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Analysis of Sheet Metal Bending Deformation Behavior in Processing Lines and Its Effectiveness*

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1 Introduction

Cold-rolled steel sheets are manufactured from hot-rolled steel sheets through many processes such as pickling, cold rolling, annealing, temper rolling, galvanizing, and coating. Flatness requirements for cold-rolled steel sheets have recently become increasingly severe. This is because the applications such as electric home appliances, sidings, kitchen utensils, and furniture require only a slight degree of deformation process such as local bending of steel sheets, with the result that even after the forming the shape of the material tends to remain practically as-received. To meet these severe flatness requirements, flatness control techniques of the highest levels are put into action in cold rolling and temper rolling, but furthermore the combined use of a tension leveler has become general practice.

In tension leveling, repeated bending deformation is given to the steel sheet while applying tension so as to eliminate differences in the transverse length of the steel sheet (local elongation). However, tension leveling sometimes causes flatness defect such as curling to the steel sheets if used improperly.

In each of the above-mentioned processes, the steel sheet is subjected to repeated bending deformation by a larger number of rolls, including leveler rolls. This deformation causes residual stresses and curling, leading sometimes to operation troubles in the succeeding processes and to flatness degradation due to local elongation.

This report introduces theoretical analysis of deformation behavior under repeated bending in strip processing lines, and some examples of its application to the correction of curling and local elongation problems.

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2 Theoretical Analysis

Symbols used for the analysis are described below

$\sigma_x, \sigma_y, \sigma_z$: Stresses in the longitudinal, transverse and thickness directions of the strip, respectively (kgf/mm^2)

$\bar{\sigma}$: Equivalent stress (kgf/mm^2)

σ_x', σ_y': Deviator stresses in the longitudinal and transverse directions, respectively (kgf/mm^2)

$d\sigma_x, d\sigma_y$: Stress increments in the longitudinal and transverse directions, respectively (kgf/mm^2)

$d\varepsilon_x, d\varepsilon_y$: Strain increments in the longitudinal and transverse directions, respectively

$d\varepsilon_{xp}, d\varepsilon_{yp}, d\varepsilon_{zp}$: Plastic strain increments in the longitudinal, transverse and thickness directions, respectively

$d\bar{\varepsilon}_p$: Equivalent plastic strain increment

M_x, M_y: Bending moments for unit width in the longitudinal and transverse directions, respectively (kgf · mm/mm)

K_x, K_y: Curvatures in the longitudinal and transverse directions, respectively (1/mm)

K_y': Value of K_y under the assumed condition of $K_x = 0$ (1/mm)

t: Strip thickness (mm)

η: Position in the thickness direction from the center of the strip thickness (mm)

D_R: Roll diameter (mm)

θ: Apparent contact angle of the strip with the roll (rad)

ρ: Curvature radius of the strip (mm)

δ_{IM}: Intermesh of the roll (mm)

ε_c: Longitudinal strain in the middle of the strip thickness

E: Young's modulus (kgf/mm^2)

ν: Poisson's ratio

$D = Et^3/\{12(1-\nu^2)\}$ (kgf · mm)

σ_e: Yield stress (kgf · mm^2)

σ_T: Mean stress on the strip (kgf/mm^2)

H: Work hardening coefficient (kgf/mm^2)

λ: Strip steepness

L: Length of an element (mm)

$\bar{L}$: Standard length of elements (mm)

ψ: Parameter for allotting σ_T to elements in the transverse direction (kgf/mm^2)

Suffix i: Roll number

Suffix j: Element number in the transverse direction

Suffix m: Number of elements in the transverse direction

Assumptions for the analysis are as follows:

(1) Plain strain $d\varepsilon_y = 0$ (Transverse strain is neglected because the strip width is sufficiently large compared to the strip thickness.)

(2) Plane stress $\sigma_2 = 0$ (Stress in thickness direction is neglected because the strip thickness is small compared to the bending radius.)

(3) Shear strain and shear stress are neglected.

(4) The longitudinal unit tension σ_T is constant during bending.

(5) The Bauschinger effect is neglected.

2.1 Relationship between Stress and Strain under Load

From the assumptions (2) and (3) and Mises' yield criterion, the equivalent stress $\bar{\sigma}$ is given by

$$\bar{\sigma} = \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x\sigma_y}, \cdots\cdots\cdots\cdots (1)$$

The equivalent plastic strain increment $d\bar{\varepsilon}_p$ is expressed by the following equation:

$$d\bar{\varepsilon}_p = \sqrt{\frac{2}{3}(d\varepsilon_{xp}^2 + d\varepsilon_{yp}^2 + d\varepsilon_{zp}^2)} \cdots\cdots\cdots (2)$$

It is assumed that the relationship between stress and strain is governed by Hooke's law on elastic deformation and by prandtl-Reuss' equation on elastic and plastic deformation. Then, the following expressions are obtained from the assumptions (2) and (3)[1]:

For elastic deformation,

$$\begin{Bmatrix} d\sigma_x \\ d\sigma_y \end{Bmatrix} = \frac{E}{1-\nu^2}\begin{bmatrix} 1 & \nu \\ \nu & 1 \end{bmatrix}\begin{Bmatrix} d\varepsilon_x \\ d\varepsilon_y \end{Bmatrix} \cdots\cdots\cdots (3)$$

For elastic and plastic deformation,

$$\begin{Bmatrix} d\sigma_x \\ d\sigma_y \end{Bmatrix} = \frac{E}{1-\nu^2}\begin{bmatrix} 1 & \nu \\ \nu & 1 \end{bmatrix}\begin{Bmatrix} d\varepsilon_x \\ d\varepsilon_y \end{Bmatrix} - \frac{1}{S}\begin{bmatrix} S_1^2 & S_1S_2 \\ S_1S_2 & S_1^2 \end{bmatrix}\begin{Bmatrix} d\varepsilon_x \\ d\varepsilon_y \end{Bmatrix} \cdots\cdots\cdots (4)$$

If Eq. (2) is similarly described, then the following equation is obtained:

$$d\bar{\varepsilon}_p = \frac{2}{3}\frac{\bar{\sigma}}{S}(S_1 d\varepsilon_x + S_2 d\varepsilon_y) \cdots\cdots\cdots (5)$$

S, S_1 and S_2 are expressed as follows using the deviator stresses σ_x' and σ_y':

$$S = \frac{4}{9}\bar{\sigma}^2 H + S\sigma_x' + S_2\sigma_y'$$

$$S_1 = \frac{E}{1-\nu^2}(\sigma_x' + \nu\sigma_y') \qquad \cdots\cdots\cdots (6)$$

$$S_2 = \frac{E}{1-\nu^2}(\nu\sigma_x' + \sigma_y')$$

Therefore, if stress condition and strain increment $d\varepsilon_x$ are known at a given time, the incremental stresses $d\sigma_x$ and $d\sigma_y$ can be calculated.

2.2 Identification of Elastic and Plastic Boundary and Method of Calculating Reverse-Direction Stresses

The yield surface for the stresses σ_x and σ_y expressed by Eq. (1) is shown as **Fig. 1**. Stresses in the elastic region are calculated by using Eq. (3) within the yield surface and those in the plastic region are calculated by Eq. (4) outside the yield surface. When the strain increment $d\sigma_{x_i}$ is given in the initial state of $\sigma_x = \sigma_y = 0$, the stress increment $d\sigma_x$ and $d\sigma_y$ are calculated by Eq. (3) and added to σ_x and σ_y in the initial state respectively, then equivalent stress $\bar{\sigma}$ is calculated by Eq. (1). If $\bar{\sigma} < \sigma_e$, then stress is present at point ① in Fig. 1. When the strain increment $d\sigma_{x_{i+1}}$ is further given, the values $d\sigma_x$ and $d\sigma_y$ calculated by Eq. (3) are added to

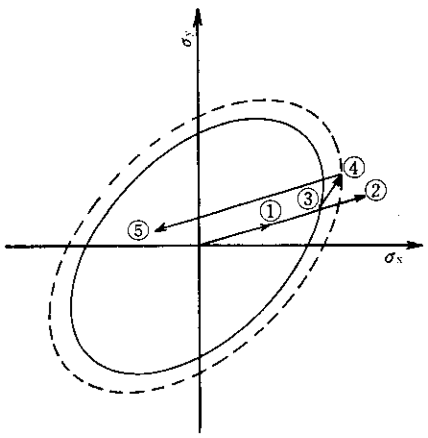


Fig. 1 Yield locus used for the analysis and variation of stress state

the values of σ_x and σ_y at point ① in Fig. 1 and then new values σ_x, σ_y and $\bar{\sigma}$ are obtained. If the new value of $\bar{\sigma}$ is larger than yield stress σ_e, which means that the plastic deformation occurred, the stresses σ_x, σ_y and $\bar{\sigma}$ should be calculated again as follows.

The intersection ③ of the stress vector $\overrightarrow{①②}$ and the yield surface gives proportional allotment of $d\varepsilon_{x_{i+1}}$ to the elastic component $d\varepsilon^e_{x_{i+1}}$ and plastic component $d\varepsilon^p_{x_{i+1}}$ by the following equation:

$$d\varepsilon^e_{x_{i+1}} = d\varepsilon_{x_{i+1}} \frac{l_{13}}{l_{12}} \quad \cdots\cdots(7)$$

$$d\varepsilon^p_{x_{i+1}} = d\varepsilon_{x_{i+1}} - d\varepsilon^e_{x_{i+1}} \quad \cdots\cdots(8)$$

where, l_{13} and l_{12} are the lengths of the vector $\overrightarrow{①③}$ and $\overrightarrow{①②}$ in Fig. 1, respectively.

The coordinates of intersection ③ gives stress σ_x, σ_y for the strain increment $d\varepsilon^e_{x_{i+1}}$. The $d\sigma_x$ and $d\sigma_y$ in the plastic region are obtained by substituting $d\varepsilon^p_{x_{i+1}}$ into Eq. (4). Adding of $d\sigma_x$ and $d\sigma_y$ to σ_x and σ_y, at the point ③ respectively, gives the stresses σ_x and σ_y for the total strain increment $d\sigma_{x_{i+1}}$, with the result that the point ④ is obtained. The new yield surface is indicated by a broken line with point ④ as the new boundary between the elastic and plastic regions.

When a strain increment in the opposite direction is generated, calculations in the elastic region are first made by Eq. (3) (④→⑤ in Fig. 1) and they are continued by a similar judgment on the elastic and plastic regions.

2.3 Method of Calculating Curling after Unloading

When the through-thickness distributions of stresses σ_x and σ_y are calculated as above, the bending moments in the x and y directions M_x and M_y are expressed by the following equations, respectively:

$$M_x = \int_{-t/2}^{t/2} \sigma_x \eta d\eta, \; M_y = \int_{-t/2}^{t/2} \sigma_y \eta d\eta \quad \cdots\cdots(9)$$

Unloading means that the integrated longitudinal stress through thickness σ_T and the bending moments M_x and M_y are reduced to zero. The σ_x and σ_y at $\sigma_T = 0$ are first calculated by varying the $d\varepsilon_x$ in the middle of the strip thickness so as to meet the following equation:

$$\sigma_T = \int_{-t/2}^{t/2} \sigma_x d\eta = 0 \quad \cdots\cdots(10)$$

Subsequently, calculations are made to reduce the moments to zero. When the curvature of the strip is zero under loading of bending moments M_x and M_y, the curvatures after unloading, K_x and K_y, are given by the following equations:

$$K_x = \frac{M_x - \nu M_y}{D(1-\nu^2)}, \; K_y = \frac{M_y - \nu M_x}{D(1-\nu^2)} \quad \cdots\cdots(11)$$

When the strip is between looper rolls, the longitudinal (x-direction) curling is apparently corrected to nearly zero. The transverse (y-direction) curvature K_y' in this state is obtained by Eq. (12).

$$K_y' = K_y + \nu K_x \quad \cdots\cdots(12)$$

Where K_x and K_y are curvatures by Eq. (11) in a condition in which longitudinal tension exists.

2.4 Method of Calculating Bending Strain

When a strip with a thickness t is bent to a curvature of inner surface ρ with the longitudinal strain in the middle of thickness ε_c, the longitudinal strain ε_x at the position η in thickness direction is given by the following equation:

$$\varepsilon_x = \frac{\eta}{\rho + (t/2)} + \varepsilon_c \quad \cdots\cdots(13)$$

When the contact between the strip and a roll of large diameter D_R such as a bridle roll or a looper roll is sufficient, curvature radius of strip being bent, ρ, is equal to the roll radius $D_R/2$. In the case of small diameter roll such as tension leveler the contact angle is acute, and curvature radius of strip, ρ, is larger than the roll radius $\rho > D_R/2$. It is assumed that the following equation proposed by Misaka[2)] holds:

$$\rho = \frac{1}{2}D_R + t\left(\alpha_1 \times \frac{2\sigma_e}{2\sigma_e + \sigma_T} \times \frac{1}{\theta^{\alpha 2}} - \alpha_3\right) \quad \cdots(14)$$

Where α_1, α_2 and α_3 are constants and θ denotes the contact angle between the strip and a roll, which is determined by a geometrical relation.

2.5 Method of Calculating Process of Flantness Correction

When the length of the strip elements, L, in the longitudinal direction varies in the transverse direction, the excessive part buckles under compressive internal stress, resulting in local elongation.

The main function of a tension leveler is to eliminate this local elongation. In general, local elongation is evaluated by the steepness λ given by the following equation:

$$\lambda = \frac{2}{\pi}\sqrt{\frac{\Delta L}{\tilde{L}}} \cdots\cdots\cdots\cdots(15)$$

Where $\tilde{L}$ denotes the standard element length in the longitudinal direction, and ΔL an element length difference $\Delta L = |L - \tilde{L}|$. Wavy edges are formed when the L at strip edges is long, while center buckles are formed when the L at the center of the strip is long.

There are a few reports on the analysis of the process of flatness correction by a tension leveler[2-6]. However, all of them are based on the theoretical solution of the elongation caused by the stretching and bending by a single roll[4]. In this method, the simple bending theory is applied to a completely plastic rigid material without work hardening, and the strain increment due to elongation, $\Delta\varepsilon$, can be very simply found as shown by the following equation:

$$\Delta\varepsilon = \frac{t}{\rho + (1/2)t} \times \frac{\sigma_T}{\sigma_e} \cdots\cdots\cdots\cdots(16)$$

In this paper, elastic-plastic deformation analysis is done in consideration of transverse stress and work hardening of material.

The strip before leveling is first virtually divided into longitudinal elements ($j = 1$ to m) in the transverse direction and the initial element length (L_{01} to L_{0m}) is given to each element so as to correspond to the initial steepness λ_0. The average tensile stress σ_T through the strip width is also given. A short element is subjected to a tensile stress larger than σ_T and the tensile stress should be smaller than σ_T for a longer element. It is assumed that the tensile stress of each element, σ_{T_j}, is given by the parameter ψ, which is allotted to each element depending on the length of a element as follows.

$$\sigma_{T_j} = \sigma_T + \left(1 - \frac{mL_j}{\sum_{k=1}^{m} L_k}\right)\psi \cdots\cdots\cdots\cdots(17)$$

In the above equation, the sum of the second term of the right side through strip width is zero and the condition that the whole tensile stress is equal to the given tensile stress is satisfied. The dimension of ψ is the same as that of Young's modulus. L_j denotes the length of the element j on the entry side of the i-th roll. If a high value of ψ is taken, the value of σ_{T_j} for a shorter element becomes higher and the correction of flatness proceeds rapidly.

The length of the shorter element as a calculated value for large ψ may sometimes become larger than the longer element at initial state after the strip passes the roll. In fact, a long element at the entry side of the i-th roll appears as a wave. Therefore, it is considered that part of the tensile stress is allotted to a long element after a short element has been stretched to the length of the long element and then a long element is elongated in the same manner as the initial short element. The reversal of the lengths of the initial longer and shorter elements should not occur. On the other hand, steepness is not improved if ψ is small, for example, $\psi = 0$. This is because in this case uniform σ_T is allotted to each element regardless of a difference in the element length. Furthermore, there might be a case where compressive stress $\sigma_{T_j} < 0$ is generated in a long element as a calculated value even in a range of ψ without the reversal of the element length. In this case, a buckled wave will occur in this element. It should not be considered that σ_{T_j} in an correspondingly short element increases to a level in equilibrium with the compressive stress. Therefore, each element should satisfy the following equation:

$$\sigma_{T_j} \geqq 0 \cdots\cdots\cdots\cdots(18)$$

Based on the consideration mentioned above, calculations were made on the assumption that Eq. (18) is satisfied for each roll and that as high a value of ψ as possible within the limits without the reversal of the element length is close to a correct solution.

A flow chart of simulation program for the deformation under repeated bending using the above-mentioned analysis method is shown in **Fig. 2**.

3 Calculated Results and Examples of Application

3.1 Analysis of Strip Curling by Tension Leveler and Results of Experiment

An experiment and calculations were made using a tension leveler in the roll arrangement shown in **Fig. 3** under the conditions given in **Table 1**. Results are described in the following. The intermesh δ_{IM} of the No. 2 and No. 4 rolls shown in Fig. 3 is adjusted. δ_{IM} is defined by the difference in the roll surface level with respect to the preceding and succeeding rolls. Therefore, bending is given to an extent corresponding to the strip thickness even if $\delta_{IM} = 0$.

The elongation shown in Table 1 is, in effect, adjusted by bridle rolls. In calculation, however, elongation is found by giving tension. Therefore, calculations were made, so as to get agreement with a initial given elongation value and a calculated one from assumed tension, by forming a calculation loop outside the loop of each roll that is the largest calculation loop in the flow chart shown in Fig. 2.

The effect of δ_{IM} on strip curl in longitudinal direction is shown in **Fig. 4**. The curvature K_x was used as the amount of strip curl. Values of K_x were measured for strips which were bent and unbent repeatedly by tens of rolls after the tension leveling, and were then cut. Both experimental and calculated values of K_x tend

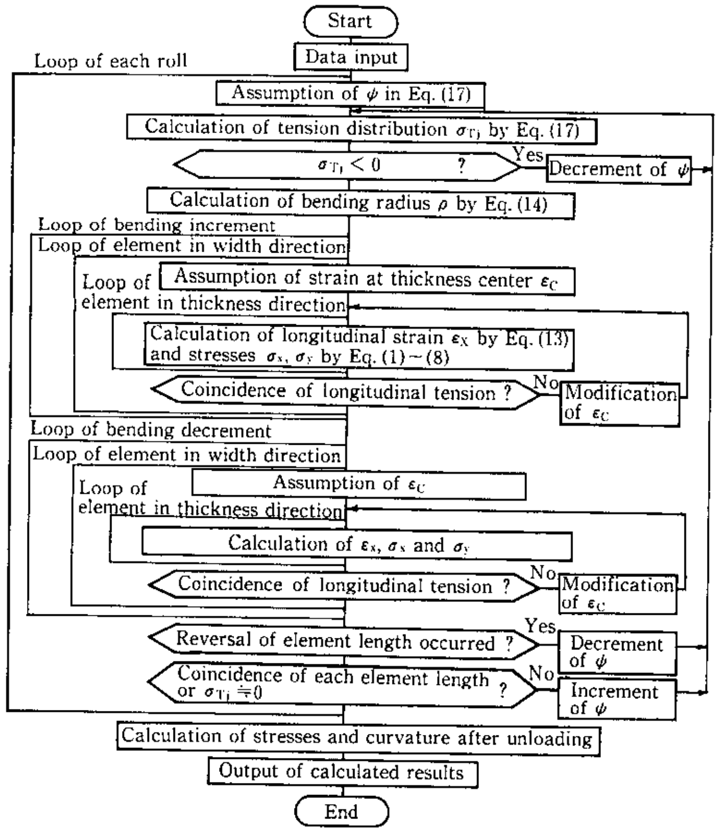


Fig. 2 Flow chart of simulation program for repeated bending analysis

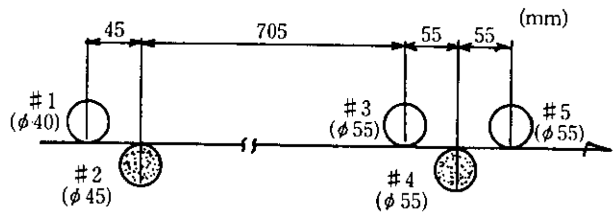


Fig. 3 Layout of tension-leveler rolls used for analysis and experiment

to increase with increasing δ_{IM} of the No. 2 and No. 4 rolls and decrease with decreasing δ_{IM} of the No. 4 roll. The calculation case No. 1 shown in the figure indicates value of K_x just after the leveler; higher K_x values than experimental values are shown. The distance from the No. 5 roll to the next roll in Fig. 3 is long for reasons of leveler arrangement. Therefore, it is considered that the actual contact angle θ is smaller than the geometrical contact angle θ when the strip leaves the No. 5 roll horizontally, and we made the calculation of case No. 2 by reducing the θ of the No. 5 roll to half. Calculated value in the case No. 2 are closer to measured values than those of case No. 1. The calculation case No. 3 indicates results of calculation in which the bending process by the many deflector rolls of process line after the leveler was taken into consideration in addition to

Table 1 Mechanical properties of strip and leveling conditions used for calculation and experiment

Mechanical properties of strip	
Thickness t	0.68 mm
Young's modulus E	21 000 kgf/mm²
Poisson's ratio ν	0.3
Yield strength σ_e	20 kgf/mm²
Coefficient of work hardening H	50 kgf/mm²
Leveling conditions	
Intermesh of roll δ_{IM}	0~12 mm
Strip elongation	0.5 %
No. of bending increment	50
No. of virtual divided strip element in thickness direction	19
No. of virtual divided strip element in width direction m	1

the conditions used for the calculation case No. 2. Calculated values of the case No. 3 are much closer to the experimental ones. When the bending curvature ρ is estimated by Eq. (14), calculated values of curling tend to agree with measured values. To improve the accuracy, it is necessary to use Eq. (14) after revision as shown in the example of calculation case No. 2. However, an

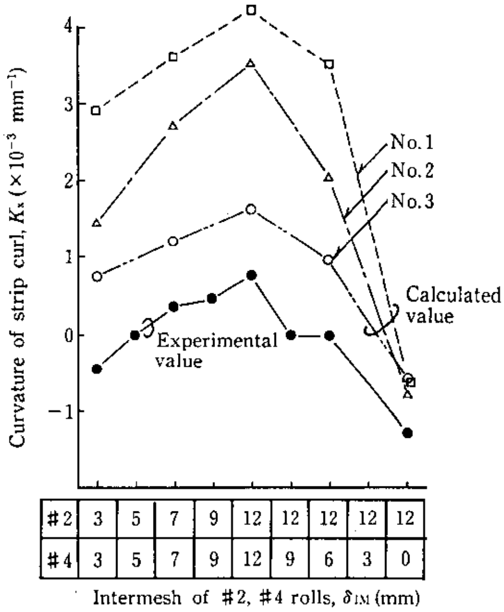


Fig. 4 Influence of roll intermesh on strip curl

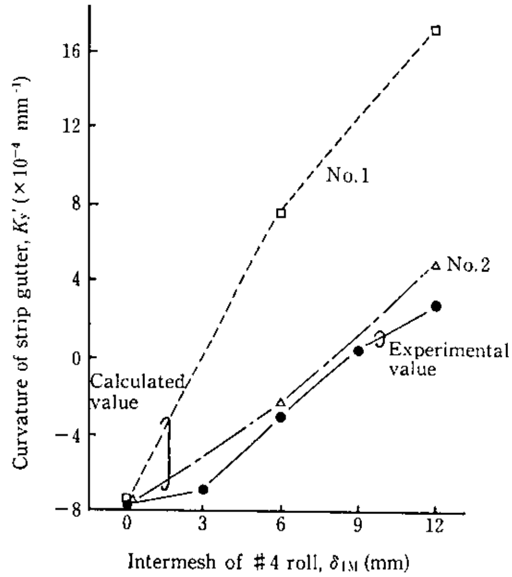


Fig. 5 Influence of intermesh on strip gutter during threading (Intermesh of #2 roll is 12 mm)

analysis for determining ρ more precisely remains as a problem to be solved.

The transverse strip curling (so called strip gutter) during threading is described in the following. Experimental values of strip gutter K_y' were measured during the threading at an inspection position after the strip passed the leveler and many processing rolls, under the condition that the longitudinal strip curvature is zero, $K_x = 0$. The effect of the δ_{IM} of No. 4 roll on K_y' are shown in **Fig. 5** using experimental and calculated values. The strip gutter decreases with increasing δ_{IM} in the range of $\delta_{IM} = 0$ to 9 mm. The sign of the gutter becomes reverse when $\delta_{IM} = 9$ mm and then the strip gutter increase with increasing δ_{IM}. Experimental and calculated values show the same tendency and results of the calculation case No. 2 with corrected θ are in good agreement quantitatively with the experimental values.

An example of calculation is described below for a case

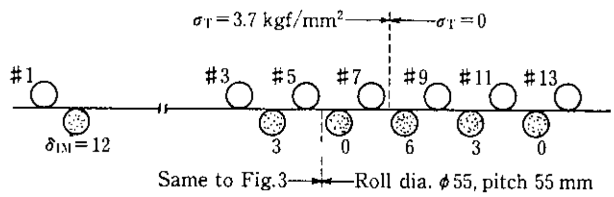


Fig. 6 Roll layout of leveler used for calculation of residual stress

where leveler rolls are added following the tension leveler shown in Fig. 3. δ_{IM} and the roll arrangement are shown in **Fig. 6**. Other conditions are the same as given in Table 1. However, $\sigma_T = 3.7$ kgf/mm^2 for the No. 1 to No. 7 rolls, and $\sigma_T = 0$ kgf/mm^2 for the No. 9 to No. 13 rolls, assuming a roller leveler. **Fig. 7** (a) and (b) show the through-thickness distribution of residual

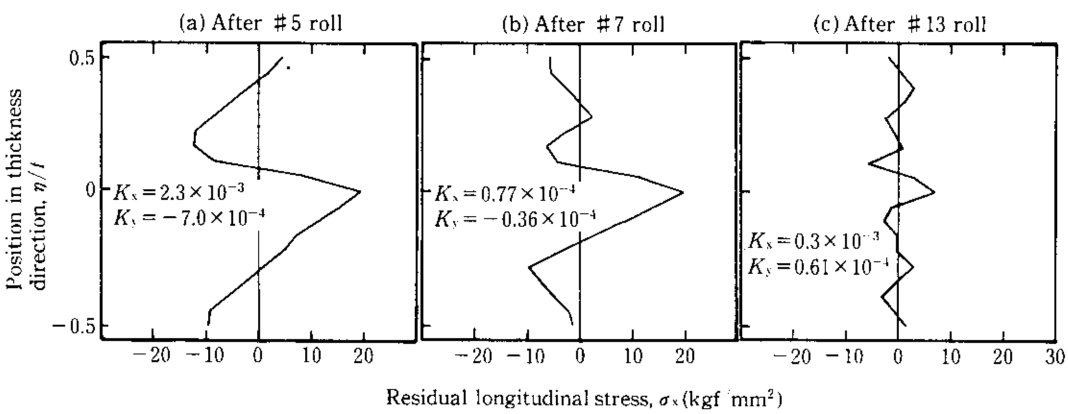


Fig. 7 Effect of number of roll on curl gutter and residual stress of strip

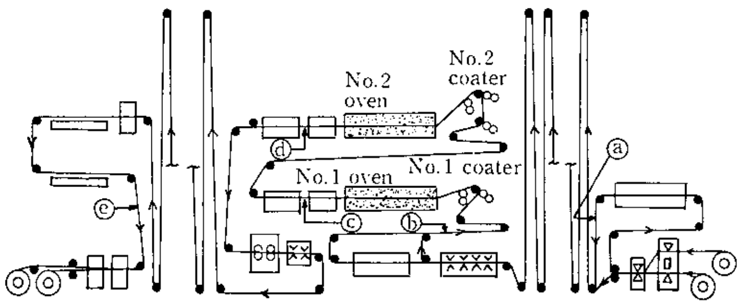


Fig. 8 Continuous color paint coating line use for calculation of strip gutter (ⓐ~ⓔ indicate measured points of strip gutter)

stress after unloading and the curvatures K_x and K_y of strip curling after the strip passed through the No. 5 roll and No. 7 roll, respectively. When attention is paid to K_x and K_y, it is found that both K_x and K_y have lower absolute values in (b) than in (a). In other words, it is possible to reduce both longitudinal and transverse curling by increasing the number of rolls.

Residual stresses are high in both (a) and (b) and especially high tensile stresses remain in the middle of the strip thickness. Even if the strip appears flat, it is feared that large curling are formed when the surface layer is removed by chemical etching, etc. Although these residual stresses can be relieved by heat treatment, they can be reduced by a roller leveler to some degree. Fig. 7 (c) shows the residual stress distribution after the strip passed through the No. 13 roll of the roller leveler. The high residual stresses observed near the center of the strip thickness after tension leveling disappeared and it is found that the residual distribution is relatively uniform. Even a roller leveler with only six rolls is thus effective in reducing residual stresses as shown in Fig. 7 (c).

3.2 Analysis of Strip Gutter in Continuous Processing Line

Strip gutters often pose a problem in operation where the strip travels while it is progressively subjected to bending. For example, threading troubles, surface defects, transverse nonuniformity in the coating thickness, etc., occur when strip gutters[7,8] occur during baking in a continuous color paint coating line or when they occur in a continuous galvanizing line. An example of application of the present analysis to the continuous color paint coating line shown in **Fig. 8** is described in the following: As shown in Fig. 8, a pretreated strip is coated by the No. 1 and No. 2 coaters and is baked in the respective ovens. On that occasion, product surface defects are formed due to rubbing of strip with the oven hearth and wall when strip gutters are large. Therefore, rolls were arranged before the No. 1 coater as shown in **Fig. 9** and an investigation was made into the effect of the intermesh δ_{1M} of roll A on strip gutters. Gutters of a strip being threaded were measured in the

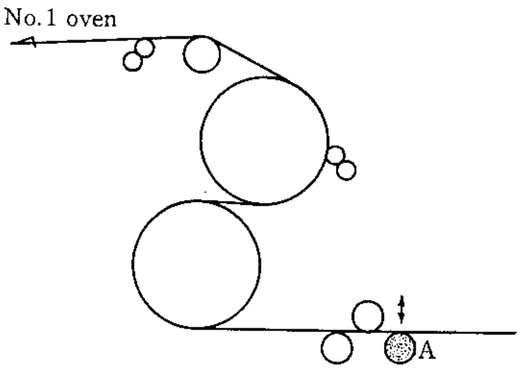


Fig. 9 Coating roll arrangement with pre-bending rolls for control of strip gutter

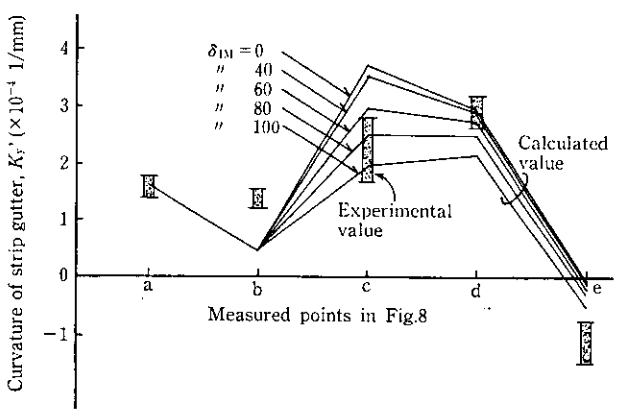
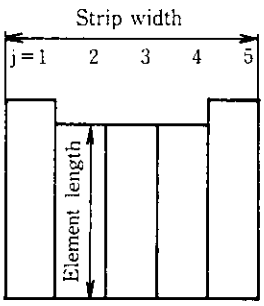


Fig. 10 Comparison between calculated and experimental values concerning strip gutter during threading through color paint coating line

five places ⓐ to ⓔ in Fig. 8 and experimental values were compared with calculated values. Results of this comparison are shown in **Fig. 10**. The tendency of calculated values is in good agreement with that of experimental values at each measuring place. Furthermore, a decrease in strip gutter with increasing intermesh of roll A shown in Fig. 9 was simulated relatively well.

3.3 Calculation of Flatness Correction

An investigation was made into the effect of the



Initial element length (mm)

j \ λ_0	2%	4%
1, 5	1 501.48	1 505.92
2, 3, 4	1 500	1 500

Strip size: 0.6 mm t × 1 219 mm W
$\sigma_e = 20$ kgf/mm²
$H = 50$ kgf/mm²

Fig. 11 Virtual divided elements model of strip with edge wave used for calculation of strip steepness

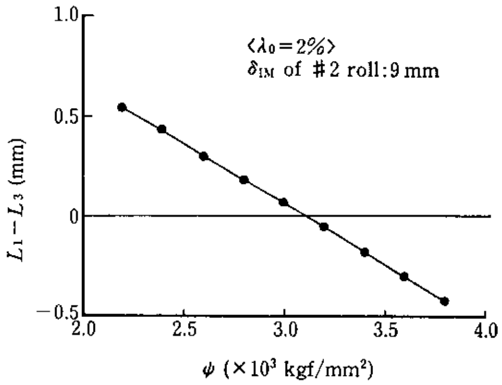


Fig. 12 Influence of parameter ψ on difference of strip length, $L_1 - L_3$, in the width direction after threading the first roll

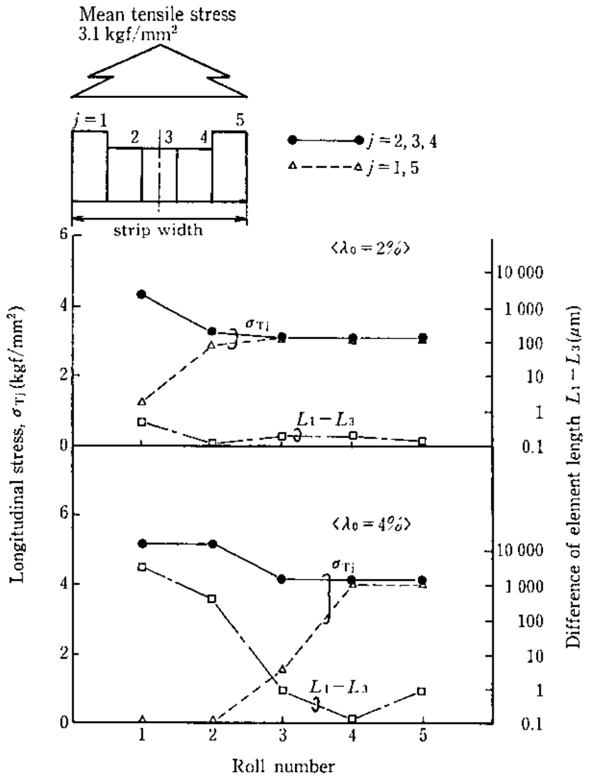


Fig. 13 Variation of longitudinal stress during tension leveling for correcting the strip steepness

intermesh and initial strip flatness on the flatness correction in the tension leveler of the roll arrangement shown in Fig. 3 using the calculation method shown in Fig. 2. The strip width was virtually divided into five elements with the same width as shown in **Fig. 11**. In consideration of wavy edges, the length of elements on both sides ($j = 1$ and 5) is given larger than the other elements. The size and characteristics of the strip used are also shown in Fig. 11.

The effect of the parameter governing the tensile stress allotment, ψ, on the difference in element length $L_1 - L_3$ on the delivery side of the No. 1 roll is shown in **Fig. 12** for a case where a strip with an initial steepness λ_0 of 2% was bent in the condition of $\delta_{IM} = 9$ mm for No. 2 roll. At $\psi > 3100$ kgf/mm², $L_1 - L_3$ is negative; this means the occurrence of reversal of the element length. When ψ is small, the effect of steepness correction is small. In calculation, all the element lengths are considered to be equal when it is satisfied that $L_1 - L_3 \leq 0.001$ mm ($\lambda = 0.05$%) and $\sigma_{T_j} \geqq 0$ for any element, and the calculation for the next roll is then made. In this case, the value $\psi = 3150.4$ is obtained after the No. 1 roll. When compressive stresses are generated, the value of ψ that satisfies compressive stress = 0 for an element in having the highest compressive stress is regarded as the maximum ψ and the calculation for the next roll is then made. In this case, the lengths of elements are scarcely equal to each other although the flatness is improved. The convergence calculation of ψ that satisfies one of the above-mentioned conditions is made in each roll. Changes in the tensile stress in each element and the difference in the element length $L_1 - L_3$ after each roll are shown in **Fig. 13**.

When λ_0 is 2%, tensile stresses are generated also in long elements ($j = 1$ and 5) after the No. 1 roll and the element length difference is within the set error ($L_1 - L_3 < 0.001$ mm). This shows that the element lengths are equal to each other after the No. 1 roll. The difference in tensile stress decreases gradually as the roll number increases and it is observed that all the elements are in a similar deformation state. When $\lambda_0 = 4$%, the element lengths are not equal to each other just after the No. 2 roll. The equality of element length requires that compressive force be generated in the long elements ($j = 1$ and 5). This, however, does not satisfy Eq. (18). Therefore, the tensile stresses are allotted to the three elements ($j = 2$, 3 and 4) before the No. 2 roll and the tensile stress for the elements ($j = 1$ and 5) is zero. Tensile stresses are allotted also to the elements ($j = 1$ and 5) while the strip is passing the No. 3 roll and all the elements obtain the same length.

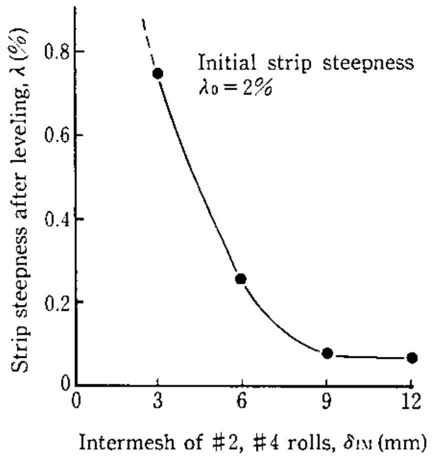


Fig. 14 Effect of roll intermesh on strip steepness after tension leveling

The effect of σ_{IM} on flatness correction of strip having initial steepness λ_0 is shown in **Fig. 14**. The λ values are those after the strip passed through the No. 5 roll and was unloaded. λ decreases with increasing δ_{IM}. This shows that in this case, products with $\lambda < 0.1\%$ can be obtained when δ_{IM} of 9 mm or more is given for the No. 2 and No. 4 rolls.

4 Conclusions

A method using plastic dynamics for analyzing the deformation behavior of a strip subjected to repeated bending was described together with the details of the simulation program of the analysis.

This analysis method was used in calculations for predicting the curls and gutters of strip after tension leveling and strip gutters during passing through a continuous color paint coating line, and the predicted values were compared with actual values. The two are in relatively good agreement. It was found, however, that additional accuracy improvement requires a modified conventional equation for bending curvature estimation. The authors demonstrated, with some examples, that a calculation for flatness correction is possible by a method in which elements are divided in longitudinal direction, and a given mean tension is distributed into each element. As a result, it was found that the larger the intermesh of rolls and the smaller the initial steepness, the easier the flatness correction, and the simulation of the steepness improvement condition of strip when passing each roll. In addition, the distribution of residual stresses was also discussed and it was found that the high residual stress that remains in the middle of the strip thickness after the tension leveler can be reduced by a roller leveler positioned following the tension leveler.

This simulation program has for several years provided information useful in solving various problems in production lines and is helping to examine the specifications of equipment to be adopted, equipment improvements, optimization of operation conditions, and production of strip with superior flatness.

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