COILER CONTROL IN ENDLESS HOT STRIP ROLLING

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Abstract: JFE Steel Corporation's East Japan Works (Chiba District) started operation of No.3 Hot Strip Mill in 1995. This line was the first in the world to achieve "endless hot strip rolling." A new Coiler Control technology was developed. *Copyright 2005 IFAC*

Keywords: Endless Rolling, Hot Rolling, Coiling Equipment, Strip Shear, Pinch Roll, Strip Floating Carrier, Model

1. INTRODUCTION

So-called "batch rolling" is normally performed in the finish rolling process in hot strip mills. This is the conventional rolling process, in which individual sheet bars are rolled into strip one by one. As a result, the strip lead end and tail end are rolled without tension, causing reduced product quality and yield as well as various other problems.

"Endless rolling" in which multiple sheet bars are joined successively at the entry side of the finish mill, was conceived by as a solution to these problems. To realize endless rolling, highly accurate process control and full automation with high reliability are necessary.

JFE Steel developed the control technologies required to realize this process, including flying joining control, finishing mill joint stabilization, flying gauge change control, and fully automatic high-speed shear and coiler control. Commercial production by the endless rolling process began in 1996 (Nikaido, et al., 1996). The arrangement of the endless rolling equipment at No. 3 Hot Strip Mill (hereinafter referred to as 3HOT) is shown in Fig. 1. This paper describes the coiling control technology developed for endless rolling, together with the results achieved.

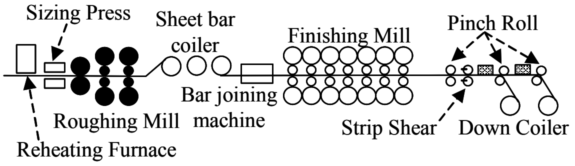

Fig. 1 Layout of 3HOT

2. COILING EQUIPMENT IN ENDLESS ROLLING

New coiling technologies were required in order to realize endless rolling. For example, the thin strip must be cut at a moment immediately before coiling, and alternating down coilers are used to receive the strip continuously at high speed. The coiling specifications of 3HOT are shown in Table 1 and Fig. 2 (Kuwano, 2000).

The major control systems for high speed shearing and coiling are shown in Fig. 3.

Table 1 Coiling specifications of 3HOT

	Endless	batch
thickness[mm]	0.8～6.0	1.2～25
width[mm]	800～1900	600～1900
coil weight[ton]	32	32
Speed[mpm]	1200	1680

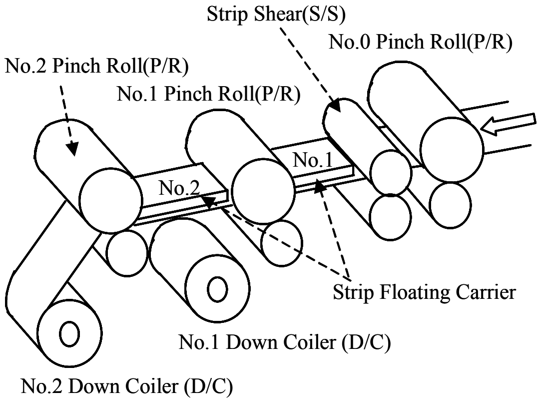

Fig. 2 Coiling equipment for endless rolling

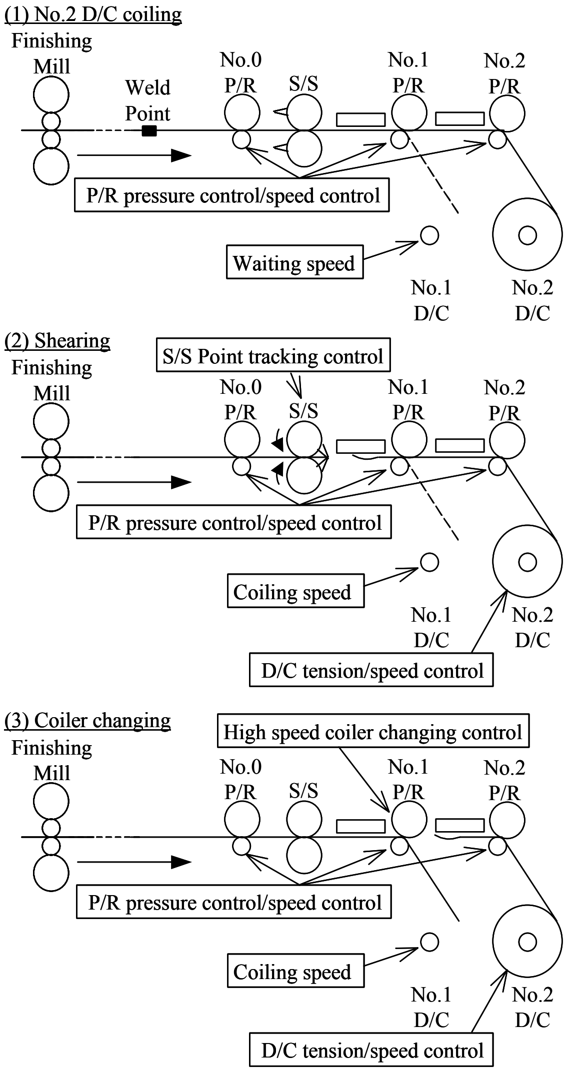

Fig. 3 Coiling control in endless hot rolling

Fully automatic operation is realized by these speed/pressure controls. In particular, because strip behavior becomes extremely unstable before and after shearing, it was necessary to solve a variety of problems. The maximum coiling speed of the strip lead end in batch rolling is approximately 800 mpm, but reaches 1200 mpm in endless rolling. The following trouble which can occur during shearing must be prevented.

(1) Head up at strip lead end ("flying" strip end)
(2) Overlap of strip lead end at pinch rolls (P/R)
(3) Coiling failure due to failure to achieve correct P/R gap setting (strip escape)
(4) Coiling failure due to incorrect P/R speed

Chapter 3 describes these four items in detail. This chapter presents an introduction to the coiling equipment necessary for stable endless rolling.

2.1 Strip Shear (S/S)

The conventional drum shear cut the strip by repeatedly performing a process of stopping → acceleration → and cutting, but is inadequate for the high speed shearing required in endless rolling. Therefore, JFE Steel developed a strip shear in which drum rotation and the cutting function are separated (Fig. 4). The drum speed is synchronized with the strip speed at all times, and the eccentric axis of the shear is rotated at the shearing point, closing the drum gap and cutting the strip.

2.2 Hydraulic Pinch Rolls (P/R)

A double chock oil-hydraulic P/R was developed (Fig. 5). Before the strip is coiled, the P/R waits at the setting gap under position control using an electric hydraulic-servo mechanism and direct operation type servo valve. During coiling, the P/R presses the strip under hydraulic control.

2.3 P/R Gate Change Device

For coiling on No. 1 D/C and No. 2 D/C, which is performed alternately after shearing, No.1 lower P/R is moved in the strip rolling direction. During coiling, this "gate change" is performed by an electric jack and hydraulic cylinder (Fig. 6, Fig. 7).

2.4 Strip Floating carrier

After the finishing mill, a shear is needed to cut the strip, and a P/R is needed to guide the strip to the proper down-coiler (D/C). To prevent trouble, the various improvements mentioned above were required in this equipment. In particular, a Strip Floating Carrier (SFC) was developed to prevent trouble in the process from the S/S to No. 1 P/R , and From No. 1 P/R to No. 2 P/R (Fig. 8).

The SFC is a guide which employs air pressure to float the strip. Running resistance is reduced by floating, while rigidity is increased by bending in the width direction (because the SFC actively applies suction to the strip center). As a result, the SFC prevents head up at the lead end of thin strips, and the strip can be stably paid off by the P/R.

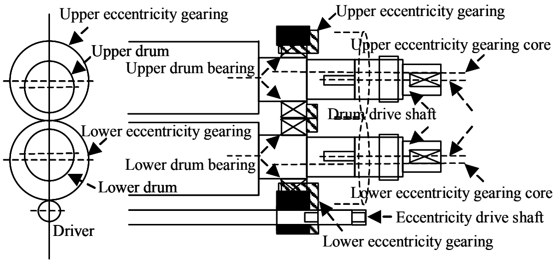

Fig. 4 Eccentricity control equation for drum shear

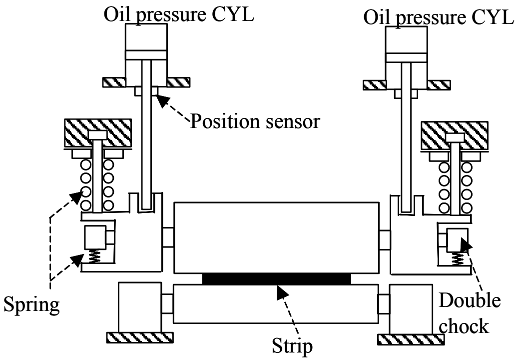

Fig. 5 Hydraulic P/R

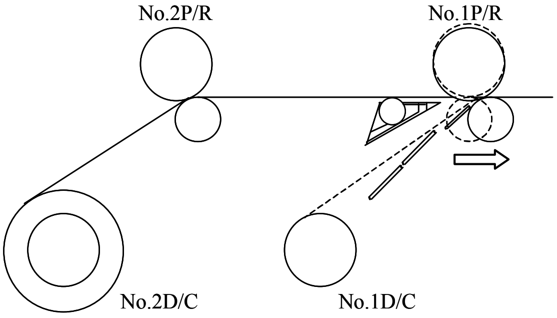

Fig. 6 Gate change for No.1 D/C Coiling set up

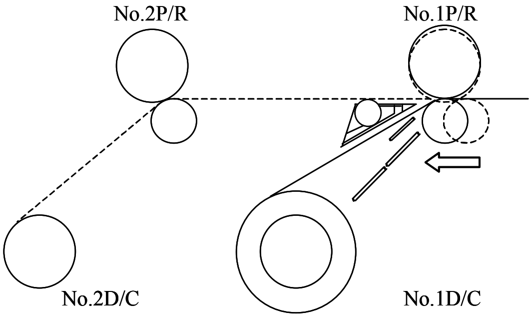

Fig. 7 Gate change for No.2 D/C Coiling set up

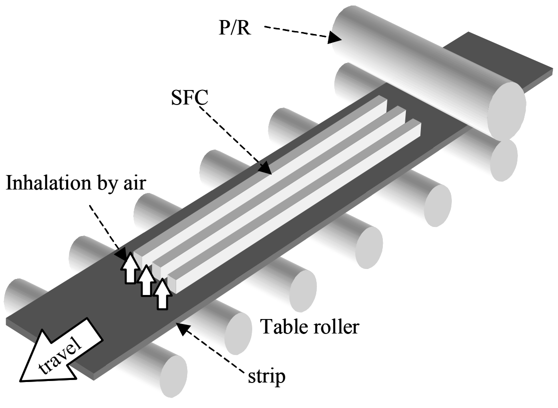

Fig. 8 Strip Floating Carrier

3. THEORETICAL ANALYSIS

3.1 Head up at strip lead end

After shear cutting, the strip lead end may rise from this line, or "head up," if an upward warp exists in the lead end or the lead end rises due to collision with the roll. This occurs because the buoyancy due to air pressure is sufficient to offset the rigidity and dead weight of the strip (Fig. 9). As a result, the strip lead end may fail to bite at the P/R, or coil overlap may occur.

The relationship between the strip speed and thickness when head up occurs can be calculated using a simple model (Fig. 10). A calculated example shows that, with a strip thickness of 1.0mm, head up is possible at 800 mpm (Fig. 11).

Therefore, the possibility of head up is high under the operational specifications of 3HOT in endless rolling, which include a strip thickness 0.8mm and speed of 1200 mpm. Based on this, development of the SFC was judged to be necessary.

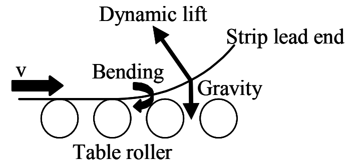

Fig. 9 Balance of forces affecting strip lead end

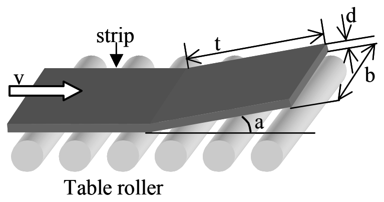

Fig. 10 Model of strip lead end

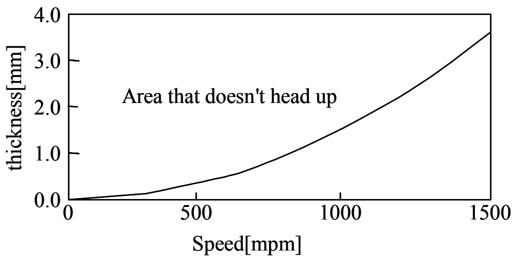

Fig. 11 Thickness/strip speed region with danger of head up

3.2 Coil overlap at strip lead end

In endless rolling, No.1 lower P/R is moved in the direction of strip advance, changing the offset relative to the upper P/R (this is called “gate change”), and the strip is coiled alternately on No. 1 D/C and No. 2 D/C as described in Chapter 2. Therefore, the rear gate of No.1 D/C is set up below the pass line, as shown in Fig. 12. Accordingly, if coil overlaps occurs at the lead end of the strip, causing the upper P/R to jump momentarily, there is a danger of coiling failure, in which the lead end is run out without being led to No.1 D/C.

Figure 13 shows an example of a simulation. here, the track of the lead end of the strip is drawn by the computer. This is an example in which coil overlap occurs at the lead end and the strip then passes through the P/R. In this case, the strip thickness is 2.6mm.

After the lead end passes, the upper P/R reaches its maximum jump at 15.6msec (Fig. 13 (1)). However, the return of the P/R gap is early due to the hard spring of the hydraulic system (Fig. 13 (2)), and as a result, the strip does not escape the rear gate of No. 1 D/C (Fig. 13 (3)).

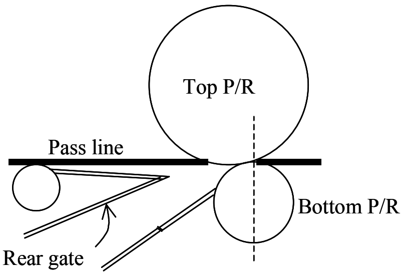

Fig. 12 Rear gate of No. 1 D/C

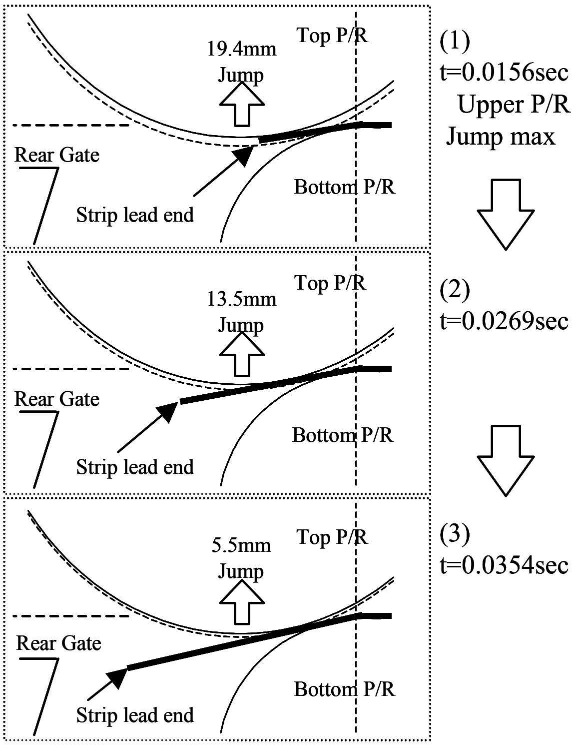

Fig. 13 Simulation of lead end overlap

3.3 Coiling failure due to failure to achieve correct P/R gap setting (strip escape)

A newly developed technique was introduced to ensure stable switching from No. 2 D/C to No. 1 D/C. With this technique, immediately before cutting, No. 1 P/R is pushed into a position where coiling by No.1 D/C is possible. Here, No. 1 P/R executes pressure control with the upper and lower P/R offset in the vertical direction. It is necessary to push No. 1 upper P/R from this stationary state to the necessary gap.

The amount of gap change is given by δx. The necessary gap change is obtained from the following balance equation.

Gap change (W_1) – Displacement in rolling direction (W_2) = Bend and bend return (W_3)

No.1 P/R gap is controlled based on this expression.

W_1, W_2, and W_3 will be explained in the following. x is the vertical direction position of the upper P/R. When the strip tension F is given, $x = 0$ is the position where the strip comes in contact with No.1 P/R. W_1, W_2 and W_3 when operating from $x = 0$ to $x = \delta x$ are as follows. Here, $P(x)$ is the pressure when No. 1 P/R is at x.

$$W_1 = \int_0^{\delta x} P(x)dx \tag{1}$$

From actual rolling data, it was found that the relationship between P/R gap displacement and P/R pressure shows the behavior of a linear function. Eq. (1) can be rewritten as follows, using pressure P_0 at a certain position.

$$W_1 = \int_0^{\delta x} P_0 \cdot \frac{x}{\delta x} dx = \frac{1}{2} \cdot P_0 \cdot \delta x \tag{2}$$

On the other hand, the following Eq. (3) is obtained considering displacement Δu in the direction of applied tension (i.e., rolling direction).

$$W_2 = F \cdot \Delta u \tag{3}$$

Moreover, the respective W_3 (bend and bend return) of the upper and lower P/R are as follows.

$$W_3 = 2 \cdot M_B \cdot \left(\frac{L_L}{R_L} + \frac{L_U}{R_U} \right) \tag{4}$$

where, M_B: bending moment of lower P/R, L: bend length, R: curvature radius, and subscripts, U: upper P/R, and L: lower P/R.

$$M_B = \frac{1}{6} \cdot \sigma_B \cdot t^2 \cdot W \tag{5}$$

where, σ: yield stress, t: strip thickness and W: strip width. When Eq. (5) at a bending moment is used, the following equation is obtained from Eq. (1), (2), (3), and (4).

$$P_0 = \frac{2F \cdot \Delta u}{\delta x} + \frac{4}{\delta x} \left(\frac{L_L}{R_L} + \frac{L_U}{R_U} \right) \frac{\sigma_B \cdot t^2 \cdot W}{6} \tag{6}$$

In an actual operation, immediately before cutting, pressure P_0 shown by Eq. (6) or higher is achieved. In addition, the P/R gap is held in order to withstand the impact during the strip escape. Stable coiling became possible by applying Eq. (6).

3.4 Coiling failure due to incorrect P/R speed

When cutting the strip, the following speed setting is used to switch stably from No. 2 D/C to No. 1 D/C.

$$V_m > V_{P1} > V_{P2} > V_s .$$

where, V_m: No. 2 D/C Coiling speed, V_{p1}: No. 2 P/R speed, V_{p2}: No. 1 P/R speed, and V_s: strip speed. V_m is necessary to pull the succeeding strip, which is to be coiled by No. 1 D/C, apart from the strip coiled by No. 2 D/C (preceding strip), and should therefore be the fastest speed among those shown here. $V_{P1} > V_{P2}$ is required in order to maintain the tension between No. 1 P/R and No. 2 P/R, and $V_{P2} > V_s$ is required in order to pull the succeeding material forward into No. 1 D/C.

Here, immediately after cutting, regeneration side torque is generated in No. 1 P/R. This is because the No. 1 P/R speed instruction is slow compared with the speed of No.2 M/D. When the tail end of the preceding strip passes directly under No.1 P/R, excessive regeneration torque may be generated because the rigidity of the strip increases as the strip thickness becomes greater. This means that it may be impossible to maintain $V_{P2} > V_s$ after the tail end of the preceding strip passes due to excessive deceleration. If this occurs, a wave may be generated in the leading end of the succeeding strip at the entry side of No. 1 P/R. It should also be noted that the interval between the tail end of the preceding strip and the head end of the succeeding strip is only approximately 0.3s.

Therefore, a method of providing a regeneration side torque limit ($T_{\min}$) at No.1 P/R was analyzed and applied.

The P/R and the motor are connected through a gear. The following motion equations are materialized in the P/R at time t. Here, $F(t)$[kN]: force which the lower P/R receives from the strip, $T_M(t)$[Nm]: motor torque (positive rotation side: +, reverse rotation side: -), J_2 [Nm^2]: moment of inertia of P/R , J_1 [Nm^2]: moment of inertia of motor, ω_2 [rad/s]: angular velocity of P/R, ω_1 [rad/s]: angular velocity of motor, $T(t)$ [Nm]: torque generated by P/R reduction gear, i: reduction ratio, D [m]: diameter of lower P/R roll.

$$\frac{1}{i} \cdot T(t) - F(t)\frac{D}{2} = J_2 \cdot \frac{d\varpi_2}{dt} \tag{7}$$

Moreover, these factors are balanced in the motor by the following equation.

$$T_M(t) - T(t) = J_1 \cdot \frac{d\varpi_1}{dt} \tag{8}$$

When $T(t)$ is eliminated from Eq. (7) and (8),

$$T_M(t) - i \cdot F(t) \cdot \frac{D}{2} = \left(J_1 + J_2 \cdot i^2\right) \cdot \frac{d\varpi_1}{dt} \tag{9}$$

Next, when the two sides of Eq. (9) are integrated,

$$\int_{t1}^{t2} \left(T_M(t) - i \cdot F(t) \cdot \frac{D}{2} \right) dt = \left(J_1 + J_2 \cdot i^2\right) \cdot \int_{\varpi_{t1}}^{\varpi_{t2}} d\varpi_1 \tag{10}$$

where, ω_{t1} and ω_{t2} are the angular velocity of the lower P/R at the respective times, t_1, t_2. In Eq. (10), $F(t)=0$ is the interval between the tail end of the preceding strip and the lead end of the succeeding strip. Therefore, when t_1: time when tail end of preceding strip passes, t_2: time when lead end of succeeding strip passes, Eq. (10) is as follows.

$$\int_{t1}^{t2} T_M(t)dt = \left(J_1 + J_2 \cdot i^2\right) \cdot \int_{\varpi_{t1}}^{\varpi_{t2}} d\varpi_1 \tag{11}$$

Immediately before the tail end of the preceding strip passes, $T_M(t)$ is a negative value (deceleration). Here, the relationship $T_M(t) > T_{\min}$ is materialized when a torque limit $T_{\min}$ on the deceleration side is provided. For the most conservative evaluation, $T_M(t)$ was set at $T_{\min}$ between t_1 and t_2. In this case, Eq. (11) can be expressed as follows.

$$\int_{t1}^{t2} T_{\min} dt = \left(J_1 + J_2 \cdot i^2\right) \cdot \int_{\varpi_{t1}}^{\varpi_{t2}} d\varpi_1 \tag{12}$$

Solving Eq. (12), the angular velocity change ($\Delta\omega$ [rad/s]) of the lower P/R at time $t_2 - t_1$ [sec] after passage of the tail end of the preceding strip can be obtained by the following equation.

$$\Delta\varpi = \varpi_{t2} - \varpi_{t1} = \frac{T_{\min} \cdot t_2}{J_1 + J_2 \cdot i^2} \tag{13}$$

Therefore, if the speed (V_s) of the lead end of the succeeding strip satisfies Eq. (14), wave will not occur in the lead end at entry side of No.1 P/R.

$$V_S \le \left(\varpi_{t1} + \Delta\varpi\right)\frac{D}{2} \cong \left(\varpi_{P2} + \Delta\varpi\right)\frac{D}{2} \tag{14}$$

Here, ω_{t1} does not become smaller than the setting angular velocity ω_{t2} of the lower P/R. Therefore, as shown by Eq. (14), no problems should occur so long as these conditions are approximated. From Eq. (13) and (14), satisfactory results can be obtained if $T_{\min}$ given by the following Eq. (15) is satisfied.

$$T_{\min} \ge \frac{2 \cdot \left(J_1 + J_2 \cdot i^2\right) \cdot \left(V_S - \varpi_{P2} \cdot 0.5 \cdot D\right)}{D \cdot t_2}$$
$$= \frac{2 \cdot \left(J_1 + J_2 \cdot i^2\right) \cdot \left(V_S - V_{P2}\right)}{D \cdot t_2} \tag{15}$$

Here, the following relationship is used:

$$\varpi_{P2} \cdot \frac{D}{2} = V_{P2} \tag{16}$$

The right side of Eq. (15) is a known value or the setting value. Therefore, by setting the torque limit as shown in the Eq. (15), wave in the tail end of the preceding strip and lead end of the succeeding strip can be prevented.

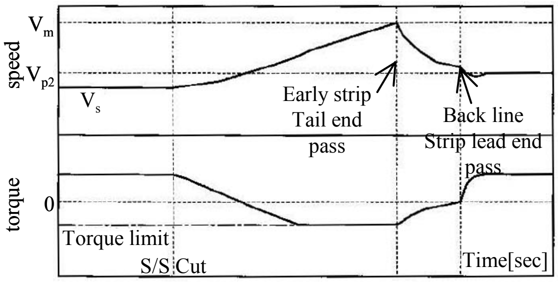

Fig. 14 Rotational speed and torque of P/R with torque limit

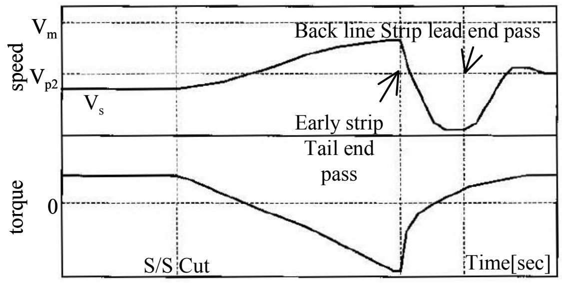

Fig. 15 Rotational speed and torque of P/R without torque limit

Figure 14 shows the rotational speed and torque of the P/R when the torque limit is applied. Compared with the chart before application of the torque limit (Fig. 15), a steady speed is maintained during bite of the lead end of the succeeding strip. In actual operation, wave does not occur.

4. CONCLUSION

A new coiling control technology for endless hot strip rolling was discussed. In particular, the strip coiling technique using the Strip Floating Carrier and speed control of the pinch rolls were described. Stable coiling has been realized in endless hot strip rolling by using this control technology.

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