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# Plant Optimal Control System for No. 5 Continuous Annealing Line (CAL) at West Japan Works (Fukuyama), JFE Steel†

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***Abstract:***

*In a continuous annealing process, the line speed of the furnace section is one of the important factors determining the qualities of cold strips. Conventionally, the line speed was set manually based on the experiences of the operators. Therefore, the setting and the timing of changing of the line speed differ with individuals. JFE Steel has developed a plant optimal control system for the No. 5 Continuous Annealing Line (CAL). In this system, the line speed is set automatically based on the optimal calculations made by the Level-2-Computer. As a result, JFE Steel has resolved the above problems and improved the quality stability of cold strips.*

## 1. Introduction

With increasing demand for tinplate and chrome sheets foreseen in China and Southeast Asia, No. 5 Continuous Annealing Line (hereinafter, Fukuyama 5CAL) was constructed at West Japan Works (Fukuyama), JFE Steel and began commercial operation in December 2010[1]. Conventionally, the line speed of the furnace section (hereinafter, line speed) in continuous annealing lines had been set based on the operator's experience, but this results in differences in the line speed setting and the timing of speed changes depending on the individual. The plant optimal control system was introduced at the Fukuyama 5CAL as a solution to this problem[2,3]. In this system, the line speed is set automatically based on the optimal calculations made by the Level-2 computer (process computer).

This paper presents an outline of the functions of the plant optimal control system and reports the results of its introduction.

## 2. Outline

### 2.1 Equipment Outline

**Figure 1** shows the line layout of the Fukuyama 5CAL. The Fukuyama 5CAL is a continuous annealing line which treats steel strips for use in tinplate, and has a heating section which is divided into 2 zones, a soaking section and 3 cooling sections. In addition to this annealing equipment, the line is also equipped with cleaning equipment, a tension leveler, entry and delivery side loopers, a skinpass mill, etc., and integrates the functions of a temper rolling mill and finishing line.

### 2.2 System Outline

**Figure 2** shows the system configuration of Fukuyama 5CAL. A general-purpose server was adopted for the Level-2 computer itself. To enable simulation tests using actual data, a development system of the same specification was also installed. Common use of the programmable logic controller (PLC) and human machine interface (HMI) is possible, and display and input of the setting values of the Level-2 computer and PLC can be performed from terminals installed in each operation room.

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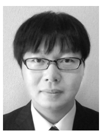

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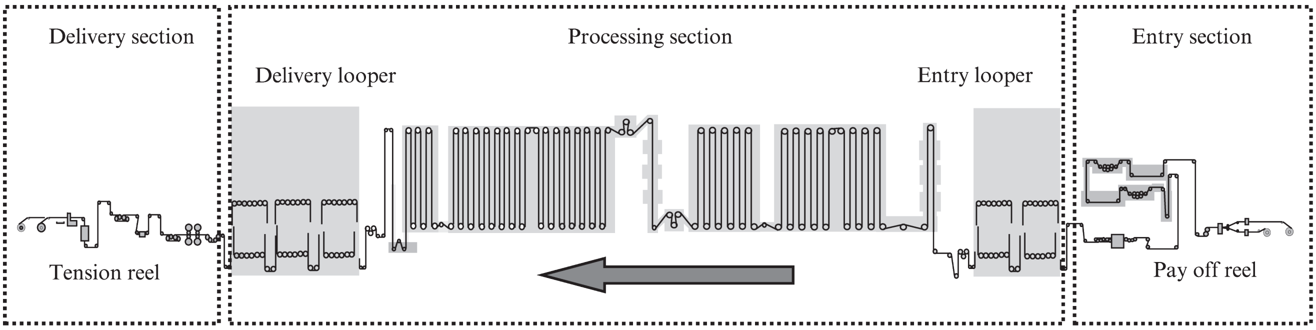


Fig. 1 Line layout of No. 5 Continuous Annealing Line (CAL)

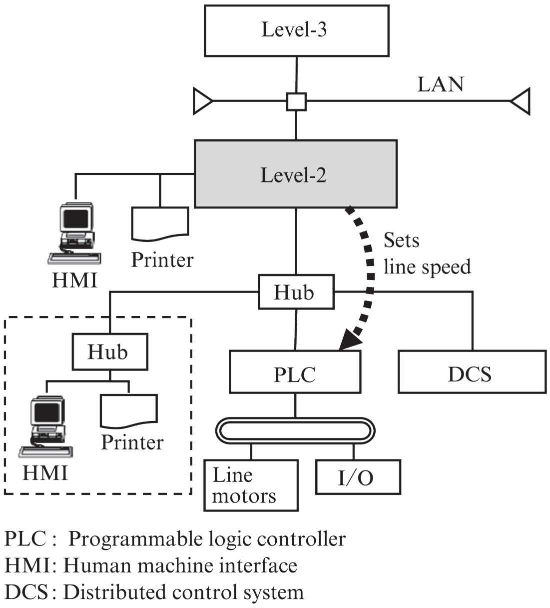


Fig. 2 System configuration diagram of No. 5 Continuous Annealing Line (CAL)

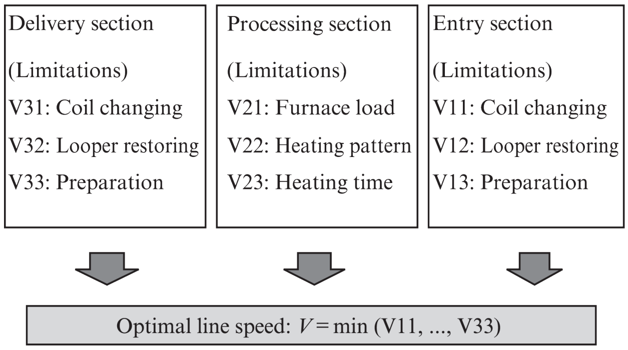


Fig. 3 Outlines of the plant optimal control system

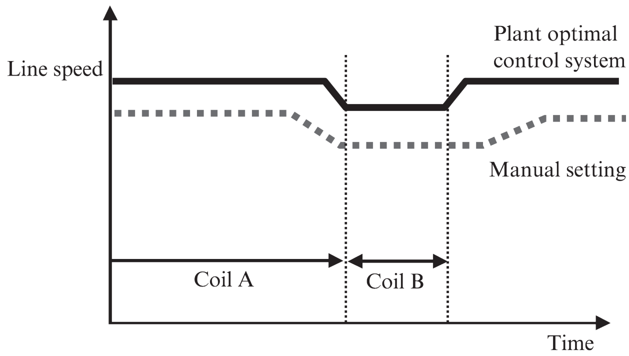


Fig. 4 Example of the line speed setting

Regarding the division of functions, while performing line tracking, the Level-2 computer also performs setting of the PLC and distributed control system (DCS) based on coil information and operating conditions from the Level-3 computer (business computer) . Setting of the line speed to the PLC is performed in the plant optimal control system. The details of this system are explained in Chapter 3.

## 3. Plant Optimal Control System

**Figure 3** shows the outline of the plant optimal control system. In order to maximize production efficiency, operation at the highest possible line speed while assuring product quality is ideal. However, at the timing of coil changes (welding) at the entry side and coil division at the delivery side, conditions occur in which the line speed must be decelerated. Since the timing at which limitations are applied to the line speed (hereinafter, line speed limitation) is influenced by coil specifications such as the coil length, etc. and by the condition of operation, the timing is not uniform, and there are also cases in which multiple limitations are applied simultaneously.

Accordingly, as shown in **Fig. 4**, the minimum line speed is determined from among the applicable line speed limitations, considering the timing of the start and end of each line speed limitation, and a line speed at which line trouble will not occur is set based on operating conditions such as the current actual line speed, etc.

Next, the calculation flow in this system will be explained. First, the line speed limitations for each coil are calculated based on the operating conditions from the Level-3 computer (**Table 1**). Next, the timing at which each limitation calculated by these line speed limitation calculations is calculated, and the target line

Table1 Line speed limitations

| Vii | Limitation | Reason for limitations |
|---|---|---|
| V11 | Coil changing | Securing time to change coils |
| V12 | Looper restoring | Securing time to restore the entry looper |
| V13 | Preparation | Securing time to prepare next coil |
| V21 | Furnace load | Limitation from furnace load |
| V22 | Heating pattern | Securing time to change heating pattern |
| V23 | Heating time | Securing heating time in processing section |
| V31 | Coil changing | Securing time to change coils |
| V32 | Looper restoring | Securing time to restore the delivery looper |
| V33 | Preperation | Securing time to prepare next coil |

speeds are determined. The target line speed obtained here is ultimately only the theoretical maximum line speed, and unexpected limitations sometimes occur due to the actual strip temperature, the actual amount of strip meandering, etc. Therefore, the target line speed is corrected based on these actual results. Finally, the final line speed is set, including the rate of acceleration/deceleration and the control cycle.

## 4. Plant Optimal Control System and Strip Temperature Control

At the Fukuyama 5CAL, strip temperature control is also performed automatically under control by the plant optimal control system. In strip temperature control, the furnace temperature setting value to achieve the desired heat treatment conditions is calculated in the Level-2 computer and output to the DCS. Here, heat treatment conditions refers to the target value of the strip temperature and the residence time in the furnace which should be achieved in each of the sections, i. e., the heating section, soaking section and so on. In order to assure product quality, it is necessary to perform control so that the strip temperature does not deviate outside the upper or lower limits. Therefore, in strip temperature control, the target is to control so that the actual strip temperature is within the allowable range of the upper/lower limits, even under unsteady conditions such as during line speed changes, strip size changes, etc.

The furnace temperature setting is calculated in the Level-2 computer by using a heat transfer model equation which expresses the heat transfer between the heating zone and the steel strip[4]. However, since the heating section at Fukuyama 5CAL is divided into a first zone and a second zone, it is necessary to calculate the furnace temperature by calculating the heat transfer equations for the two zones as simultaneous equations. The simultaneous Newton method was used in the convergent calculation of the furnace temperature. Equations (1) and (2), which were used in the calculations, are shown below.

First half of furnace:

$$cs \cdot \gamma \cdot D \cdot \frac{\Delta\theta_{j}}{\Delta t} = \phi_{cg} \cdot \sigma \cdot (\theta_{g1}^{4} - \theta_{i}^{4}) \quad \cdots\cdots\cdots\cdots (1)$$

Second half of furnace:

$$cs \cdot \gamma \cdot D \cdot \frac{\Delta\theta_{m}}{\Delta t} = \phi_{cg} \cdot \sigma \cdot (\theta_{g2}^{4} - \theta_{m}^{4}) \quad \cdots\cdots\cdots\cdots (2)$$

Where,

$\theta_{g1}$: First half furnace temperature (K)
$\theta_{g2}$: Second half furnace temperature (K)
$\theta_{i}$: Entry strip temperature (K)
$\theta_{m}$: Intermediate strip temperature (K)
$D$: Strip thickness (m)
$\gamma$: Specific weight of material (kg/m$^3$)
$\varphi_{cg}$: Overall heat absorptivity
$\sigma$: Stefan-Boltzmann constant (kcal/m$^2 \cdot$h$\cdot$K$^4$)
cs: Specific heat of material (kcal/kg$\cdot$K)

Although the furnace speed changes instantaneously in accordance with the acceleration/deceleration rate of the PLC, changes in the furnace temperature in the heating section require time, as the heating section uses radiant tubes as actuators for heating. Therefore, if the plant optimal control system and strip temperature control are allowed to function independently, the furnace response will not follow changes in line speed and strip size, and the strip temperature will deviate outside the upper or lower limit.

To solve this problem, we developed a new feedforward strip temperature control function which links strip temperature control with the plant optimal control system. As a feature of this function, a line speed schedule is calculated into the future, and this is transmitted to the strip temperature control function in advance. This function makes it possible to implement furnace temperature changes at the optimal timing considering the response characteristics of the furnace.

**Figure 5** shows the flow of this function. First, a line speed schedule is prepared by calculating the calculations of the plant optimal control system for future coils. Next, the furnace temperature schedule which will be necessary in the future is prepared in the temperature control function based on the line speed schedule. The furnace temperature and target strip temperature which should be set at present are also calculated, considering the response delay of the furnace temperature. This process enables feedforward control of the furnace temperature anticipating future acceleration and deceleration of line speed, and thus can prevent deviations of the strip

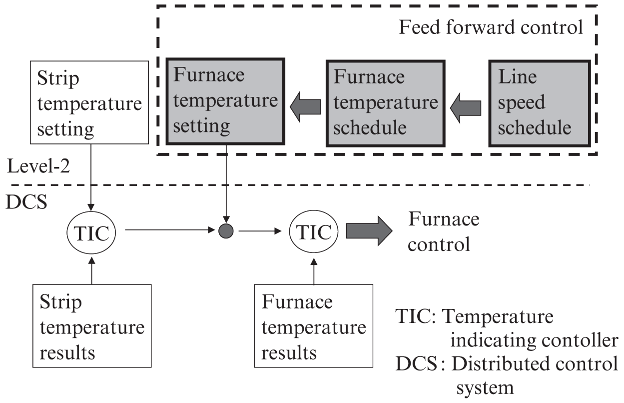


Fig. 5 Block diagram of feed-forward (FF) strip temperature control

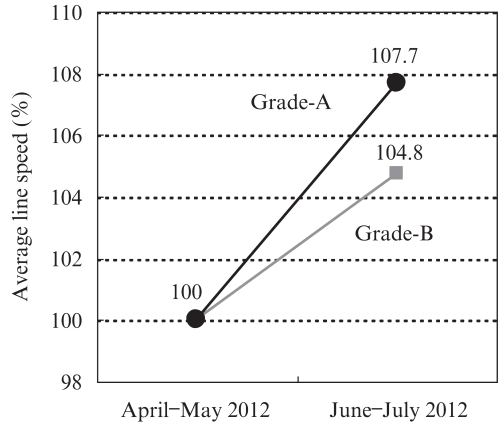


Fig. 6 Average line speed (Strip thickness <0.24 mm)

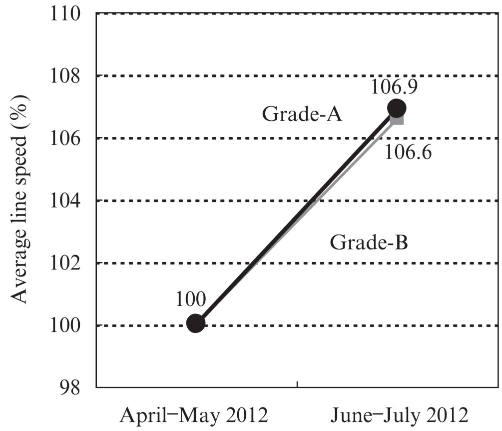


Fig. 7 Average line speed (Strip thickness ≧0.24 mm)

temperature from the upper/lower limits due to furnace temperature response delay.

## 5. Results of Application

Application of the plant optimal control system began in June 2012. The application rate of the plant optimal control system in June 2012 was 85.8%, and an application rate of 92.2% was achieved in next month. Excluding emergency trouble and other cases in which human intervention is essential, automatic operation is performed at all times. Because the line speed is set in accordance with the setting values of the Level-2 computer during automatic operation, deviations in line speed setting depending on individuals have been eliminated, and this has contributed to quality stability. Feedforward control of strip temperature has also made it possible to prevent deviations of strip temperature from the upper and lower limits in unsteady parts. **Figures 6** and **7** show the average line speed before and after application of the plant optimal control system. A comparison of the application rate by steel grade and strip thickness showed that increases in line speed were achieved in all cases after application. In particular, a remarkable increase in the average line speed could be seen with Grade-A coils, which have strip thicknesses of less than 0.24 mm and are not greatly affected by line speed changes. This is attributed to the fact that the increment of the line speed increase becomes correspondingly larger as the rate-determining condition due to furnace heating (or cooling) becomes smaller.

## 6. Conclusion

Application of a newly-developed plant optimal control system to No. 5 Continuous Annealing Line (Fukuyama 5CAL) at West Japan Works (Fukuyama), JFE Steel was completed. As of July 2012, an automation rate of 92.2% was achieved, and except for cases in which human intervention is essential, automatic operation is now performed at all times. This system has made it possible to eliminate deviations in line speed setting depending on individual operators, thereby contributing to quality stability. A strip temperature feedforward function was also developed and has made it possible to prevent deviations of the strip temperature from the upper and lower limits in unsteady parts.

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