significantly reduces the strip length in which elongation does not fall within a target range that occurs immediately after a mill set-up change such as a change of processed steel strips. In addition, when a high-accuracy simulator is effectively used for the development of a new process control technique and the application of the developed control technique to a real production facility, the steps from verification of control functions to fine tuning of control gains can be carried out off-line and as a consequence, the total development period is reduced and high quality of the developed technique is secured.

The AEC technique herein presented has been successfully applied to Nippon Steel's CGL in-line skin pass mills, contributing to the enhancement of their productivity.