STRIP WALK SIMULATION FOR CONTINUOUS PROCESSING LINES

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ABSTRACT

Although the prevention of lateral instability on continuous processing lines called "strip walk" is important in achieving high productivity and improving quality for steel industry, empirical systems have been applied to specific problems for many years. To meet various requirements, a general-purpose numerical simulation model based on spring-mass system was developed, which can predict the unsteady-state walking behavior of strip on a multiple-pass continuous processing line.

NOMENCLATURE

B	:Width of strip
b	:Length of parallel portion of strip
C_1, C_2, C_3	:Proportional constants
E	:Young's modulus of strip
EI	:Flexural rigidity of strip
$G(s)$	:Transfer function of steering device control system
h	:Thickness of strip
K_s,L_s	:Time constant of control system
L	:Roll span
L_c	:Camber length
M_i	:Rotating moment due to frictional force between roll and strip
q	:Distributed external force acting on strip between rolls
R	:Radius of roll
T	:Longitudinal tension acting on strip
$T_p(\eta)$	:Tension distribution in width direction of strip due to strip shape
$T(\eta)$	:Tension distribution in width direction of strip
t	:Time
Δt	:Time increment

V	:Travel speed of strip
x	:Coordinate in longitudinal direction
y_i	:Displacement of strip in width direction of roll
dy_i/dt	:Displacement speed of strip in width direction of roll
α	:Correction factor
γ_0	:Taper angle of taper roll
$\gamma(\eta)$	:Shape of roll crown in radian
$\delta(x)$	:Camber
η	:Coordinate in width direction of roll
θ_i^{ni}	:Roll angle in entering span
θ_i^{no}	:Roll angle in exiting span
θ_i^c	:Equivalent web angle at crown roll
θ_i^d	:Strip edge angle due to deformation
θ_i^e	:Longitudinal slope angle of strip camber
θ_i^{in}	:Overall equivalent web angle
θ_i^s	:Relative web angle at roll
θ_i^u	:$(y_i - y_{i-1})/L$
μ	:Coefficient of friction between strip and roll
ϕ_0	:Wrap angle of strip at roll in circumferential direction
i	:Roll number

INTRODUCTION

As steel strip widens, thins and softens in keeping with the product diversification of late, technology for stably tracking strip on continuous processing lines has come to be important to secure high productivity and product quality. The prevention of lateral instability in strip tracking called "strip walk" is essential particularly on the processing lines designed for higher speed to meet the current brisk demand for sheet products.

Steering devices, crown rolls and many other devices are employed to control the walking of strip. However, there exists no established system as yet to evaluate quantitatively the effects of these devices in both steady and unsteady states in the context of the entire strip transfer system including adjoining entry and delivery equipments. In the past, empirical systems have been applied to specific problems.

To solve these problems, mathematical models based on the beam theory are proposed for the case of a strip of good shape being processed with flat rolls[1)-3)].

This paper describes a general-purpose numerical simulation model that can predict, during the design of an actual transfer equipment, the walk behavior of various shapes of strip in a multiple-pass continuous heat treating furnace with its control system.

It is shown that the strip travel on rolls can be represented by an equivalent mass-spring-dashpot system. Modeling considerations about individual strip control methods, such as crown rolls and steering devices, are described. Finally, the validity of the mathematical model is verified by comparing predicted valued with measured values in the application of the simulator to an actual continuous heat treating furnace.

FORMULATION

Basic Principle of Strip Travel on Rolls

The strip that winds round each roll with a given angle to the center line of the processing line moves on the rolls according to the so-called bobbin principle. If V is the strip travel speed and θ_i^{in} is the strip web angle at the ith roll in the entering span as shown in Fig. 1, the strip displacement speed dy_i/dt in the width direction of the roll is given by

$$\frac{dy_i}{dt} = -V\theta_i^{in} \tag{1}$$

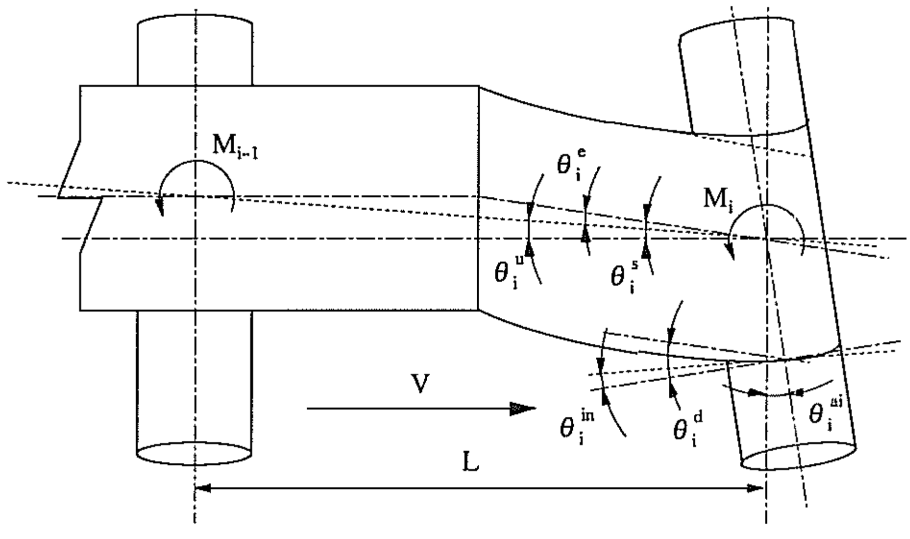


Fig. 1 Definition of web angle of strip at roll

The strip travel on the roll is represented by a first-order lag system and is equal to the movement of a spring-dashpot system. When the inertial force of the strip is taken into account, the strip travel can be seen to be equivalent to the model illustrated in Fig. 2.

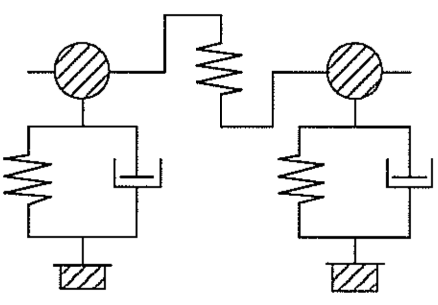


Fig. 2 Equivalent mass-spring-dashpot system

Nonlinearity is considered for the individual coefficients, however.

The angle θ_i^{in} in Eq. (1) is assumed to be the sum of the following angles in view of roll alignment and relative strip positions at the upstream and downstream rolls:

$$\theta_i^{in} = \theta_i^s + \theta_i^c + \theta_i^{ai} \tag{2}$$

where θ_i^s is actual web angle at the ith roll; θ_i^c is equivalent web angle at a crown roll;

and θ_i^{ai} is roll angle in the entering span.These terms are discussed in detail in the following section.

Calculation of Web Angle at Roll

The relative web angle θ_i^s at the ith roll is given as the sum of the web angle θ_i^u arising from relative strip positions at the upstream and downstream rolls, the longitudinal inclination angle of strip camber θ_i^c due to an angular weld, and the strip edge angleθ_i^d due to the friction of the strip with the ith roll and the inertial force acting on the strip between the rolls by

$$\theta_i^s = \theta_i^u + \theta_i^c + \theta_i^d \tag{3}$$

where,

$$\theta_i^u = (y_i - y_{i-1}) / L, \qquad \theta_i^c = \text{given} \tag{4}$$

where y_i is strip displacement in the width direction of the ith roll.

If the strip span L between the rolls is modeled as a beam that is simply supported at both ends and subjected to the longitudinal tension T (equivalent flexural rigidity denoted by EI), the strip edge angle θ_i^d is expressed by[4)]

$$\theta_i^d = C_1 M_i + C_2 M_{i-1} + C_3 q \tag{5}$$

where,

$$\begin{aligned} C_1 &= \frac{\sinh(L/j) - \cosh(L/j)/j}{T\sinh(L/j)} \\ C_2 &= \frac{1/j - \sinh(L/j)/L}{T\sinh(L/j)} \\ C_3 &= \frac{\sinh(L/j)L/2 + \{1 - \cosh(L/j)\}j}{T\sinh(L/j)} \\ j^2 &\equiv EI/T \end{aligned} \tag{5'}$$

where M_i and M_{i-1} are in-plane rotating moments acting on the ith roll and (i-1)th roll due to frictional force and other factors, respectively, and q is distributed load acting on the strip between the ith and (i-1)th rolls.

If $T(\eta)$ is the tension distribution in the width direction of strip of the width B, R is the diameter of the roll, ϕ_0 is the web angle at the roll, and μ is the coefficient of friction, the rotating moment M_i in the entering span due to the frictional force between the roll and strip is given by

$$\begin{aligned} M_i &= \int_{-B/2}^{B/2} \int_0^{\phi_0/2} \mu \frac{T(\eta)}{R} \cos\phi\, \eta R\, d\phi\, d\eta \\ &= \mu \sin(\phi_0/2) \int_{-B/2}^{B/2} T(\eta)\eta\, d\eta \end{aligned} \tag{6}$$

Considering the tension distribution $T_p(\eta)$ due to strip shape and the difference in tension between the strip edges due to the relative strip positions at the upstream and downstream rolls, the tension distribution $T(\eta)$ is given by

$$T(\eta) = T_p(\eta) + \frac{Eh(\theta_i^u + \theta_i^{ai})\eta}{L} \tag{7}$$

where E is Young's modulus, and h is the thickness of the strip. The rotation moment of the strip at the upstream roll is similarly considered.

Next, the inertial force alone is considered here as distributed load acting on the strip between the rolls.

Concept of Roll Crown

There are various ways of thinking about the ability of roll crown to control strip walking. Here is used the method of equating the average taper angle in the roll/strip contact region with the equivalent web angle, as described in Ref 5). That is,

$$\theta_i^c = \alpha \int_{-B/2+y_i}^{B/2+y_i} \gamma_i(\eta) d\eta / B \tag{8}$$

where γ is taper angle of the roll and α is correction factor, denoting the state of contact between the roll and strip that is governed by the shape of strip and the coefficient of friction, etc. If the strip is in good contact with the roll, the correction factor α is about 0.35 according to Ref 5).

For example, take a straight taper roll with $\gamma(\eta) = \pm\gamma_0(|\eta|>b/2)$ where b is the length of the level portion of the roll. On the range where strip edges do not come off the taper portion of the roll, Eq. (8) may be rewritten as follows:

$$\begin{aligned} \theta_i^c &= \alpha\{ \int_{-B/2+y_i}^{-b/2} (-\gamma_0) d\eta + \int_{-b/2}^{b/2} (0) d\eta + \int_{b/2}^{B/2+y_i} (+\gamma_0) d\eta \} / B \\ &= \frac{2\alpha\gamma_0}{B} y_i \end{aligned} \tag{9}$$

Concept of Roll Alignment

Discussed here are rolls misalignment and roll inclination in the steering device. For the misalignment of fixed rolls, random numbers are generated over an appropriately assumed distribution, and the roll misalignment angle θ_i^{ai} and θ_i^{ao} in the entering span and existing span, respectively, are given. The roll angle in the steering device is calculated from the output of the control system or cylinder manipulated variable, and is successively given.

The user can define an arbitrary transfer function for the dynamic characteristic G(s) of the control system, including cylinder operation. When a hydraulic unit of the servo valve type is used, the following dynamic characteristic is used:

$$G(s) = K_s \frac{e^{-L_s s}}{s} \tag{10}$$

where Ls is time lag between the detecting element and final controlling element, and Ks is proportional constant between the detecting element and final controlling element. Presented in this paper are examples of calculation for simple feedback control.

Estimation of Weld Point Camber

A strip weld is nominally shaped like an angle. The angle-shaped weld detracts from the straight travel of the strip and often causes it to walk.

For the shape of strip camber across a weld point, the finite deformation of a beam subjected to longitudinal tension as shown in Fig. 3 is analyzed by the finite element method that takes into account finite deformation, using the measured strip edge angles at the weld points. The deflection curve of the beam is obtained as a result.

The deflection curve almost converges, irrespective of the total length of the coil, if the camber length L_c is 200 m or more.

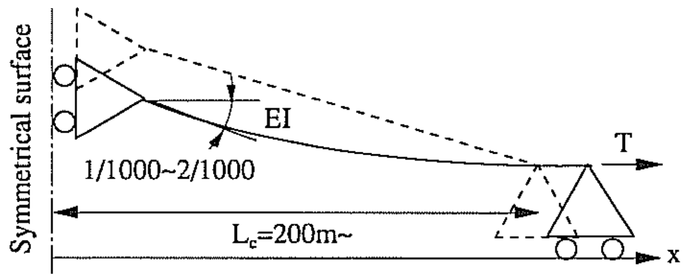


Fig. 3 Estimation of weld point camber profile

Analytical Procedure

The lateral displacement speed of strip at each roll is calculated by the equations presented in the preceding sections and is integrated over time by the simple Euler method, as expressed by the following equation. Response in each time step is successively obtained.

$$y_i(t+\Delta t) = y_i(t) + \Delta t \cdot \frac{dy_i}{dt}(t) \tag{11}$$

Fig. 4 gives an overall flowsheet of this analytical procedure.

EXAMPLE OF ANALYSIS

The walking behavior of strip across weld points was simulated for a continuous annealing furnace of the Yawata Works, Nippon Steel Corporation, as an example. As to the walking amplitude, the calculated lateral displacement of the strip is compared with the measured value to verify the validity of the model.

Analytical Conditions

Fig. 5 shows the profile of the preheating to heating zones of the continuous annealing furnace where the measurement is made. The entry steering device is composed of two transfer rolls. The analytical conditions are as listed in Table 1. The roll misalignment is assumed to be zero, and the deflection curve of the weld point camber is approximated as follows:

$$\delta = A\exp(-B|x|) \tag{12}$$

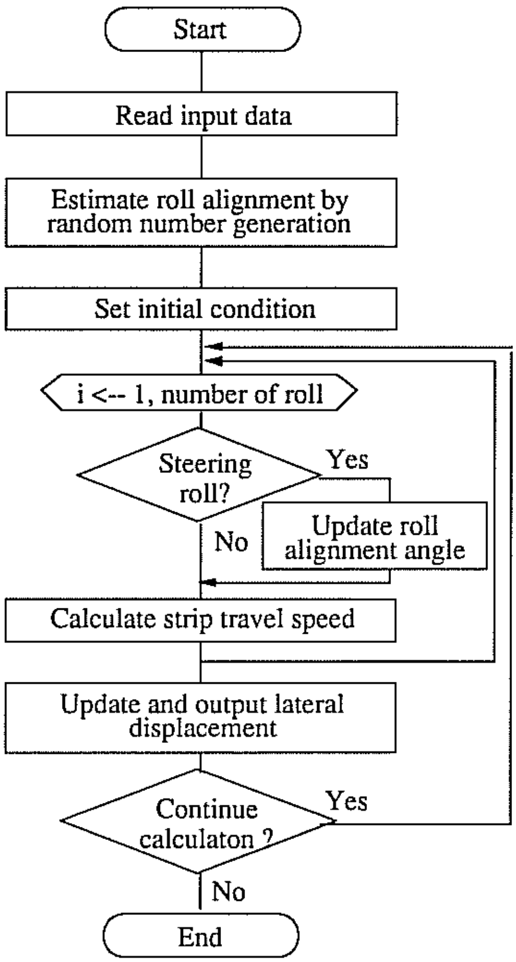


Fig. 4 Flowsheet of analytical procedure

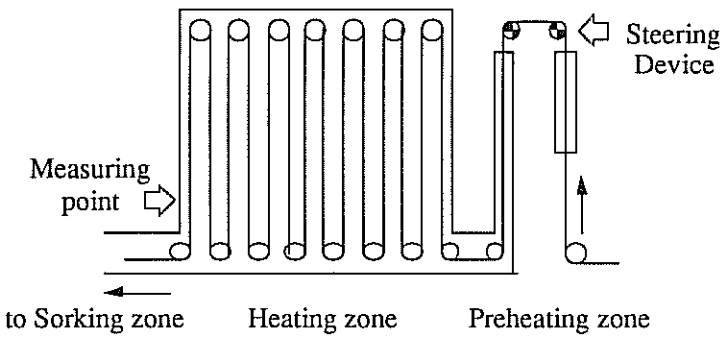


Fig. 5 Construction of line for analysis

Table 1 Analytical conditions

Threading conditions	
Speed Tension	160 m/min 9.8 N/mm^2
Strip conditions	
Strip size Strip rigidity EI EA	1220 x 0.9 mm $5.7 \times 10^{12} N \cdot mm^2$ 1.9×10^8 N
Line conditions	
Roll span (heating zone) Hearth roll taper angle	20.000 m 3.2×10^{-3} rad
Steering device	
Type Ks in eq. (10) Ls in eq. (10)	2 transfer rolls 0.1 sec^{-1} 0.5 sec
Camber shape	
Weld point camber Over 10 m A in eq. (12) B in eq. (12)	 10, 20 mm 23, 46 mm $4.4 \times 10^{-5} m^{-1}$

Method for Measuring Strip Lateral Displacement Data

The lateral displacement of strip in the entry looper, steering device, and final heating zone pass was, measured visually. The weld point camber over 10 m before and after the weld point was measured with three video cameras installed at 10-m interval along the 20-m entry looper (number of samples: 10).

Results of Analysis

The calculated and measured values of weld point camber and strip lateral displacement are proportional, and the calculated values and measured values are in good agreement.

Fig. 7 shows the change in the lateral displacement of strip at each measurement point is shown as ratio to the value obtained in the entry looper. The calculated values are not based on the magnitude of weld point camber.

Fig. 8 shows th calculated changes with time in the lateral displacement of strip at the entry looper, steering device and final (14th) heating zone pass and in the cylinder stroke. The calculated lateral displacement of strip is first reduced to about 50% by the steering device at the time of weld point passage, but is then returned to the original level at the final heating furnace pass. This behavior agrees with actuality.

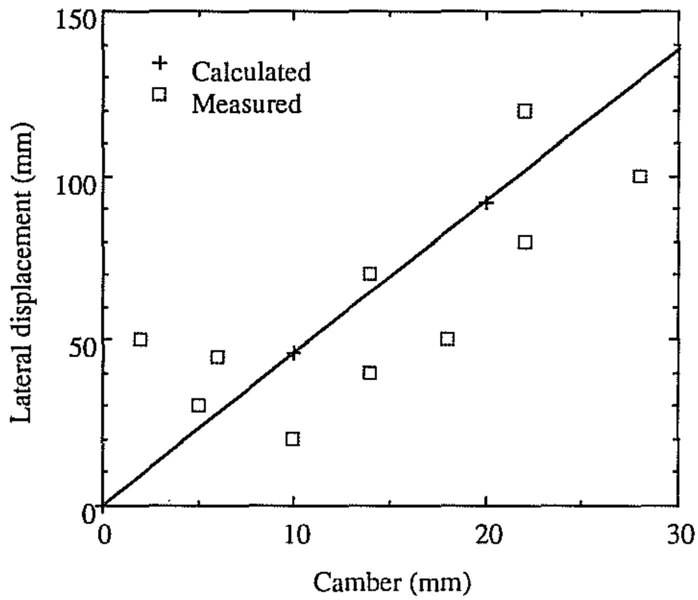


Fig. 6 Relationship between weld point camber and lateral displacement

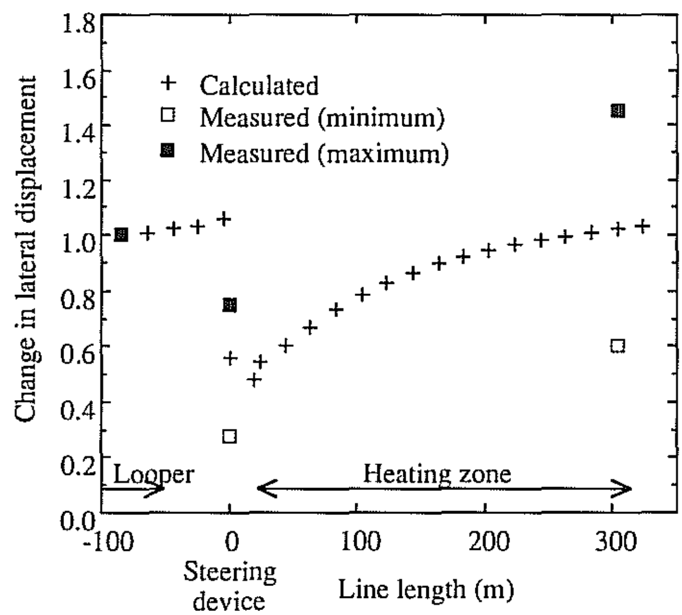
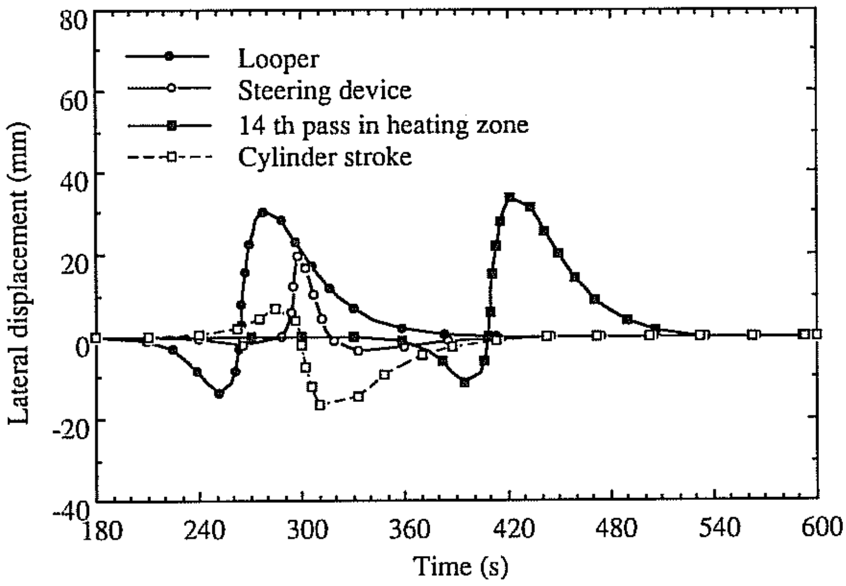
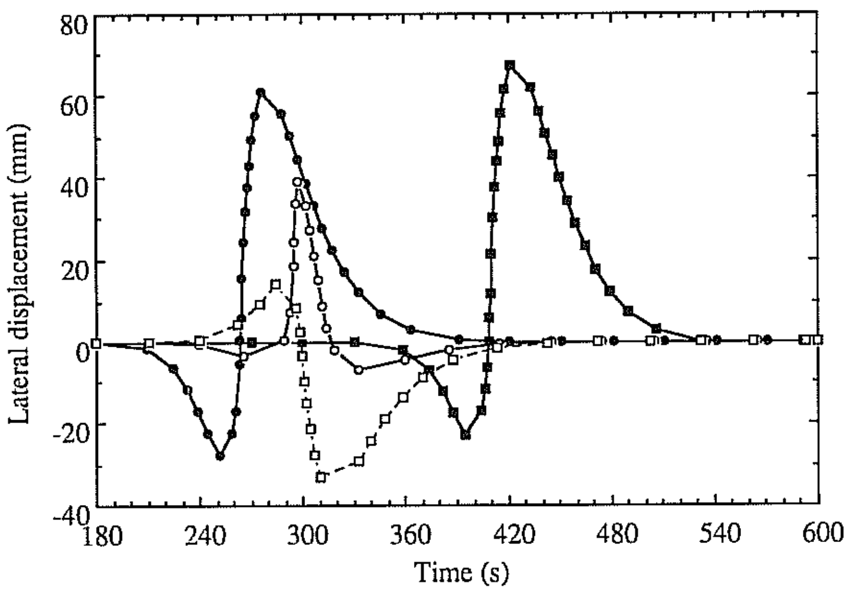


Fig. 7 Change in lateral displacement of strip along line



(a) Camber of 10 mm (over 10 m before and after weld point)



(b) Camber of 20 mm

Fig. 8 Changes with time in lateral displacement of strip and cylinder stroke

CONCLUSIONS

A numerical simulation model was developed to predict the unsteady-state walking behavior of strip on the continuous processing line, including the control system. The results of analysis by the model agreed well with the measured values and verified the effectiveness of the model. The model is contributing to the design of Nippon Steel's continuous strip processing lines.

The findings obtained from this study are follows:

(1) The lateral displacement of strip produced by the passage of a weld point is proportional to the camber of strip at the weld point.

(2) The lateral displacement of strip is first reduced by the control device, but then gradually increases and returns to the original level.

(3) The new model makes it possible to quantitatively predict the lateral displacement of strip on continuous processing lines.

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QUESTIONS AND ANSWERS

Q. Can you calculate the accumulation of the lateral displacement?

A. Yes. It could be accumulated. But, if the strip goes way out of the center line, the strip could keep the position around roll edges due to its stiffness. And also, as there are misalignments with the rolls, those misalignments could compensate the roll out caused by the other initiation. Therefore, it is not always accumulated.

Q. Can't you set up the rolls precisely?

A. No, there are many misalignments, because the furnace can be set up in the only room temperature, and it is operated in high temperature. Therefore, we have to consider those misalignments with random numbers.

Q. Are there any imperfections in the shape of the strip?

A. Yes, there is camber across a weld point.

Q. What is the temperature of the furnace?

A. In the heating zone, the temperature varies from room temperature to 850 degrees Centigrade.

Q. Isn't it difficult to have a steering device in such a high temperature atmosphere?

A. Yes, usually it's very difficult to have a steering device in the heating zone. But, we have developed a steering device for high temperature, so we can set the steering device in any point of the zone.

Q. Don't you need to consider the thickness distribution?

A. No. Because the thickness is very precise compared to the other factors. I don't think that we need to consider the thickness distribution in this case.

Q. What kind of steering device do you use?

A. In this case, we have a two roll type device whose rolls incline to change the entering angle of the strip.