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Longitudinal buckling behavior in temper rolling of thin steel strips with delivery angle

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Abstract. The shape defect referred to as "longitudinal buckling" or "longitudinal buckle" tends to occur in temper rolling of double-reduced thin strips. In our previous study, we carried out an experiment to investigate the effect of the delivery angle on longitudinal buckling, and showed that longitudinal buckle completely disappears when the delivery angle exceeds a certain angle. The change of the buckling mode (number of longitudinal buckles) depending on the delivery angle calculated with a buckling model of a flat plate with curvature agreed with the experimental results under the condition of a delivery angle over 10°, but not under the condition of 10°. In this paper, it was found that the experimental results for the delivery angle of 0° could be explained by the Komori model, which assumes flat plate buckling of a length corresponding to the roll bite length. A FEM analysis of the limit buckling stress assuming constraint by the work roll proved that the limit buckling stress was larger than the estimated widthwise stress, indicating that initiation of buckling did not occur in the winding part on the work roll. On the other hand, a rolling experiment revealed that the buckling shape of many micro-waves generated near the roll bite could change in the winding part. These results suggest that longitudinal buckling begins around the roll gap and varies with the shape of the sheet wrapped around the work roll.

Introduction

Surface patterns called cross buckles or longitudinal buckles may occur during temper rolling of thin steel sheets. In particular, longitudinal buckles appear as a waveform parallel to the longitudinal (rolling) direction, and are considered to occur easily in sheets subjected to cold rolling and annealing followed by secondary cold rolling. Sheets with this type of surface defect often require additional processing such as a correction process.

Longitudinal buckling of steel sheets is considered to be a buckling phenomenon generated on the delivery side of a rolling mill due to the residual stress of the sheets caused by rolling [1]. Various studies have investigated the buckling phenomena of thin plates. Abdelkhalek et al. proposed a FEM model of flatness defects that appear during rolling of thin sheets [2]. Abdelkhalek et al. also used a FEM model to study the flatness behavior that may occur when rolling tension is released [3]. Fischer et al. and Friedl et al. used analytical buckling calculations to predict the buckling modes of thin plates related to rolling and leveling [4, 5], and Coman used an analytical buckling model to estimate the critical loads and buckling modes with a linear distribution of residual stresses [6]. Liu et al. proposed buckling model replacing the elastic modulus constant with the distribution function of tangent modulus in order to consider the effect of uneven distribution of material property in hot rolled strip [7]. Tran et al. conducted an experiment to simulate the flatness defect of a thin plate using thermal stress, and the behavior showed good agreement with the FEM results [8, 9].

On the other hand, few studies have investigated longitudinal buckling. Kijima et al. conducted an experimental investigation of the effect of rolling conditions on the occurrence of longitudinal buckles, which revealed the following trends [10]:

・As the rolling load decreases, the wave height decreases.

・Longitudinal buckles occur regardless of the rolling tension.

・The wave height can be reduced by reducing the work roll roughness.

・The wave height increases with an increase in the delivery angle at the outlet side of the rolling mill.

Komori obtained the wavelength of waves formed by longitudinal buckling under a condition in which no delivery angle was given by an elementary analysis of buckling, and showed that the wavelength of the longitudinal buckles obtained by the analysis was in good agreement with the trend of the experimental value [11]. The analytical results also showed that buckling is less likely to occur when the arithmetic mean roughness of the temper roll is low, which is also consistent with the experimental results.

Changing the rolling load and/or work roll roughness is a possible approach to prevent longitudinal buckling. However, in many cases, these changes have a significant impact on product characteristics and are difficult to implement in practice. Therefore, in order to prevent longitudinal buckling, it is important to change the delivery angle, which has relatively little effect on product characteristics. In a typical temper mill, auxiliary rolls are provided on the exit side for screw stabilization, tension measurement, etc., and these rolls can also be used to give the strip a delivery angle relative to the horizontal pass line at the exit side of the mill.

In a previous study, Kijima et al. investigated the effect of the delivery angle in laboratory experiments with delivery angles ranging from 0° to 4° [10]. The present authors [12] conducted an experiment in which strips were given a delivery angle, and showed that longitudinal buckle completely disappeared when the delivery angle exceeded a certain angle. However, the change of the buckling mode (number of longitudinal buckles) depending on the delivery angle calculated by a buckling model of a flat plate with curvature agreed with the experimental results under the condition of delivery angles over 10°, but not under the condition of 10°.

On the other hand, the wavelength of the longitudinal buckle when a delivery angle is not given (i.e., delivery angle = 0°), which Komori obtained by the elementary analysis of buckling, agrees well with the trend of the experimental value. This paper reports the results of an investigation of the effect of the exit side delivery angle on the buckling generation behavior when a delivery angle is given, which was clarified experimentally in our previous study, by comparison with the elementary analysis model of buckling by Komori [11].

Moreover, in the above-mentioned study by the authors [12], we conjectured that the longitudinal buckling phenomenon could be divided into buckling generation behavior in which many micro-waves were generated near the roll bite and buckling generation behavior in which the buckling shape changed as rolling progressed and disappeared in some cases. In order to verify this hypothesis, this paper describes the results of a FEM buckling mode analysis and experimental observation to verify whether the buckling mode can occur or change in the winding part, where the rolled material is wrapped around the roll.

Buckling analysis model

The change of longitudinal buckling in the experiment with the delivery angle was compared with the buckling mode obtained by the elementary analysis. As mentioned above, the results of the buckling model of a plate with curvature [12] agreed with the experimental values under high delivery angle conditions (>10°), but not under low delivery angle conditions.

The buckling model of a plate with curvature [12] calculates the critical buckling stress for each buckling mode from the thickness, width, curvature, delivery angle, Young's modulus, and Poisson's ratio of the flat plate. Komori's model [11] calculates the buckling mode from the plate thickness, material yield stress, rolling load per unit width and parameters about roll surface roughness.

Komori's model [11] and its assumptions for calculating the buckling mode in the buckling model of a plate with curvature are described below. Table 1 shows the assumptions of both models. In both models, the boundary condition of the plate edge, the stress distribution in the rolling direction, the number of waves in the longitudinal direction (wavenumber), and the assumption of contact with the roll are the same. However, the modeling area and the plate shape are different. Figure 1 and Figure 2 show the area in which the buckling mode is modeled as a flat plate. Komori's model assumes that buckling occurs during rolling, and the rolling direction length of the roll bite is assumed to be the plate length in the buckling mode derivation. In the buckling model of a plate with curvature, the length of the plate in determining the buckling mode is defined as the area where the rolled material is wrapped around the roll from just below the roll center.

Table 1 Comparison of analysis conditions

	Komori's model [11]	Flat plate model with curvature [12]
Modeling area	Rolling direction: Range of contact length with roll (equivalent to roll bite) Width direction: Calculable regardless of the plate width	Rolling direction: Range where the plate is wrapped around the roll, beginning from the bottom dead center of the roll Width direction: Plate width
Plate shape	Plate without curvature	Plate with curvature
Boundary condition of plate ends	Rotating end	
Material deformation	Elastic deformation	
Stress distribution	Constant regardless of rolling direction position	
Longitudinal wave number	1	
Contact with roll	Neglected for buckling cycle calculations in elementary analysis	

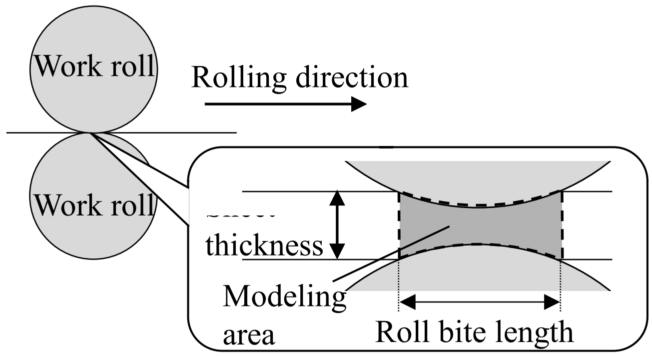

Figure 1 Modeling area in Komori's model

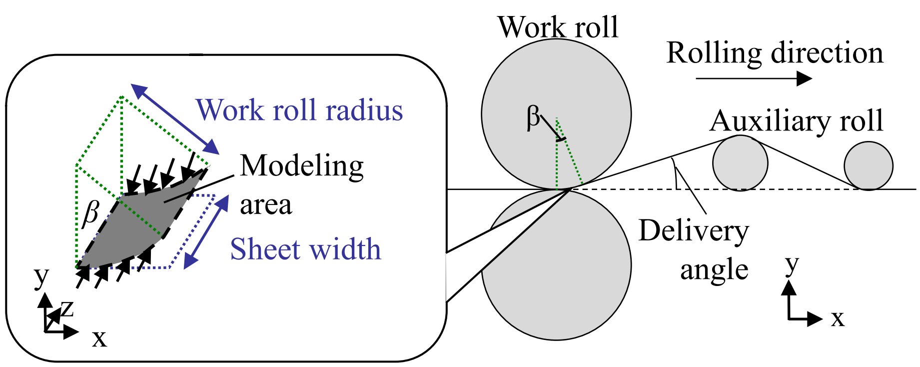

Figure 2 Modeling area in buckling model of flat plate with curvature

Table 2 Conditions of elementary analysis of buckling

Rolling load per unit width [kN/mm]	5.3
Thickness at entry side [mm]	0.15
Roughness of work roll surface Ra [µm]	1.3
Roughness of work roll surface RSm [µm]	90
Delivery angle [°]	0
Young's modulus [GPa]	200
Poisson's ratio [-]	0.3
Yield stress [MPa]	657

It has been shown that the wavelength obtained by the elementary analytical model of buckling proposed by Komori agrees with the experimental value under the condition in which no delivery angle is given (delivery angle = 0°) [11]. Using Komori's model, the wave cycle for the delivery angle of 0° was calculated under the conditions in the experiment [12]. The conditions are as shown in Table 2. The rolling conditions were a rolling load of 5.3 kN/mm, roughness of work roll surface Ra of 1.3 µm and roughness of work roll surface RSm of 90 µm. The rolled material had a thickness of 0.15 mm and a yield stress of 657 MPa, Young's modulus was 200 GPa and Poisson's ratio was 0.3.

As a result, the wave cycle calculated by Komori's model was 14 mm. However, according to the experimental results [12], the wave cycle of longitudinal buckle was relatively close to 22 mm when the delivery angle was 0°.

In addition, the length of the flat plate used in determining the buckling mode is considered. As mentioned above, Komori's model assumes that buckling occurs during rolling, and the rolling direction length of the roll bite is taken as the plate length in the buckling mode derivation. The roll bite length is calculated to be 26.9 mm by the method of Komori's model under the rolling conditions in the experiment [12]. In the buckling model of a plate with curvature, the length of the plate is proportional to the delivery angle. Figure 3 shows the winding length with respect to the delivery angle in the buckling model of a plate with curvature. At the delivery angle of 9.3°, the length of the plate is equivalent to the roll bite length of 26.9 mm calculated by the Komori model.

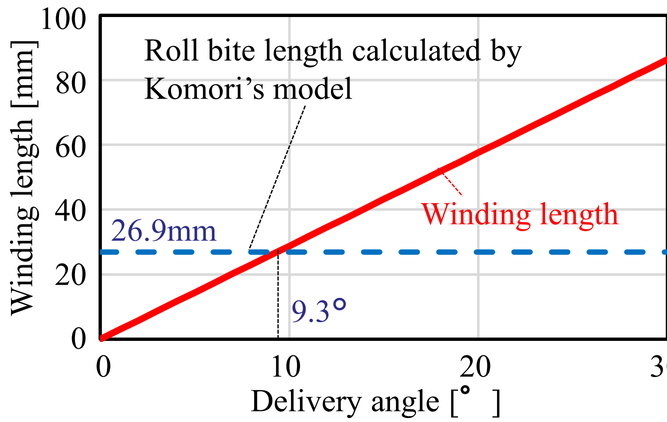

Figure 3 Winding length in buckling model of plate with curvature

Based on the above examination, the effect of the delivery angle on the number of longitudinal buckles is considered. The experimental results can be explained by the Komori model under the condition of the delivery angle of 0°, and it is considered that the phenomenon which occurs is close to the buckling of a flat plate with a length corresponding to the roll bite length assumed in the model. As shown in Figure 3, under the condition that the delivery angle is less than 9.3°, the winding length is calculated to be smaller than the roll bite length calculated by the Komori model. Therefore, it is considered that the buckling mode diverges from the actual phenomenon because the buckling mode is calculated for a narrower range than the roll bite.

Regarding the behavior when the delivery angle is increased, the change in the number of longitudinal buckles can be explained from the buckling behavior of the plate with curvature, and the shape of the winding part is considered to have a large influence on the buckling behavior.

FEM analysis

In the preceding section, it was considered that the shape of the part wrapped around the work roll affected the buckling behavior when the delivery angle was increased. However, as a real phenomenon, tension is applied to the rolled material, and the rolled material is pressed against the work roll in the winding part. The buckling model of the flat plate with curvature does not consider the constraint received from the work roll, but in practice, this constraint is expected to make the occurrence of buckling difficult.

To verify this point, the buckling limit stress was calculated by FEM, and the difference between the behavior of the material with and without constraint by the work roll was investigated. Abaqus/Standard Ver. 6.12 was used as the solver. As shown in Figure 4, the part corresponding to the winding part was modeled. The material was 0.15 mm in thickness and 300 mm width. Other conditions included a WR diameter of 330 mm, Young's modulus of 21,000 kg/mm^2 and Poisson's ratio of 0.3. The conditions under which the delivery angle β was 4° were analyzed. In the previous study, the FEM analysis for the delivery angle β = 4° confirmed that there is a region where the rolled material and the roll are in contact [12]. Therefore, the critical buckling stress when stress is applied in the width direction to the part corresponding to the winding part was calculated.

As shown in Figure 4, the analysis was carried out for Case 1 without constraint by the work roll and Case 2 with constraint by the work roll. In Case 2, the modeled portion is pressed against the work roll with a uniform surface pressure of 0.0909 MPa, which corresponds to the pressure on the work roll when the longitudinal tension is 100 MPa. Longitudinal tension is not applied in the analysis, but is applied as the pressure on the work roll. The friction coefficient of the contact surface was 0.05 [13-15].

The results are shown in Figure 5. This paper also shows the widthwise stress (173 MPa) generated in the rolled material at the roll bite side estimated in the previous study [12]. In Case 1 without constraint by the work roll, the critical buckling stress is smaller than the estimated widthwise stress regardless of the buckling mode, indicating that buckling can occur. However, in Case 2 with constraint by the work roll, the limit buckling stress is larger than the estimated widthwise stress regardless of the mode, which means that buckling cannot occur.

This result suggests that initiation of buckling is unlikely to occur in the winding part, even in the real phenomenon. Therefore, it is presumed that buckling is not initiated in the winding part, but occurs in the vicinity of the roll bite, and the buckling shape then changes in the winding part and disappears when the delivery angle is over a certain value.

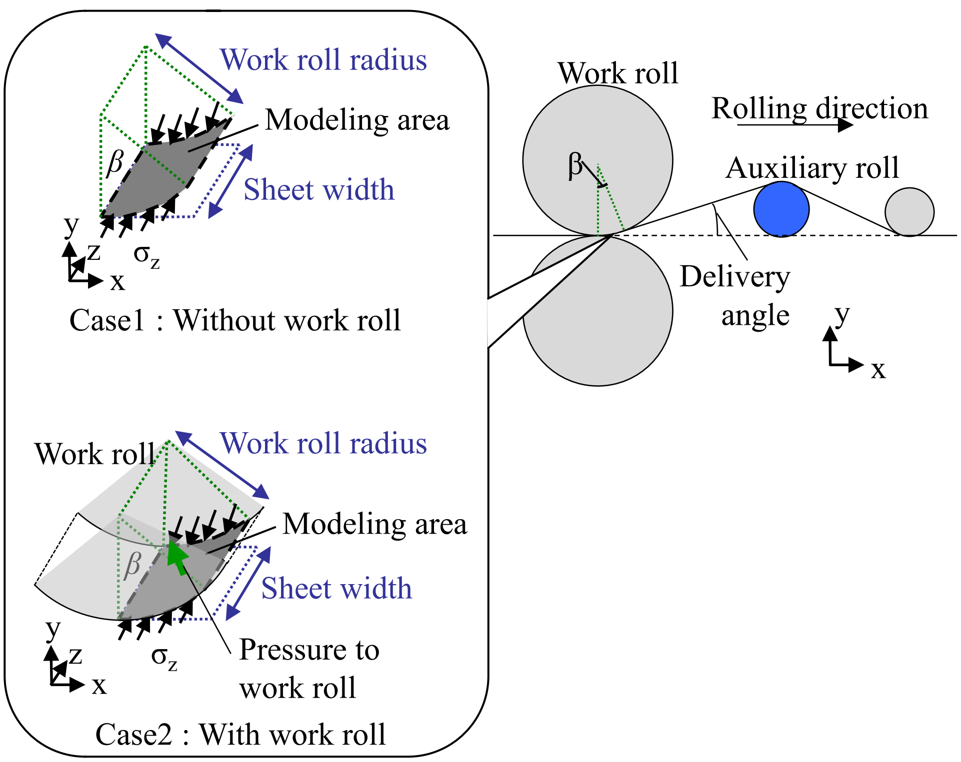

Figure 4 Modeling area in FEM buckling analysis

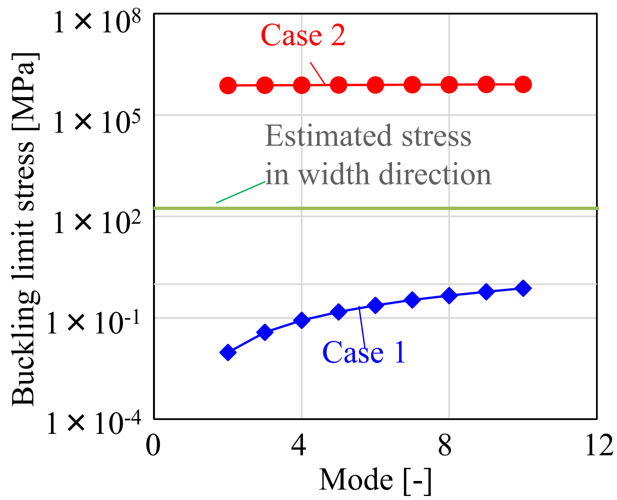

Figure 5 Modeling area in FEM buckling analysis

Experiment

From the examination in the preceding paragraph, it was hypothesized that buckling which generates many micro-waves in the vicinity of the roll bite occurs, and the buckling shape changes in the winding part and disappears when the delivery angle is over a certain value. To establish this hypothesis, it is assumed that the change in the buckling shape occurs in the winding part. For verification, the buckling shape of the winding part was observed in a rolling experiment.

Figure 6 shows a schematic diagram of the laboratory rolling mill used in the experiment. An auxiliary roll was installed on the rolling stand exit side of the 2Hi mill, and the delivery angle was set to 27.6°.

The rolling conditions are shown in Table 3. The work roll diameter was 330 mm, the test material was 0.05 mm in thickness and 300 mm in width, and 50 % cold rolling was applied to the material after annealing. A thin material was used to prevent the waves from disappearing under the conditions with the delivery angle [16].

The roll gap of the work roll in the unrotated state was reduced to the position where the widthwise load was 0.4 tonf/mm for the full length of the unrolled rolled material. From this state, the work roll was rotated with the lowering position fixed, and rolling and observation were started. The inlet and outlet tensions were 120 MPa, and the lubrication condition was dry.

A video camera was installed on the rolling outlet side to observe the winding part. In the photographed image shown in Figure 7, it can be confirmed that the winding part and the noncontact area where the rolled material has left the work roll are in the field of view. As can be seen in Figure 7, there are many fine waves in the width direction at 3.2 seconds after the start of rolling, but as rolling progresses, the wave number decreases at 6.0 seconds, and the wave which existed at 6.0 seconds disappears at 6.4 seconds after the start of rolling.

These observation results confirmed that a change of the wavenumber, that is, a change of buckling shape, can occur in the winding part. Based on this fact, as mentioned above, there is a possibility that buckling which generates a large number of micro-waves in the vicinity of the roll bite occurs, and the buckling shape then changes in the winding part and disappears when the delivery angle is over a certain value. However, it is not obvious that the wavenumber change in the winding part coincides with the wavenumber expected in the buckling model of the plate with curvature. Therefore, the reason for this difference requires further examination.

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Table 3 Experimental conditions

Rolling load per unit width [kN/mm]	0.4
Thickness at entry side [mm]	0.05
Width [mm]	300
Unit tension at entry side [MPa]	120
Unit tension at delivery side [MPa]	120
Work roll diameter [mm]	330
Delivery angle [°]	27.6
Lubrication	Dry

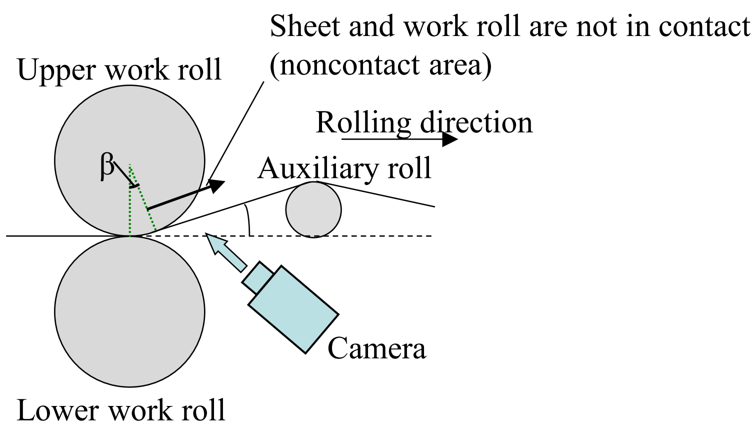
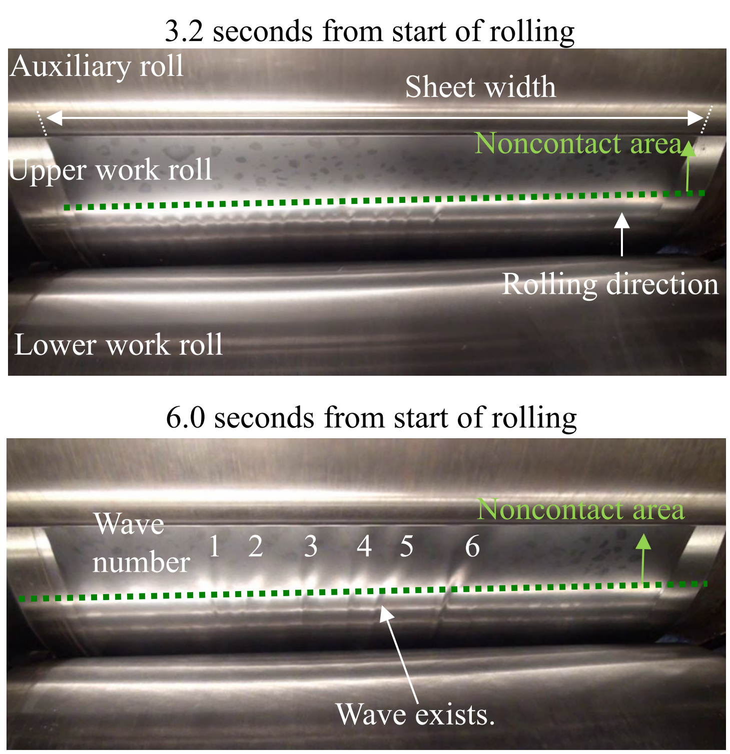


Figure 6 Outline of experimental apparatus



6.4 seconds from start of rolling

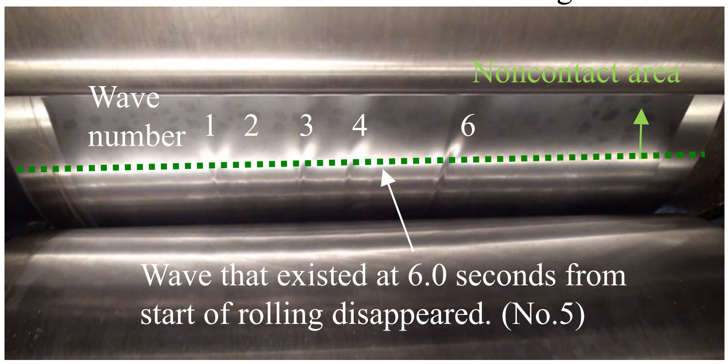


Figure 7 Appearance of winding part during rolling

Summary

This paper investigates the effect of the delivery angle on the longitudinal buckle generation behavior in temper rolling of secondary cold-rolled steel sheets by comparison with an elementary analysis model of buckling. The existence of a change in the buckling mode in the winding part was verified by a laboratory experiment. The following findings were obtained.

1) When the delivery angle is 0°, the experimental results can be explained by the Komori model assuming flat plate buckling with a length corresponding to the roll bite length.
2) In the buckling model of a flat plate with curvature, the winding length is calculated to be smaller than the roll bite length under the condition of a delivery angle of less than 9.3°, and this is considered to be different from the actual phenomenon. When the delivery angle is increased, the change of the wavenumber can be explained from the buckling behavior of the plate with curvature, and the shape of the winding part appears to have a large influence on the buckling behavior.
3) The results of a FEM analysis suggested that buckling cannot occur under a condition of constraint by the work roll. Therefore, it is presumed that initiation of buckling does not occur in the winding part, where the material is in contact with the work roll, but occurs in the vicinity of the roll bite.
4) The results of verification by a rolling experiment confirmed that a change in the wavenumber occurred in the winding part. Based on this fact, it is presumed that buckling occurs in the vicinity of the roll bite, and the buckling shape then changes in the winding part.

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