Warp Control in Strip Processing Plant

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Strip is bent many times by turn rolls in the continuous annealing and surface treatment lines. Roll diameter of the turn rolls is usually made as small as possible due to limitation of space and cost. Therefore, plastic bending occurs and at the same time, the strip thus treated develops longitudinal and transverse warps (curvatures). It is proposed in this paper to refer to these two features as "curl" and "gutter", respectively.

Curl is restrained by line tension, but gutter (crossbow) appears down-stream of the turn roll. Gutter causes some line problem, especially in the plating line where it causes nonuniformity of coating thickness across the strip width.

This report provides theoretical analysis and basic information about gutter and how to control it in order to unify coating thickness in electrogalvanizing and hot dip galvanizing line. In the former line, gutter elimination just before the vertical plating cells, in the latter line, configuration of pot rolls are the main technical points to be discussed.

KEY WORDS: warp; gutter; crossbow; curl; surface treatment; strip; roll; bending; flatness.

1. Introduction

In strip processing plants such as continuous annealing line, galvanizing line and coating line, there are from 100 to 200 turn rolls (deflector roll, hearth roll, sink roll, steering roll, etc.) where the strip is bent under line tension. If the strip is bent plastically by turn rolls, the strip develops longitudinal and transverse warps (curvatures), which are called "curl" and "gutter", respectively. Curl is restrained by line tension, but gutter appears downstream of the turn roll. Therefore, it becomes important to control this gutter, especially in the coating section, because gutter directly effects the uniformity of coating thickness.

Curl and gutter after repeated bending by a tension leveler have already been examined both theoretically and experimentally by one of the authors.¹⁾

Applying this procedure, first, effects of roll diameter, strip thickness, line tension and yielding stress on gutter were calculated.

Second, the effect of restriction distance on reducing gutter value was experimentally examined.

Third, adequate roll diameter of the vertical plating cells in electrogalvanizing line to reduce gutter generation was studied. It was confirmed that repeated bending by turn rolls of gradually increasing diameter, just before the plating cells, and using large diameter rolls in the plating cells reduced gutter.

Fourth, roll arrangement at the zinc pot in hot dip galvanizing line to control gutter was experimentally studied, and desirable roll arrangement with suitable roll diameter was decided by numerical calculation.

2. Basic Studies by Numerical Calculation and Model Test

2.1. Theory of Curling and Guttering¹⁾

2.1.1. General Assumptions

(1) The strip elongates under the plane-strain condition (since stretch-bending is applied to thin and wide strips, the width to thickness ratio is large.)

(2) The stress in the thickness direction σ_z may be ignored.

(3) Sections plane before the process remain plane afterward.

(4) The tensile stress is applied uniformly across the strip width and the tension loss may be ignored.

(5) The Baushinger effect may be ignored.

2.1.2. Stress-Strain Relation

It is assumed that the stress-strain relation follows Hooke's Law in the elastic region and the Prandtl-Reuss equation in the plastic region. We shall use rectangular coordinates so that x, y, z denote the strip length, width and thickness direction, respectively. The material is assumed to be isotropic with uniform expansion of the yield locus and to satisfy the von Mises yield condition. From assumption 2, the equivalent stress $\bar{\sigma}$ and the equivalent plastic strain increment $d\bar{\varepsilon}_p$ are written as follows:

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

$$d\bar{\varepsilon}_p = \sqrt{\frac{2}{3}(d\varepsilon_{x,p}^2 + d\varepsilon_{y,p}^2 + d\varepsilon_{z,p}^2)} \quad \dots\dots\dots(2)$$

If the relation between $\bar{\sigma}$ and $d\bar{\varepsilon}_p$ is written as $\int d\bar{\varepsilon}_p = f(\bar{\sigma})$, strain increments are written as follows from assumptions 1 and 2, where H' is equal to $(df(\bar{\sigma})/d\bar{\sigma})^{-1}$.

$$\left. \begin{aligned} d\epsilon_x &= (d\sigma_x - \nu d\sigma_y)/E + (2\sigma_x - \sigma_y)\{(2\sigma_x - \sigma_y)d\sigma_x \\ &\quad + (2\sigma_y - \sigma_x)d\sigma_y\}/4H'\bar{\sigma}^2 \\ d\epsilon_y &= (d\sigma_y - \nu d\sigma_x)/E + (2\sigma_y - \sigma_x)\{(2\sigma_x - \sigma_y)d\sigma_x \\ &\quad + (2\sigma_y - \sigma_x)d\sigma_y\}/4H'\bar{\sigma}^2 = 0 \\ d\epsilon_z &= -\nu(d\sigma_x + d\sigma_y)/E - (\sigma_x + \sigma_y)\{(2\sigma_x - \sigma_y)d\sigma_x \\ &\quad + (2\sigma_y - \sigma_x)d\sigma_y\}/4H'\bar{\sigma}^2 \end{aligned} \right\} \dots\dots\dots(3)$$

In Eq. (3), if σ_x and σ_y are known, $\bar{\sigma}$ and H' are determined from the above relations, then when one of $d\epsilon_x$, $d\epsilon_z$, $d\sigma_x$ and $d\sigma_y$ is given, Eq. (3) can be solved. Because the longitudinal strain ϵ_x and the curvature κ are related in $\epsilon_x = \kappa \cdot z + \epsilon_e$, we may compute $d\epsilon_x$ from the curvature history.

The ϵ_e is the elongation of the middle fiber of the strip and is decided so as to satisfy the following relation:

$$\int_{-a}^a \sigma_x(z) dz = 2a \cdot \sigma_T \dots\dots\dots(4)$$

where, a : the half strip thickness

σ_T : the nominal applied tensile stress.

Predicting the value of a $d\epsilon_x$, Eq. (3) is solved, and by using $\sigma_y/\sigma_x = \alpha$, stress increments and an equivalent plastic strain increment are written as follows:

$$\left. \begin{aligned} d\sigma_x &= l(\alpha)d\epsilon_x \\ d\sigma_y &= m(\alpha)d\epsilon_x \\ d\bar{\epsilon}_p &= n(\alpha)d\epsilon_x \end{aligned} \right\} \dots\dots\dots(5)$$

where, $l(\alpha) = \{4H'(1 - \alpha + \alpha^2) + E(2\alpha - 1)^2\}/A$
 $m(\alpha) = \{4H'(1 - \alpha + \alpha^2)\nu - E(2 - \alpha)(2\alpha - 1)\}/A$
 $n(\alpha) = 2(1 - \alpha + \alpha^2)^{1/2} \{(2 - \alpha) + \nu(2\alpha - 1)\}/A$

and

$$\begin{aligned} A &= (5 - 4\nu)(1 + \alpha^2) + (10\nu - 8)\alpha \\ &\quad + 4H'(1 - \alpha + \alpha^2)(1 - \nu^2)/E \end{aligned} \dots\dots\dots(6)$$

In elastic deformation,

$$\left. \begin{aligned} d\sigma_x &= \{E/(1 - \nu^2)\} d\epsilon_x \\ d\sigma_y &= \{\nu E/(1 - \nu^2)\} d\epsilon_x \\ d\bar{\epsilon}_p &= 0 \end{aligned} \right\} \dots\dots\dots(7)$$

2.1.3. Spring Back (Curl and Gutter)

After the strip is bent and straightened around the

turn roll, the applied tension force and bending moment are released producing the residual curvatures, curl and gutter. But under the line tension, only M_y , which is calculated from the stress distribution of σ_y , is released, producing gutter $K_{y\text{res}}$. $K_{y\text{res}}$ is written in the following form by assuming that the flat strip after straightening is under the bending moment $-M_y$,

$$K_{y\text{res}} = -M_y/\bar{D} \dots\dots\dots(8)$$

where $\bar{D}$ is the flexural rigidity of the strip

$$\bar{D} = E(2a)^3/12(1 - \nu^2) \dots\dots\dots(9)$$

Using the strip width W , gutter C is written as follows:

$$C \doteq K_{y\text{res}} \cdot W^2/8 \dots\dots\dots(10)$$

2.1.4. Curvature

In turn rolls, curvature κ is equal to $2/D$, where D is the diameter of the turn rolls. When the strip does not conform to the rolls, κ is equal to $1/\rho_m$, where ρ_m is the effective radius of curvature for tension leveler.¹⁾

2.2. Numerical Calculations

In the analysis, any form of stress-strain curve can be used, but for simplicity, linear work-hardening is assumed in the following calculations, as shown in Fig. 1. Then the stress-strain relation is written as $\epsilon = \sigma/E + (\sigma - \sigma_e)/F$, and H' becomes a constant ($H' = F$) in Eq. (6), and especially in the case of an elastic-perfectly plastic solid, $H' = 0$.

2.2.1. Mechanism of Gutter Occurrence

The mechanism of gutter occurrence is shown in Fig. 2(a). The strip is bent at point P_E and straightened at point P_D . Typical stress distribution at point P_D is shown in Fig. 2(b). Restriction by the turn roll is removed downstream, so that the bending moment based on σ_y distribution at the stage P_D , generates the residual curvature $K_{y\text{res}}$, giving rise to the final stress distribution as shown in Fig. 2(c). Distribution of σ_y changes making transverse moment equal to zero, but distribution of σ_x changes very little because line tension and longitudinal moment are kept.

Fig. 1. Stress-strain curve used in the calculation.

Fig. 2. Mechanism of gutter occurrence.

2.2.2. Effects of Some Factors on Guttering

(1) Effect of Line Tension σ_T

The change of tension under actual working conditions has minimal effect on guttering, as shown in Fig. 3.

(2) Effects of Strip Thickness $2a$ and Yielding Stress σ_e

The larger the σ_e and the smaller the $2a$, the smaller the gutter becomes as shown in Fig. 3.

(3) Effect of Turn Roll Diameter D

The gutter abruptly decreases when D becomes larger as shown in Fig. 4.

(4) Effect of Work-hardening F

When $F=0$, the gutter value does not change after the 3rd or 4th bending, as shown in Fig. 5. When $F \neq 0$, the gutter value gradually decreases as bending times increase and finally is saturated.

2.3. Effect of Roll Interval on Gutter Restriction (1/4 Scale Model Test)

When the roll interval is very short, the gutter value is reduced by restriction of rolls. This restriction was measured by changing the roll interval and tension, as shown in Fig. 6. The effect of roll restriction is plotted in Fig. 7. The shorter the roll interval L , the thinner the strip thickness $2a$, and the higher

the line tension, the smaller the gutter value becomes. When L is greater than 9 to 10 times the strip width, the effect of roll restriction decreases and the gutter value is saturated. This restriction factor $C/C_{\max}$ is considered in following estimation of the gutter using the values in the graph.

2.4. Effect of Shape Defects on Guttering (1/4 Scale Model Test)

Flat strip, center buckle strip and wavy edge strip (0.4×300^w , $\sigma_e = 216 \text{ N/mm}^2$) were bent and straightened by $\phi 200$ or $\phi 250$ rolls under the condition of $\sigma_T = 9.8 \text{ N/mm}^2$ and the gutter was compared with the roll interval $L = 875 \text{ mm}$. In the case of wavy edge strip, the gutter value changes very little compared with flat strip because edge wave keeps its shape after bending and edge wave does not change to gutter, but in the case of center buckle strip, center buckle changes to gutter by the restriction of rolls and line tension as shown in Fig. 8 so that the gutter value increases in proportion to the shape defect λ (Fig. 8). The cross section profile of the gutter is almost an arc, but the pass line goes down in center buckle strip because of the higher tension on the strip edge portion (Fig. 9). For example in electrogalvanizing line, it is usually to set anodes in both sides of pass line at the same distance, so that this large shift from pass line also causes nonuniformity of coating thickness as well as gutter.

2.5. Comparison of Measured and Theoretical Gutters

1.6×877^w steel strip ($\sigma_e = 148 \text{ N/mm}^2$) was processed in the entry loop of a coating line and the gutter was measured at four points (A to D) with two

Fig. 3. Effect of various factors on gutter.

Fig. 4. Relationship between roll diameter and gutter.

Fig. 5. Effect of work-hardening on gutter.

Fig. 6. Measuring gutter.

Fig. 7. Effect of roll restriction on gutter (by experiment).

Fig. 8. Effect of steepness on gutter.

Fig. 9. Relationship between gutter and pass line.

levels of L as shown in Fig. 10. Table 1 shows the comparison of the measured gutter C with the theoretical gutter, assuming $F=0$. This table also shows that the gutter value does not change at the four points A to D and that the effect of work-hardening is very small. The calculated value is slightly larger than the measured one, but is accurate enough for practical use.

3. Gutter Improvement in Electroplating Line^{2,3)}

In the vertical cells of electroplating line, it is most important to decide diameters of the sink roll and the conductor roll in order to prevent gutter, which adversely effects uniformity of coating application in the plating section. Applying the above calculations and the restriction factor of Fig. 7, the appropriate roll diameter was examined for the maximum thickness and width strip ($1.6t \times 1600w$, $\sigma_e = 176$

Fig. 10. Accumulator roll dimension and position of gutter measurement.

Table 1. Comparison between measured and calculated gutters. (mm)
($\sigma_T = 5.9$ N/mm², $\sigma_e = 148$ N/mm²)

Measured point	Measured value				Calculated value	
	A	B	C	D	σ_e (N/mm ²)	
					148	157
L (m)	7.8	28	21	22	31	29
	4.0	23	21	26	28	26

Table 2. Estimation of gutter value. (mm)
($1.6t \times 1600w$, $\sigma_T = 8.9$ N/mm², $\sigma_e = 176$ N/mm²)

L (m)	D (mm)			
	650	800	1 000	1 200
∞	77.3	31.2	9.5	3.9
3.9	29.4	11.9	3.6	1.5
1.95	13.1	5.3	1.6	0.7
1.95 (Crown roll)	8.6	3.5	1.1	0.4

∞ : No restriction by the roll

Crown roll: Using support rolls with reverse crown at $L/2$

N/mm²) under constant line tension $\sigma_T = 9.8$ N/mm². Calculated results are shown in Table 2. L is the interval of the sink and conductor roll. $L = \infty$ means no restriction and crown roll means support rolls located at $L/2$ with reverse crown of the strip.

When roll diameter $D \geq 1000$ mm and $L \leq 3.9$ m, the gutter value becomes very small. From the view point of space and cost, the diameter of the turn rolls, not including the vertical cells, should be as small as possible. To realize this selection, gutter elimination method just before the vertical cells was examined. Fig. 11 shows the calculated results of gutter on several strips after repeated bending with gradually increasing diameter rolls ($\phi 650 \rightarrow \phi 800 \rightarrow \phi 1000 \rightarrow \phi 1200 \rightarrow \phi 1500$). It shows that gutter becomes very small after this repeated bending for any strip sizes and mechanical properties.

These calculated results show that repeated bending just before the plating cells by the successive turn roll of which diameter increases in order decreases gutter and following large diameter turn rolls in plating cells minimize gutter for uniform coating.

4. Gutter Improvement in Hot Dip Galvanizing Line⁴⁾

To obtain thin and uniform coating, it is necessary to place the jet nozzles as close as possible to the strip. In order to do this, it is very important to reduce gutter and also vibration of the strip. For this purpose an appropriate configuration of pot rolls to control gutter was determined by model tests and numerical calculations. Gutter control experiments were performed using a laboratory hot dip strip coating line. The experiments were conducted using ultra low carbon steel (0.6^t to $1.0^t \times 300^w$, $\sigma_e = 123$ to 176 N/mm²). The strip was processed through two types of roll arrangements as shown in Fig. 12, after which gutter was measured, changing the intermesh of A roll and tension σ_T .

Fig. 13 shows the change of gutter by the distance from A roll. The gutter value is saturated when the distance becomes 4 to 5 times the strip width.

Fig. 14 shows the relationship between gutter and A roll intermesh. The diagrams in the left are type (a), and the diagrams in the right are type (b) (as discussed in Fig. 12). The 2 upper diagrams show experimental results and the 2 lower diagrams show calculated results. Calculated results using the effective radius of curvature for tension leveler¹⁾ and measured results agreed with an accuracy sufficient for

practical use.

Using this calculating method, an appropriate pot roll configuration for the production line was examined. Type (b) was chosen and modified in this report, because it had the advantage that pass line of strip from zinc pot was not moved by changing A roll intermesh. General inclinations to control gutter in this configuration were as follows.

First, A roll makes minus gutter. B and C rolls make plus gutter. C roll constantly generates gutter, so that it is preferable to use large diameter roll.

Second, A roll diameter is equal to B roll diameter or A roll diameter is larger than B roll diameter, then control range of gutter inclines to plus.

Third, when A roll is put near B roll, gutter control becomes abrupt. But, when A roll is too far from B roll, gutter control fails to work.

Fourth, off-set of C roll enlarges minus gutter.

Based on these results, configuration of type (b) was modified for stability of gutter control as follows (Fig. 15);

- ① $D_C > D_B > D_A$,
- ② $L_1 \approx 1/2 D_B$,
- ③ $0.45(L_4 - D_C/2 + 2L_1) < L_2 < 0.55(L_4 - D_C/2 + 2L_1)$,
- ④ $0 < L_3 < 40$ (variable),
- ⑤ $1.05 D_C < L_4 < 1.5 D_C$,
- ⑥ $0 < L_0 < 15$

Fig. 11. Effect of configuration in which roll diameter is gradually increased.

Fig. 12. Configuration of pot rolls.

Fig. 13. Variation of gutter.

Fig. 14. Comparison between experimental and calculated results on gutter.

Fig. 15. Configuration of pot rolls. (Modified type (b))

- where, D_A : diameter of the lower snap roll (A)
 D_B : diameter of the upper snap roll (B)
 D_C : diameter of the sink roll (C)
 L_1 : distance between bath level and center of B roll
 L_2 : distance between bath level and center of A roll
 L_3 : intermesh of A roll
 L_4 : distance between bath level and center of C roll
 L_0 : off-set value of C roll

In this case the relationship between A roll intermesh and gutter is shown in Fig. 16 ($D_A=215$, $D_B=270$, $D_C=650$, $L_1=135$, $L_2=380$, $L_3=-10\sim 40$, $L_4=850$, $L_0=10$). By putting A roll at the center portion between B and C rolls, gutter control became smoother and change of intermesh had dull sensitivity to gutter. It means easy operation for gutter control.

5. Conclusions

The principal results obtained from the present theoretical and experimental investigation relating to the elimination of gutter (crossbow) on steel strip are summarized below:

(1) Gutter is inevitably generated by plastic bending. An analytical method of calculating the gutter quantitatively has been developed. This method has been proved to have an accuracy sufficient for practical use. Using this method, the effects of some factors on guttering were calculated. Gutter was strongly effected by strip thickness, yield stress and coefficient of work-hardening, but it was only slightly effected by line tension.

(2) Gutter is decreased by roll restriction, because the roll surface profile is nearly straight. This restriction factor was decided by model test, (for the function of roll interval and line tension) to estimate real gutter.

(3) The effect of strip flatness defects on guttering was examined by model test. Wavy edge strip has minimal effect on gutter, but center buckle strip enlarges the gutter. The gutter profile is almost an arc.

(4) Gutter elimination in the vertical type electrogalvanizing line was examined. From the view point of space and cost, it is preferable to use smaller

Fig. 16. Relationship between intermesh and gutter.

rolls. To meet this demand, the appropriate roll diameter was examined. Bending with rolls of gradually increasing diameter just before the vertical cells and the choice of larger diameter rolls in the following vertical cells proved to be effective in minimizing gutter.

(5) Gutter elimination in the coating section of the hot dip galvanizing line was also examined. Using the effective radius of curvature for tension leveler, the analytical method was applicable to determine the appropriate configuration of pot rolls. A configuration of pot rolls which consists of a sink roll (C) and two snap rolls (A and B) was suggested, where the upper roll (B) is fixed and the lower roll (A) is located the middle between B and C rolls, and is movable horizontally. Set up of these rolls can be determined by numerical calculation.

On the basis of these results, a new electrogalvanizing line was installed at Kashima Steel Works and a new hot dip galvanizing line was installed at Wakayama Steel Works of Sumitomo Metal Industries, Ltd. They are both running successfully. This analytical method has also been applied for warp control in other strip processing lines.

Nomenclature

- $2a$: strip thickness (mm)
 C : gutter value per strip width (mm)
 D : roll diameter (mm)
 E : Young's modulus (N/mm^2)
 F : coefficient of work-hardening (N/mm^2)
 IM : intermesh (mm)
 W : strip width (mm)
 x, y, z : rectangular Cartesian coordinates (—)
 x : strip length
 y : strip width
 z : strip thickness
 σ_e : yield stress of uniaxial tensile test (N/mm^2)
 σ_T : nominal applied tensile stress (N/mm^2)
 ν : Poisson's ratio (—)

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