Technology for Reducing Strip Meandering in Tandem Cold Mill

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Strip meandering in a tandem cold mill causes strip breakage troubles and must be suppressed. The issue of meandering has been studied for a long time, but many of the studies focused on runout of the strip tail end with tension released, or on the inter-stand meandering behavior during tandem rolling. On the other hand, even at the entry side of a tandem cold mill with a tension lower than that of inter-stand, strips may meander due to various disturbances and cause problems. Hence, an analysis model of meandering behavior was constructed while considering the restraint by bridle rolls disposed on the entry side of a tandem cold mill. The effect of entry-side tension on meandering behavior was investigated, and the calculation results were verified by rolling experiments. It was found that the tension enhancement on the entry-side was effective for the suppression of meandering. Consequently, the entry-side tension of the tandem cold mill of Kakogawa Works was increased, and this has reduced the problems due to meandering.

Introduction

Tandem cold rolling is an intermediate process that supplies semi-products to the annealing and galvanizing processes and is important in creating the thickness of cold-rolled and surface-treated steel products. In tandem cold rolling, it is essential to stably supply semi-product to the subsequent process. One of the factors that inhibit stable production in the tandem cold rolling is that a steel strip may be rolled off-center in the rolling mill (hereinafter referred to as "meandering"). If this happens, there is a risk that the steel strip will be partially buckled, folded into a roll bite and broken. Once a steel strip breaks, the clean-up takes a long time, resulting in a significant loss of opportunity, as well as economic losses caused by yield loss and roll damage. Hence, the reduction of meandering is a challenge that must be addressed for the stable operation of cold-rolling mills.

The problem of meandering in strip rolling has been studied for a long time, including the construction of analysis models, experimental verifications, and the development of techniques for controlling meandering.[1)-7)] Many of these studies focused on "runout of strip tail end," in which tension is released at the tail end of the coil, and "inter-stand meandering behavior" in tandem rolling. On the other hand, since the tension on the entry side of tandem rolling is lower than the inter-stand tension, meandering may easily be caused by non-symmetric components such as a difference in mill rigidity between the work side (WS) and drive side (DS), leveling difference in roll gap, wedging of hot-rolled strip (thickness difference between left and right sides), and camber. Particularly in the case of high-tensile-strength steel, which causes greater roll-separating force, the effect of asymmetry in rolling becomes even more significant.

Hence, an analysis was performed to see how the entry-side tension of the rolling mill influences meandering. The effect of the entry-side tension was evaluated by the laboratory and rolling experiments using an actual apparatus, and it was clarified that the strip meandering can be suppressed by increasing the entry-side tension of the mill. On the basis of these results, the tension on the entry side of the tandem cold rolling mill at Kakogawa Works was increased; making this change has greatly reduced the troubles caused by strip meandering. This paper reports on the outline of that approach.

1. Analysis of strip meandering behavior during rolling

The hitherto proposed methods for analyzing strip meandering during rolling include the deformation analysis of the rolling mill, deformation analysis of material and the relational expressions between the incident angle or left/right speed difference and meandering. Each analytical method has led to an examination result showing that the amount of meandering gradually increases if there is an initial irregularity such as a roll gap leveling difference (the difference in the gap between the left and right sides of the rolling mill, hereinafter referred to as "leveling difference").[1)-7)] On the entry side of the tandem rolling mill, however, the strip is restrained gently by tension, and meandering rarely continues to increase, even when an initial irregularity such as a leveling difference exists. Thus, the conventional methods of analysis do not necessarily represent the actual phenomena.

Hence, the model shown in **Fig. 1** was devised on the assumption that there is a meandering retention mechanism involving tension. Fig. 1 shows an example where there is an initial irregularity of leveling difference. If the rolled material is not restrained at its rear (Fig. 1, bottom), the rolled material rotates around a point directly below the roll and enters the roll bite at an incident angle of θ_S (Fig. 1 (a)), as is the case with conventional analytical methods. On the entry side of the tandem rolling mill, however, the rolled material is fixed by a bridle roll in the width and traveling directions and cannot rotate on the entry side of the rolling mill. Due to this constraint, a tension distribution, $\sigma'_E(x)$, is formed on the entry side of the rolling mill (Fig. 1(b)). This entry-side tension is generated by the in-plane bending back of the strip, and the distribution is such that the tension on the narrow side of the roll gap is low and the tension on the wide side of the roll gap is high. Due to such a tension distribution, the load on the side with a narrow roll gap increases, and, while the load on the side with a wide roll gap decreases so as to cancel the difference in the roll gap. If the rolling is further continued and the rolled material meanders more, the difference in tension between the left and right sides increases, and the initial leveling difference between the left and right sides disappears completely. As a result, the rolled material enters the rolling mill at an incident angle of 0, and meandering stops (Fig. 1 (c)).

Fig. 2 shows the numerical calculation method for analyzing meandering on the basis of the above concept. First, assumptions are made for initial irregularities such as the leveling difference, wedging, and initial amount of meandering. Next, taking the bridle roll on the entry side of the tandem rolling mill as a rigid support, the deformation of the strip between the bridle roll and the head stand is calculated to determine the tension distribution at the entry side of the head stand. This entry-side tension distribution is used to calculate the

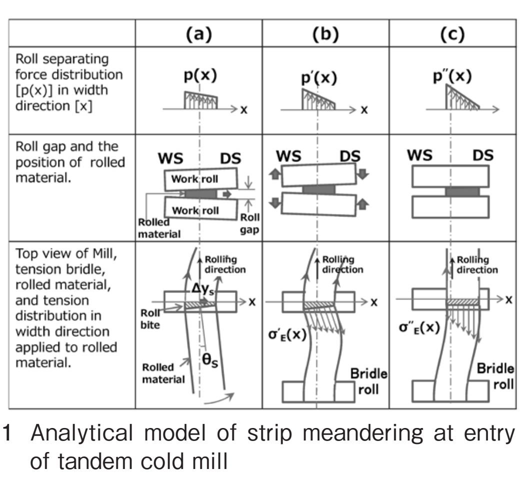


Fig. 1 Analytical model of strip meandering at entry side of tandem cold mill

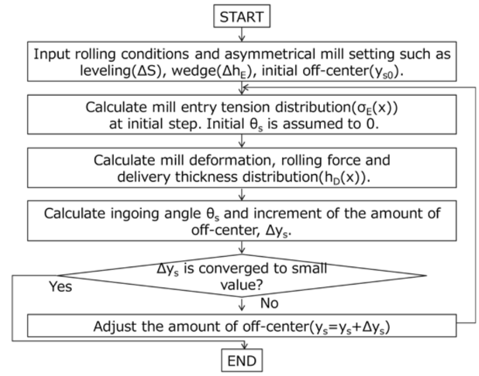


Fig. 2 Method of calculating strip meandering at entry side of cold strip mill [8)]

deformation of the rolling mill, the rolling load distribution, the strip thickness distribution on the exit side, and the difference in reduction ratio between the left and right sides. The incident angle θ_S is obtained from the difference in reduction ratio between the left and right sides, and the meandering increment Δy_S during the minute time Δt is added to the initial value or the amount of meandering obtained in the previous calculation. The entry-side tension distribution is calculated for the renewed amount of meandering. Similarly, the meandering behavior of the strip is calculated by repeatedly calculating the load distribution, strip thickness distribution, reduction ratio difference, and amount of meandering increment. It should be noted that the incident angle θ_S and meandering increment Δy_S are calculated using the following geometric equation, in which v_s is the strip speed on the entry side of the rolling mill.

$$\Delta y_S = v_s \cdot \tan\theta_S \cdot \Delta t \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1)$$

Fig. 3 shows a calculation example for the amount of strip meandering and the tension distribution in the strip width direction at the entry side of a rolling mill. The calculation conditions are shown in the figure. Considering the availability of material for comparison of the calculation results with those of laboratory rolling described later, aluminum is used here. Referring to Fig. 3, when the strip meanders on the entry side of the rolling mill, a compressive stress is formed toward the inside of the bend and a tensile stress is formed toward the outside of the bend due to the in-plane bending of the strip. These stresses are added to the initially loaded tension. As the amount of meandering increases, the stress toward the inside of the bend (the left side of each graph in Fig. 3) becomes compressive even after the addition to the loaded tension (Fig. 3 (b)). The strip does not buckle when the compressive stress is small; however, when under a compressive stress above a certain level,

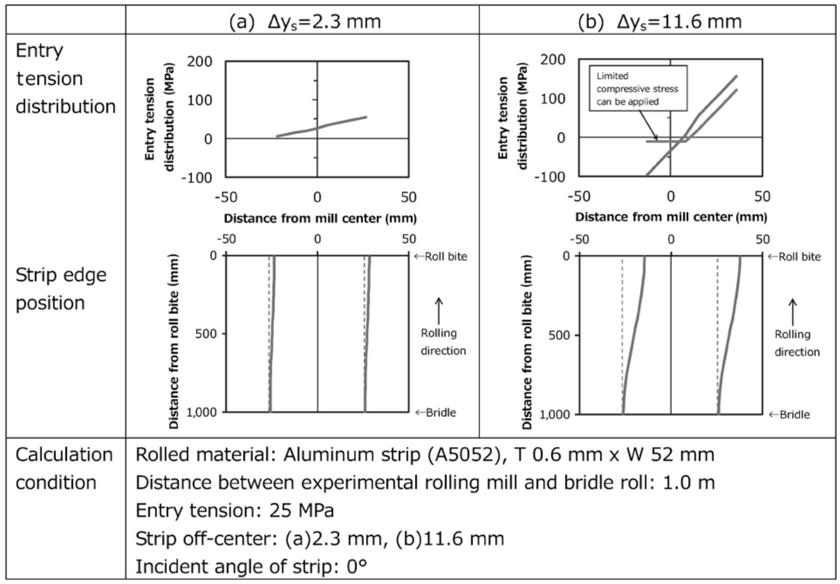


Fig. 3 Examples of calculation of tensile distribution caused between off-center value of rolled strip and entry side of rolling mill

Table 1 Conditions of strip meandering calculation

Experimental Rolling mill	4H, Work roll: Φ 50 mm ×L 200 mm Back up roll: Φ 200 mm ×L 200 mm
Rolled Material	Aluminum, A5052 T 0.6 mm ×W 52 mm
Reduction	24%
Entry tension	(1)(2)30 MPa (3)100 MPa
Delivery tension	50 MPa
Roll gap leveling	(1)50 μm (2)(3)250 μm
Length between entry side bridle roll and Rolling mill center	1,000 mm

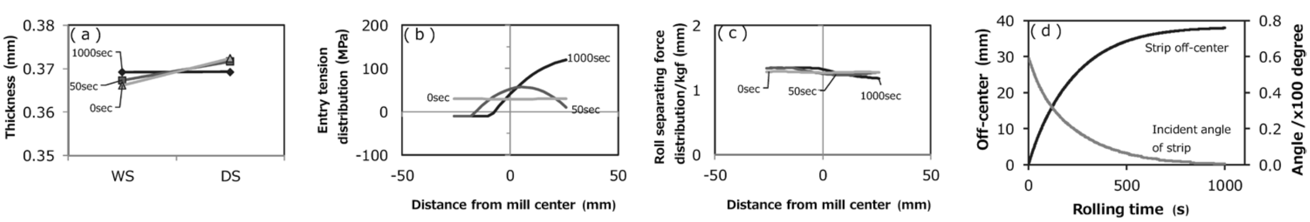


Fig. 4 Analytical result (1) with small initial roll gap leveling difference.
(a) Thickness of rolled material at exit side of roll bite.
(b) Tension distribution along width direction at entry side of roll bite.
(c) Roll separating force distribution along width direction. (d) Strip meandering and incident angle.

out-of-plane deformation of the strip occurs due to local buckling. It is estimated that the compressive stress at which no local buckling occurs (allowable compressive stress) depends on the strip thickness and strip width; hence, this analysis employed an adjustment parameter determined by experiments and other means.

The strip thickness distribution, load distribution, tension distribution, and amount of meandering were sequentially calculated in accordance with the flow in Fig. 2. **Table 1** shows the analysis conditions. Here, leveling difference is taken up as an asymmetry factor. **Fig. 4** shows the analysis results when the leveling difference is 50 μm, **Fig. 5** shows the analysis results when it is 250 μm, and **Fig. 6** shows the analysis results when the leveling difference is 250 μm and the entry-side tension is 100 MPa. Since there is a leveling difference in either case, a difference in strip thickness is found between the left and right sides at the beginning of the sequential calculation (Fig. 4-6 (a): rolling time=0 s). As the calculation is repeated, the strip gradually meanders to the wide side of the gap (Fig. 4-6 (d)), increasing the tension difference

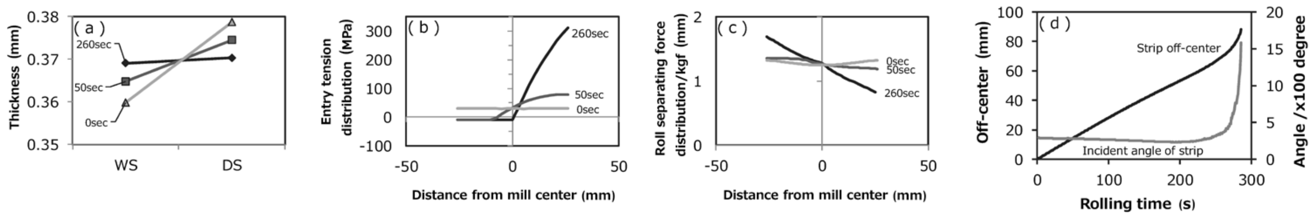


Fig. 5 Analytical result (2) with large initial roll gap leveling difference.
(a) Thickness of rolled material at delivery side of roll bite.
(b) Tension distribution along width direction at entrance of roll bite.
(c) Roll separating force distribution along width direction. (d) Strip meandering and incident angle.

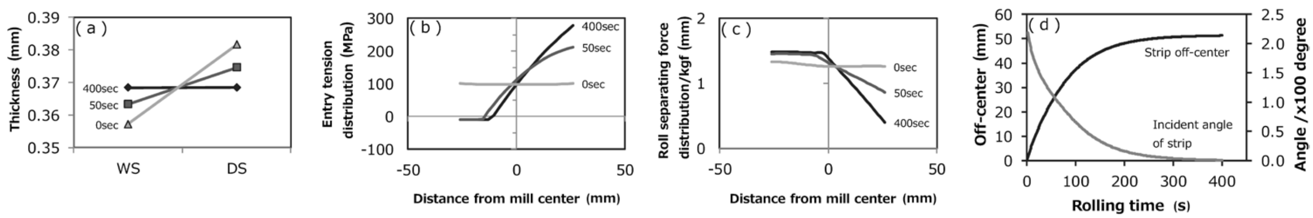


Fig. 6 Analytical result (3) with large tension being applied to strip at entry side of roll bite.
(a) Thickness of rolled material at exit side of roll bite.
(b) Tension distribution along width direction at entry side of roll bite.
(c) Roll separating force distribution along width direction. (d) Strip meandering and incident angle.

between the left and right sides (rolling time=50s). As a result, the rolling load on the side where the strip meanders decreases (Fig. 4-6 (c)), and the difference in strip thickness between the left and right sides gradually decreases (Fig. 4-6 (a): rolling time=1,000, 260, 400s). Through such a process, when the given leveling difference is small (Fig. 4) and after the meandering of about 40 mm, the thickness difference between the left and right sides is eliminated, the incident angle becomes zero, and the meandering stops. Under the condition of a great leveling difference (Fig. 5), when the amount of meandering increases, the compressive stress due to in-plane bending of the strip increases, expanding the region with compressive stress exceeding the allowable range. Further expansion of this region does not increase the tension difference between the left and right sides, and the load difference between the left and right sides does not increase. As a result, the meandering continues to propagate without resolving the thickness difference of the strip (divergence of meandering).

On the other hand, when the entry-side tension is increased (Fig. 6), even if the strip greatly meanders, the differences in tension and load between the left and right sides can be increased without expanding the region where compressive stress exceeds the allowable range. As a result, the difference in strip thickness is eliminated, the incident angle becomes 0 degrees, and the meandering stops (Fig. 6).

2. Method of meandering experiment using test rolling, experimental results and discussion

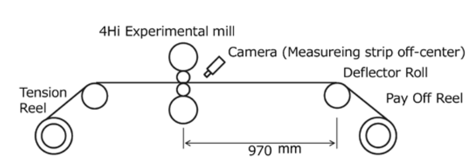
In order to confirm the validity of the method of analyzing meandering, testing was conducted using an experimental rolling mill. **Table 2** shows a diagram of the experimental rolling mill and the testing conditions. The strip was filmed by a camera installed above the entry side of the rolling mill, and the amount of meandering of the strip was calculated by reading the position of the strip end in the captured image.

Fig. 7 shows the experimental and analytical results of the meandering behavior when the leveling difference is changed. In the case of the experimental rolling mill, meandering stopped under the conditions where the leveling difference was

Table 2 Schematic diagram of experimental rolling mill and experimental conditions

Experimental Rolling mill	4H, Work roll: Φ 50 mm ×L 200 mm Back up roll: Φ 200 mm ×L 200mm
Rolled Material	Aluminum, A5052 T 0.6 mm×W 52 mm
Reduction	33 %
Entry tension	10-80 MPa
Delivery tension	24 MPa
Roll gap leveling	0-200 μm

Schematic diagram of experimental rolling



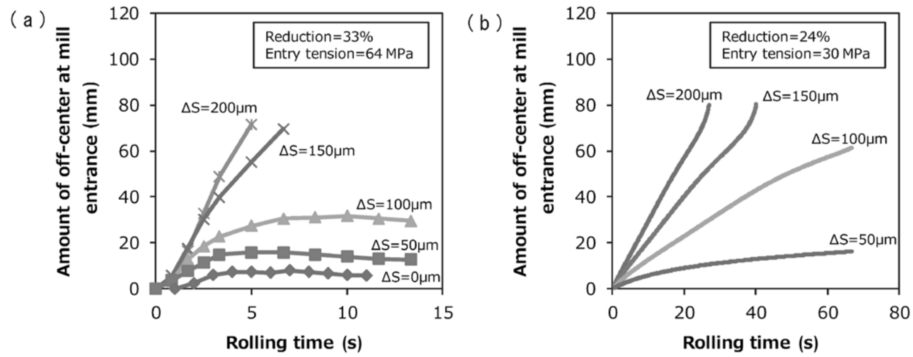


Fig. 7 Relationship between roll gap leveling difference ΔS and strip off-center, (a) experimental result and (b) analytical result

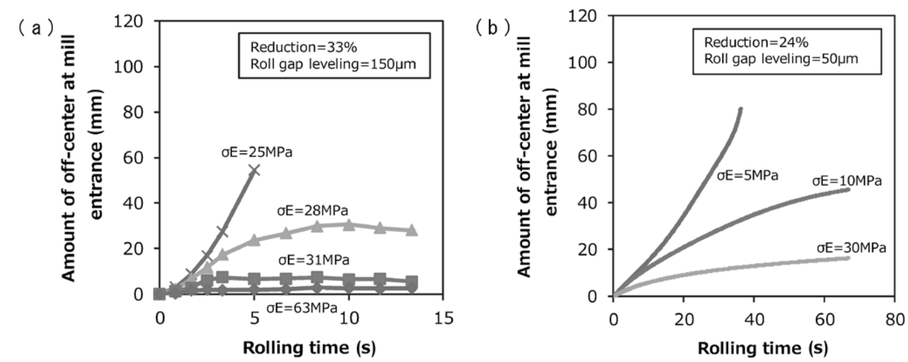


Fig. 8 Relationship between entry-side tension σE and strip off-center, (a) experimental results and (b) analytical results

small (less than 100 μm). When a certain threshold (between 100 μm and 150 μm) was exceeded, however, the meandering rate (the increase in meandering when rolling for a certain length) rapidly increased and the meandering diverged. In the meandering analysis also, meandering stopped when the leveling difference was 50 μm, and diverged when the leveling difference was 150 μm or greater. When the leveling difference was intermediate, 100 μm, however, the amount of meandering continued to increase while the meandering rate gradually slowed down.

Fig. 8 shows the experimental and analytical results of the meandering behavior when the entry-side tension is changed. In the case of the experiment using the rolling mill for testing (Fig. 8 (a)), meandering stops when the tension is high, as in the case where the leveling difference is changed. As the tension is gradually decreased, however, the amount of meandering when the strip meandering ends gradually increases, and when the tension falls below a certain threshold (28 MPa), meandering increases rapidly and diverges. Meanwhile, in the analysis, meandering stops when the tension is high, and amount of meandering increases and gradually diverges when the tension is low. There is, however, no clear transition between diverging and stopping as in the experimental results.

The meandering behavior on the entry side of a tandem rolling mill will be discussed while considering the above experimental and analytical results. First, the strip starts meandering due to initial irregularities such as a slight leveling difference, wedging, and a difference in mill stiffness (**Fig. 9** (a)). If the initial irregularity that induces such meandering is small, the entry-side tension distribution generated by slight left-and-right meandering of the strip eliminates the difference in thickness between the left and right sides of the strip, and the meandering stops (Fig. 9 (b)). Normally, it is considered that rolling is performed in such a manner.

On the other hand, when the initial irregularity is great, the compressive stress in the longitudinal direction caused by the in-plane bending of the strip exceeds the critical limit of buckling, and the tension difference between the left and right side does not increase. As a result, the difference in rolling load between the left and right sides does not increase, the difference in thickness between the left and right sides of the strip is not eliminated, and the meandering continues to propagate (divergence of meandering) (Fig. 9 (c)). Increasing the entry-side tension prevents buckling from occurring because the region where compressive stress is formed is limited to a narrow range even if the tension difference between the left and right sides is increased. Therefore, the differences in the tension

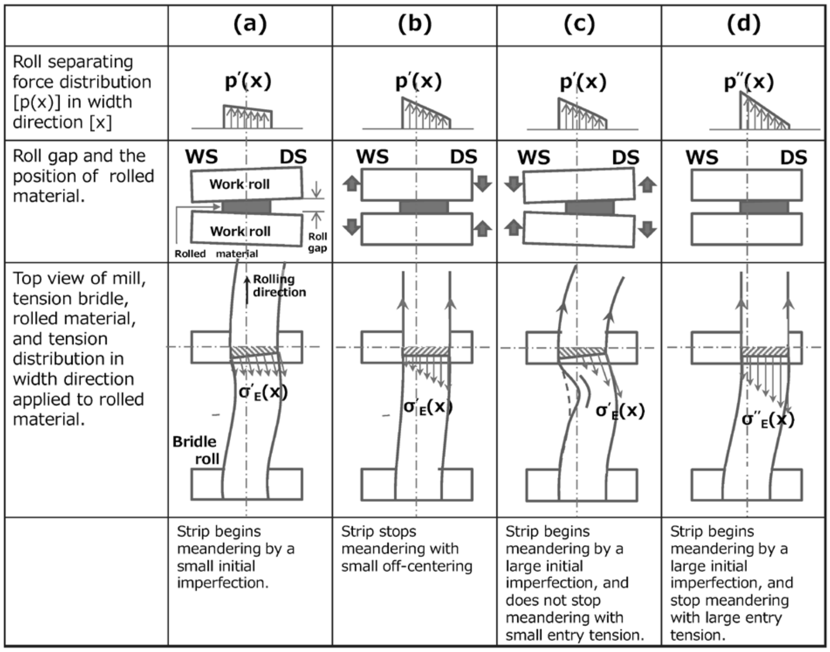


Fig. 9 Mechanism of retention and divergence in strip meandering phenomenon at tandem cold mill

and load continue to be corrected until the thickness difference between the left and right sides of the strip is eliminated and the meandering stops (Fig. 9 (d)).

Moreover, the experimental and analytical results (Figs. 7 and 8) show a difference in the propagation time of meandering. This is considered to be due to the following reasons: When there is an initial irregularity in the rolling conditions, the advance rate and reverse rate differ on the left and right, causing a left-and-right-side difference in the length of the entry side material entering the roll bite. In the experiment, the difference in entry-side length on the left and right sides accumulates as rolling proceeds, while the analysis does not take into account the accumulation of this difference in length. Therefore, the out-of-plane deformation due to entry side compressive stress occurs earlier in the case of the experiment, and meandering propagates. Also, since the ultimate tension distribution is reached earlier in the experiment, the time before stopping becomes shorter than that in the analysis.

If meandering follows the above mechanism, the following facts are considered to hold:

(1) When the strip is thick on the entry side, the allowable compressive stress is increased, making buckling less likely to occur, which makes it easier to stop meandering.
(2) When the strip is wide, a slight meandering causes a difference in an in-plane tension that is greater than that for a narrow strip between the left and right sides, which makes meandering less likely.
(3) Even if the distance between the rolling mill and entry side restraint rolls, such as bridle rolls, is made smaller, the difference in tension between the left and right sides during meandering is increased, making meandering more likely to stop.
(4) If the original strip is not flat enough when entering the rolling mill and becomes wavy on the entry side of the rolling mill, a large in-plane tension difference cannot be formed, making meandering likely to diverge.

It is difficult to change the equipment layout of the existing tandem rolling mill. From the above considerations, however, it is thought that the tension can be increased on the entry-side of the rolling mill, where the strip is relatively thick, and thereby the meandering can be stopped without its diverging.

3. Suppression of meandering by increasing entry-side tension of actual tandem cold mill

3.1 Equipment outline of tandem cold mill

Fig.10 shows the overview of the tandem cold mill at Kakogawa Works of Kobe Steel. The rolling mill comprises a total of 5 stands, and entry-side tension is imparted by the bridle rolls on the entry side of the mill. Tension-meter rolls for measuring the strip tension are disposed on the entry and exit sides of each stand and is controlled so that the tension value inputted beforehand in a table is imparted.

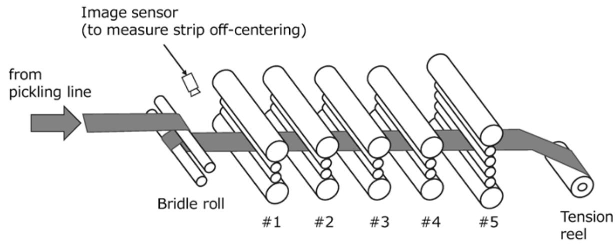


Fig.10 Overview of tandem cold mill in Kakogawa Works

The motor output that imparts the tension is 8,000 kW for each stand, while that of the bridle roll on the mill entry side is 360 kW. Thus, the entry side of the mill is configured to impart a tension smaller than the tension imparted between the stands.

3.2 Experimental method

In order to confirm that increased entry-side tension has a suppressive effect on meandering, the relationship between the mill entry-side tension and amount of meandering was investigated using an actual cold tandem rolling mill.

The rolling was performed using the actual cold tandem mill in a steady state with stable rolling conditions. Next, a leveling difference of 150 μm was applied to the #1 stand so as to initiate meandering, and the applied leveling difference was maintained for 15 seconds after the start of operation in order to measure the amount of meandering of the strip rolled during that period. A CCD camera was fixedly disposed at the middle position of the center-position-control device, the strip roll closest to the #1 stand of the tandem rolling mill, and the amount of meandering was measured on the image of the strip, the strip-edge position having been extracted using an image processing apparatus. Since the strip centering is performed by the center-position-control device, the amount of strip meandering measured at the intermediate position is considered to be about half of the amount of strip meandering directly under the #1 stand.

The experimental conditions are shown in **Table 3**. The tested material was a 980MPa grade high-tensile-strength steel, the strip thickness at the entry side of the #1 stand was 2.3 mm, the strip width was 1,250 mm, and the rolling load was 1,500 tonnes. The mill entry-side tension was set at 2 levels, a reference condition and 0.7 times the reference condition.

3.3 Experimental results

Fig.11 shows the measurement results for strip meandering in the cases where a leveling difference of 150 μm was imparted for each condition and the plate-feed state was maintained for 15 seconds after the start of operation.

Table 3 Conditions of strip meandering experiment using actual mill

Rolled material	980 MPa class high tensile strength steel T 2.3 mm ×W 1,250 mm
Rolling force	1,400 tonf
Roll gap leveling	150 μm
Tension at entry side of #1	Standard tension, Standard tension×0.7
Tension between #1 and #2	Standard tension
Rolling speed	50 mpm
Lubricant	Emulsion
Measuring method of strip off-centering	Measured by image sensor (KEYENCE CV-3500)

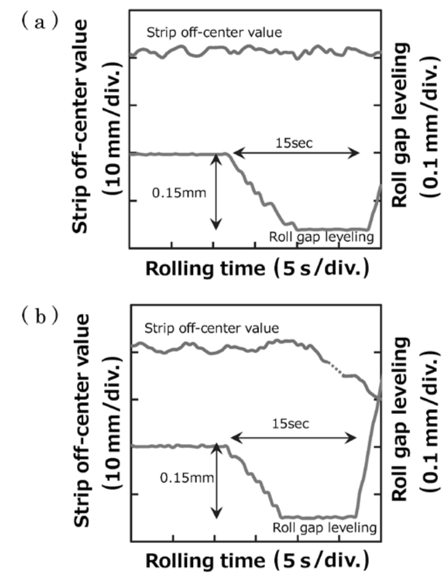


Fig.11 Result of strip meandering experiment with actual mill ((a)standard tension (b)standard tension ×0.7)

When the entry-side tension was in the reference condition, the amount of meandering remained almost unchanged for 15 seconds after the leveling difference had been imparted. On the other hand, when the entry-side tension was 0.7 times the reference condition, the amount of meandering exceeded 10 mm. These results suggest that meandering can be suppressed by increasing the tension even in the actual tandem rolling mill.

3.4 Results of actual machine improvement

On the basis of the test results on the mill entry-side tension and amount of strip meandering, the entry-side tension was increased for the tandem rolling mill at the cold strip mill of Kakogawa Works. The outline of this reinforement is given in **Table 4**. The motor output of the bridle roll for imparting tension at the entry side of the #1 stand was increased from 360 kW to 1,410 kW.

On the basis of the analysis of the constructed meandering model, the conditions that would

Table 4 Reinforcement of tension bridle at entry side of tandem cold mill in Kakogawa Works

	Before reinforcement	After reinforcement
Motor power of tension bridle	Total 360 kW	Total 1,410 kW

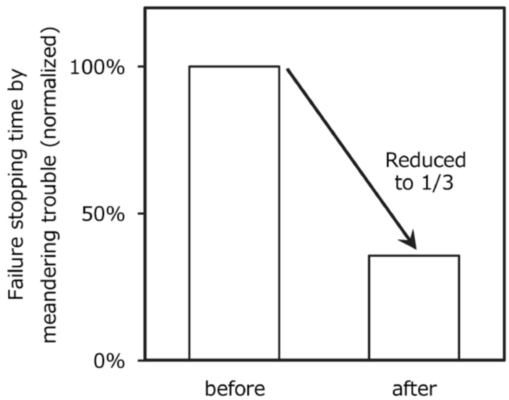


Fig.12 Change in failure downtime caused by meandering trouble before and after reinforcement of tension bridle

stop meandering were found even for the initial irregularities that can occur in operation, and the tension conditions on the entry side of the rolling mill were set for each rolling specification.

Fig.12 compares the failure shut-down rates due to strip meandering at the #1 stand before and after the entry-side tension enhancement. After the entry-side tension was increased, the time consumed by meandering trouble in #1 stand was reduced to 1/3 of what it had been before the increase, which greatly contributed to stable production.

Conclusions

Taking into account the tension distribution on the entry side of a rolling mill, a model was constructed to analyze the meandering phenomena in the entry side of a tandem cold mill, and the validity of the analysis was confirmed by laboratory rolling.

The analysis revealed that the meandering of the strip during rolling can be stopped by increasing the entry-side tension, and the meandering phenomenon was confirmed to stop in an actual cold rolling mill.

On the basis of this knowledge, the electric motor was strengthened in the entry-side bridle roll of the cold tandem rolling mill at Kakogawa Works and the entry-side tension of the mill was optimized. As a result, meandering troubles in the rolling mill have been reduced.

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