On Longitudinal Curvature and Transition of Strain of Sheet Steel in Forming a Groove with Wide Flanges by Cold Roll Forming

By

Jun-ichi KOKADO* and Yoshitomi ONODA*

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Abstract

Roll forming of sheet steel into a trapezoidal groove with wide flanges has hitherto been carried out by a progressive development of bends (turn-up treatment). Since the allowable pass height per stand is small for this process, many roll stands must be provided to prevent edge waves and flawing. In order to rectify this defect, an experimental investigation of a method of transforming a circular arc groove into a trapezoidal groove has been carried out under several conditions.

It is found that the value of longitudinal curvature is proportional to 2.1 power of the thickness of sheet steel and also to several powers of the pass height. It increases with the increase in the width of the specimen, ranging from the length measured along the roll profile to twice this length, and has a constant value for a width of specimen over twice the length measured along the roll profile. It was also found that the curvature depends strongly on the inlet angle. Other factors such as the ratio of roll diameters, the ratio of surface velocities, and so on, affect the curvature but little. Finally, it has been confirmed through experiments in tandem roll forming that the value of the surface strain varies complexly and remarkably with the position, but that the value of the membrane strain is small and within the elastic limit. Therefore, it is considered that forming a groove by this method is approximately a pure bending process.

1. Introduction

The principal advantage of cold roll forming as compared with other methods of fabrication is high production capacity, but this forming method has defects whereby the abnormal longitudinal curvature and edge wave of the product may occur according to certain forming conditions. To rectify these defects and clarify the behavior of the specimen during the forming, some investigations have been carried out.

In 1964, in Japan, it was reported by Dr. Masuda and Dr. Murota[1] that the deformation process of aluminum strip in forming a circular arc section by a single

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* Department of Mineral Science and Technology

roll mill might be treated as a biaxial bending problem from the experimental result that the membrane strain of strip was less than one tenth of the surface bending strain. In 1969, it was reported by Dr. Suzuki and Dr. Kiuchi[2),3)] that the deformation path of the specimen, distribution and transition of redundant components of strain occurred in forming a circular arc, *V* and a trapezoidal shape played an important part for the quality of the product shape.

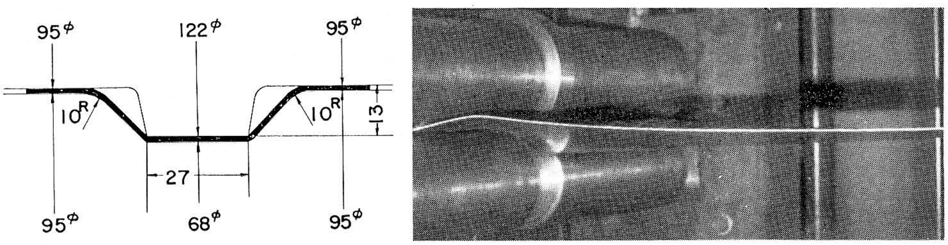
On the other hand, the investigations worth noting on the forming of a groove with wide flanges have hardly been carried out, as compared with the investigations on the forming of a narrow profile without flanges, as mentioned above.

We have carried out experimental investigations on the behavior of sheet steel in forming a single or double trapezoidal grooves with wide flanges by cold roll forming since 1963[4)]. As a result, it is found that the forming method which transforms a circular arc groove into a trapezoidal groove can provide fewer roll stands than the method of a progressive development of bends. Also, it can hold within very close dimensional tolerances.

This paper deals with the experimental results on the characteristics of the longitudinal curvature of the product and the transition of strain of sheet steel during roll forming.

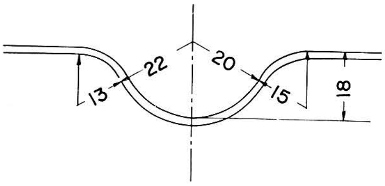
2. Determination of Roll Profile

Figure 1. (b) shows the deformation state of sheet steel (thickness: 1.2 mm, width: 300 mm) bitten by calibre rolls in forming a trapezoidal groove as shown in Fig. 1. (a). On the other hand, Fig. 2 (b) shows the deformation state of sheet steel (thickness: 1.2 mm, width: 300 mm) bitten by calibre rolls in forming a circular arc groove as shown in Fig. 2. (a). In comparison with Fig. 1. (b), undulation of the edge portion of sheet steel in forming the circular arc groove as shown in Fig. 2. (b) is small in spite of a large pass height. That is to say, a path

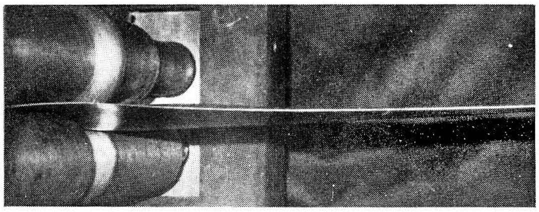


(a) Shape of calibre rolls, (b) A photograph of sheet steel bitten by calibre rolls.

Fig. 1. An example of forming process of sheet steel in forming a trapezoidal groove.



(a) Shape of calibre rolls.



(b) A photograph of sheet steel bitten by calibre rolls.

Fig. 2. An example of forming process of sheet steel in forming a circular arc groove.

difference between the edge and the groove portions is small. For this reason, the occurence of the edge wave of the product diminishes remarkably as compared with the turn-up treatment. Therefore, good results are expected to be obtained in both the number of roll stands and the dimensional accuracy of the product, as compared with the turn-up treatment by preceding the forming of the circular arc groove in the forming of the trapezoidal groove.

Consequently, we mainly state the results of our investigation on the behavior of deformation of sheet steel in forming the circular arc groove.

3. Roll Profiles and Dimensions of Rolls

The circular arc section of roll profile is determined by five factors which are pass height (h), opening width of groove (l), length measured along the roll profile (S), transverse bending radius of the groove part and shoulder part of the roll profile (R) and (r) and bending angle (θ). Taking the notation as shown in Fig. 4, the following three expressions can be obtained for the convex roll profile.

$$(R_n+r_n)(1-\cos\theta_n) = h_n$$
$$2(R_n+r_n)\theta_n = S \ (= 77 \text{ mm})$$
$$2(R_n+r_n)\sin\theta_n = l_n$$

where n means the n-th stand roll.

Taking the pass height and the transverse bending radius of the shoulder part of the roll profile $h_1=14$ mm, $r_1=20$ mm, $h_2=18$ mm, $r_2=15$ mm, and $h_3=23$ mm, $r_3=10$mm, the convex roll profiles for the forming of the trapezoidal groove by tandem roll forming are shown as in Fig. 3. Dimensions of each stand roll used for the experiment are shown in Table 1.

Besides, on sheet steel, the specimen SPC-1 (JIS・G3310) was mainly used, but the specimen SPN (JIS・G3301) was also used when necessary for comparison.

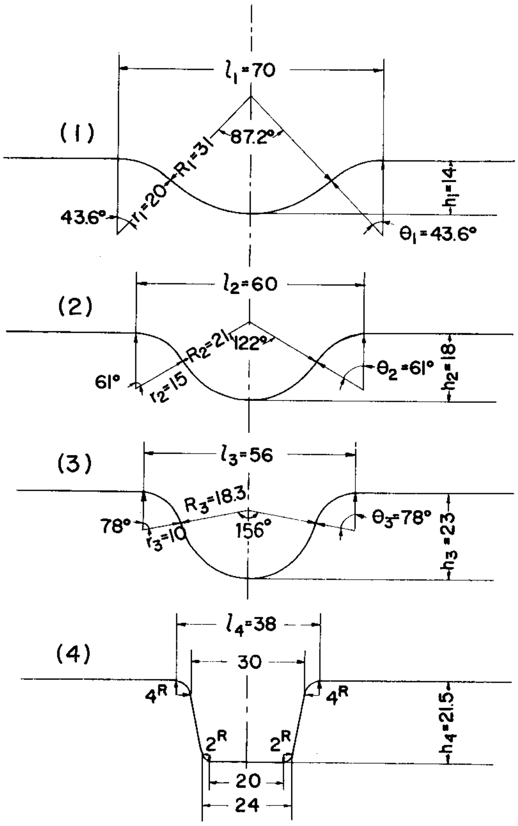


Fig. 3. Geometries of several convex roll profiles used for the experiment.

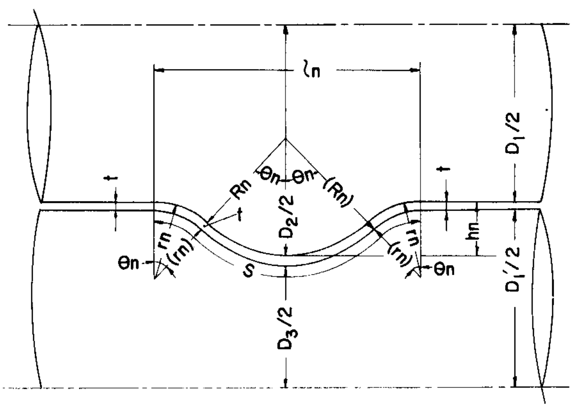


Fig. 4. Notations of roll profile.

Table 1. Dimensions of each stand roll

Rolls for the experiment	Barrel diam. of male roll D_1 (mm)	Max. diam. of male top roll D_2 (mm)	Barrel diam. of female roll D_1'(mm)	Min. diam. of female bottom roll D_3 (mm)	Ratio of roll diams. $D_2/D_3=i$	Length measured along the roll profile S (mm)	Pass height h (mm)	Opening width of groove l (mm)	Forming ratio h/l
No. 1 roll	110	138	110	78	1.77	77	14	70	0.2
No. 2 roll	95	131	95	57	2.3	77	18	60	0.3
No. 3 roll	95	141	95	51	2.76	77	23	56	0.41
No. 4 roll	95	138	95	55	2.51	70	21.5	38	0.57

4. Relation between Forming Conditions and Longitudinal Curvature of the Product in a Single Stand Roll Forming

4.1 Effect of the thickness of the specimen on the longitudinal curvature of the product

Figure 5 shows the relation between the thickness of the specimen (t) and the longitudinal curvature of the product ($1/\rho$), taking the ratio of the width of the specimen to the length measured along the roll profile (b/S) for the parameter in the first roll mill. Here, the ratio of maximum convex to minimum concave roll diameters is $(i)=1.77$, the ratio of surface velocities of flat part of lower roll to that of upper roll is $(V)=1.0$, and the inlet angle of the specimen to rolling axis is $(\alpha)=0°$.

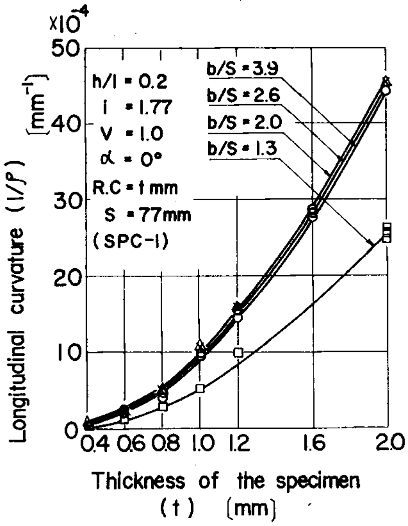


Fig. 5. Effect of the thickness of the specimen (t) on the longitudinal curvature of the product ($1/\rho$), where R.C means roll clearance.

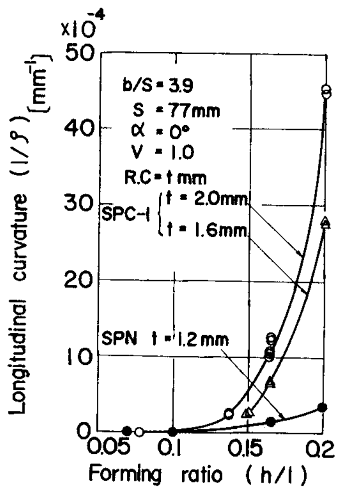


Fig. 6. Effect of the forming ratio (h/l) on the longitudinal curvature of the product ($1/\rho$).

From this figure, it is found that the value of the longitudinal curvature of the product is in proportion to 2.1 power of the thickness of the specimen in any value of parameter (b/S).

Consequently, this is the matter which must be considered in tandem roll forming of a thick specimen.

4.2 Effect of the ratio of forming height to opening width of groove on the longitudinal curvature of the product

Figure 6 shows the relation between the ratio of the forming height to the opening width of groove (h/l) per roll mill and the longitudinal curvature of the product $(1/\rho)$.

From this figure, it is found that the value of the longitudinal curvature of the product increases abruptly with the increase in (h/l), and this tendency is remarkable to the thick specimen.

Therefore, if the increase of the forming ratio (h/l) per roll mill is taken less than 0.1, the longitudinal curvature of the product is considered to be worth little consideration in tandem roll forming.

4.3 Effect of the width of the specimen on the longitudinal curvature of the product

Figure 7 shows the relation between the ratio of the width of the specimen

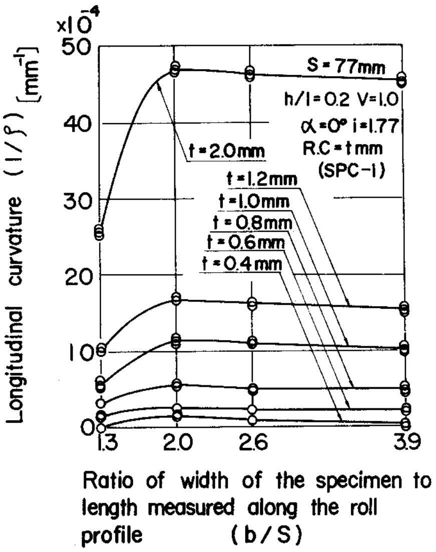


Fig. 7. Effect of the ratio of width of the specimen to length measured along the roll profile (b/S) on the longitudinal curvature of the product $(1/\rho)$.

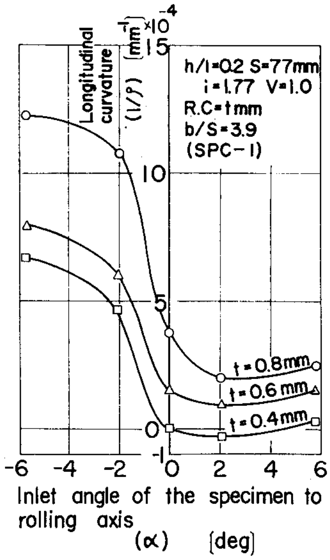


Fig. 8. Effect of the inlet angle of the specimen to rolling axis (α) on the longitudinal curvature of the product $(1/\rho)$.

to the length measured along the roll profile (b/S). It also shows the longitudinal curvature of the product ($1/\rho$) taking the thickness of the specimen (t) for the parameter in the first roll mill, where $i=1.77$, $V=1.0$ and $\alpha=0°$.

From this figure, it is found that the longitudinal curvature of the product increases with an increase in (b/S), and has a nearly constant value for $(b/S)\geq 2$.

4.4 Effect of the inlet angle of the specimen to rolling axis on the longitudinal curvature of the product

Figure 8 shows the relation between the inlet angle of the specimen to the rolling axis (α), and the longitudinal curvature of the product ($1/\rho$) in the first roll mill, where $i=1.77$, $V=1.0$ and $b/S=3.9$. Here, $1/\rho \gtrless 0$ means that the product curves on the concave or the convex roll side respectively.

From this figure, it is found that the value of the longitudinal curvature of the product increases remarkably with the increase in the negative inlet angle, and the product becomes anticlastic. On the other hand, in the case of the positive inlet angle, the value of the longitudinal curvature of the product becomes minimum at $\alpha \fallingdotseq 2°$ and increases again for $\alpha > 2°$. Furthermore, an edge wave occured for

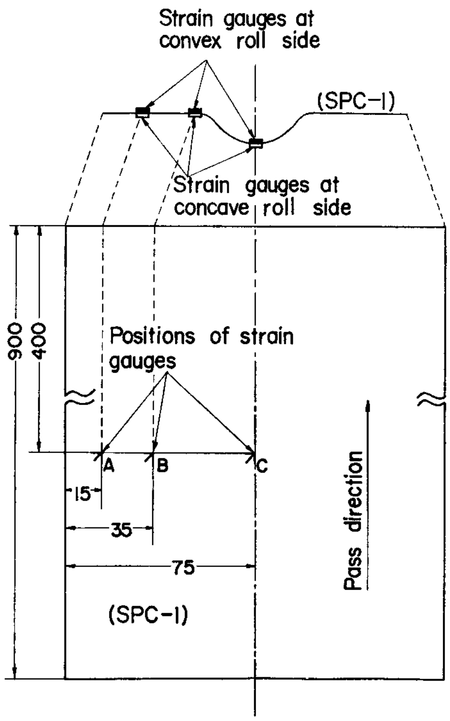


Fig. 9. Location of resistance wire strain gauges pasted on the surfaces of the specimen.

$\alpha > 4°$.

Other factors such as the ratio of roll diameters (i) and the ratio of surface velocities of rolls (V) affected the longitudinal curvature but little.

5. Strain of the Specimen in a Single Stand Roll Forming

Strain was measured by the electric resistance wire strain gauge pasted on both surfaces of the specimen ($t=1.0$ mm, $b/S \simeq 2$), as shown in Fig. 9.

Firstly, the transitions of three directional surface strains and membrane strains are shown in Fig. 10, with the distance from the point being beneath the center of rolls, in forming a circular arc groove by the first roll mill, where $i=1.77$, $V=1.0$ and $\alpha=0°$. In this figure, a portion where the solid or dotted line does not exist is due to broken lead wire of the electric resistance wire strain gauge during measurement.

From Fig. 10, we can see the following observations. Namely, the transitions of both the three directional surface strains of the flange (points A and B) and the longitudinal surface strain of the groove (point C) are sinuous and mean the state of repeated bending. The forming process of the circular arc groove, from the transition of the transverse strain of point C, is that the progressive bending

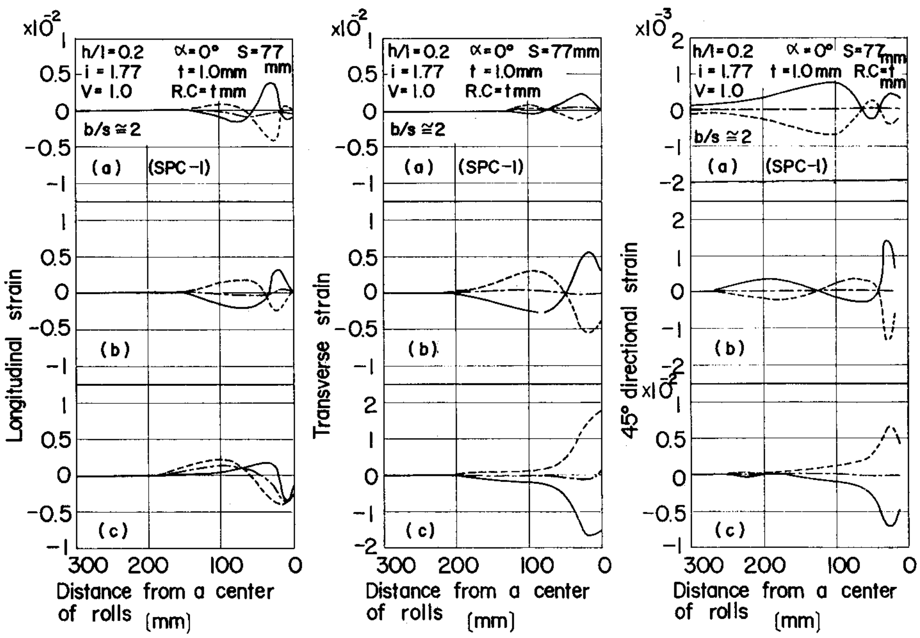


Fig. 10. Transition of longitudinal, transverse, 45° directional surface strains and their membrane strains in a single stand roll forming (Solid line: Surface strain at convex roll side, Dotted line: Surafce strain at concave roll side, Broken line: Membrane strain).

of the circular arc begins from a point about 210 mm before the center of the rolls, and the transverse bending becomes maximum at the center of the rolls. As the value of this maximum transverse bending strain approximates the bending strain 1.58×10^{-2} calculated from the bending radius of the roll profile, the specimen is in contact with the convex part of the convex roll along the roll profile. The value of the membrane strain, in general, is small and within the elastic limit; but the value of the longitudinal membrane strain of the groove (point C) is large as compared with that of other points. Furthermore, from this transition where the value of the membrane strain varies from tension side to compression side, the groove part of the product contracts longitudinally after all. This is the characteristic of the deformation process of the specimen in forming a circular arc groove with wide flanges by cold roll forming.

Secondly, the transitions of the principal strains of the upper surface of the specimen are shown in Fig. 11, with the distance from the point being beneath the center of rolls, as the result of the calculation of three directional surface strains shown in Fig. 10.

In this figure, we can divide the deformation surface before the rolls into

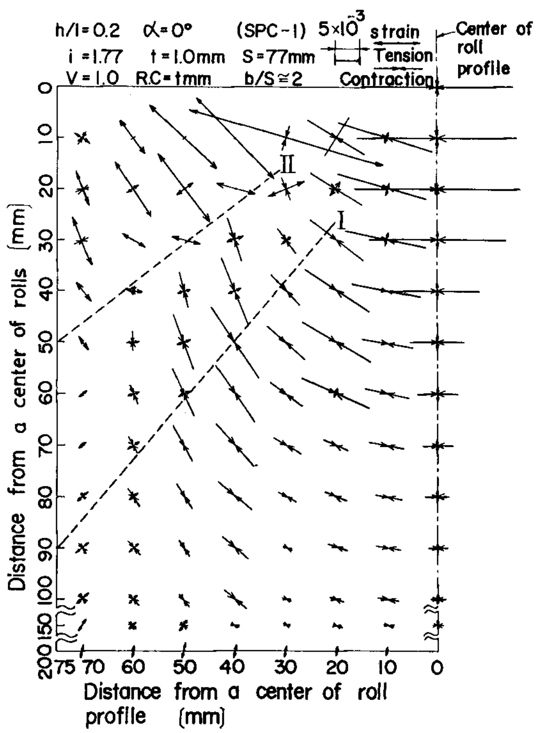


Fig. 11. Transition of principal surface strain at convex roll side.

three zones. Namely, in the wide zone before the dotted line *I* the specimen is bent downward, and in the zone between the dotted line *I* and *II* the specimen is bent upward. The complex three dimensional surface is formed by the effect of the shoulder part of the concave roll profile. Further, in the zone between the dotted line *II* and the solid line of roll center, the edge of the specimen is bent upward by the effect of the flat part of the upper roll and forms an undulation as shown in both Fig. 1. (b) and Fig. 2. (b).

6. Transition of Longitudinal Curvature and Strain of Sheet Steel in Tandem Roll Forming

6.1 Transition of longitudinal curvature

Longitudinal curvature of sheet steel through tandem roll mills is affected by the pass height in each roll mill, stand distance and difference of roll height.

The set-up angle β, in Fig. 12 and Fig. 13, satisfies the following expression.

$\tan \beta = H/L$

where, L: stand distance

H: difference of roll height

β is positive when the N-th mill rolls are higher than the $(N+1)$ th mlli rolls.

Figure 12 shows the transition of the longitudinal curvature of sheet steel through tandem roll mills according to the roll profiles as shown in Fig. 3, where $\beta = 0°$. In this figure, the value of the longitudinal curvature of the specimen decreases once in the second roll mill and increases again in the subsequent roll mills. The longitudinal curvature, as stated before, increases with the increase in pass height and has a tendency to decrease when the inlet angle of the specimen becomes positive. The reason why the longitudinal curvature decreases in the second roll mill is that the decrease of the longitudinal curvature due to the

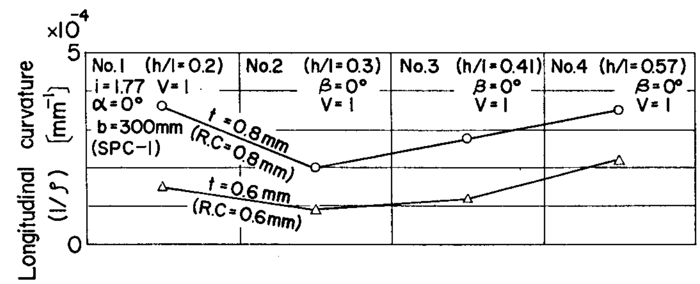


Fig. 12. Transition of the longitudinal curvature $(1/\rho)$ through tandem roll mills in the case of standard pass-line $\beta = 0°$ ($\beta = \tan^{-1}(H/L)$, H: Difference of roll height [m], L: Stand distance [m]).

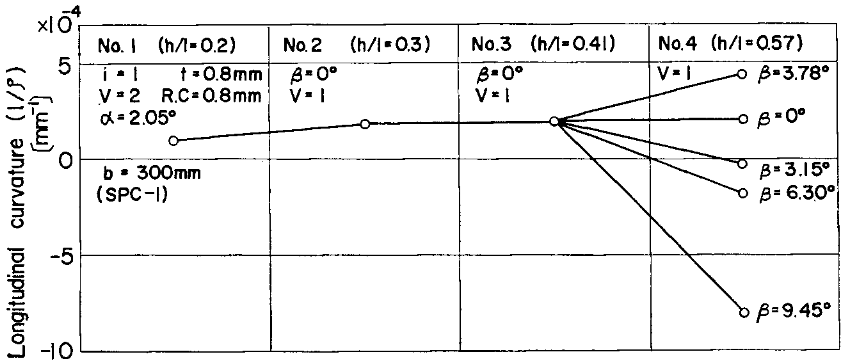


Fig. 13. Transition of the longitudinal curvature ($1/\rho$) through tandem roll mills, especially for the variation of the set-up angle (β) to No. 4 stand rolls.

positive apparent inlet angle of the specimen (which is 4.3° and 2° to the rolling axis in the second mill for $t=0.8$ mm and $t=0.6$ mm respectively) exceeds the increase of that due to the increase of the pass height. In both the third and the fourth mills, on the other hand, it is considered that the increase of the longitudinal curvature due to the increase of the pass height exceeds the effect of the positive apparent inlet angle.

Figure 13 shows another example of the experimental result in tandem roll forming, when the inlet angle of the specimen in the first roll mill is selected to make the longitudinal curvature minimum in consideration of the result mentioned in 4.4, and the set-up angle β is changed in the fourth roll mill. In this figure, as the longitudinal curvature is small in the outlet of the first roll mill, and the apparent inlet angle to the rolling axis in the second roll mill cannot have enough positive value to decrease the longitudinal curvature, its curvature increases unlike the case of Fig. 12. The values of the longitudinal curvature of the specimen in the outlet of the third and the fourth roll mill are much the same as in the case of $\beta=0°$, but its value in the fourth roll mill is much affected by the set- up angle β. In this experiment, its value becomes almost zero, when $\beta=3.14°$.

This suggests that the finished product with no longitudinal curvature can be obtained by slightly changing the set-up angle in the finished roll mill, as long as the longitudinal curvature before the finished roll mill does not become large in particular in tandem roll forming.

6.2 Transition of strain

Measurement of the strain of sheet steel through tandem roll mills according to the roll profiles as shown in Fig. 3 was done by the electric resistance wire strain gauge pasted on both surfaces of the specimen ($t=0.4$ mm, 0.6 mm and 0.8 mm,

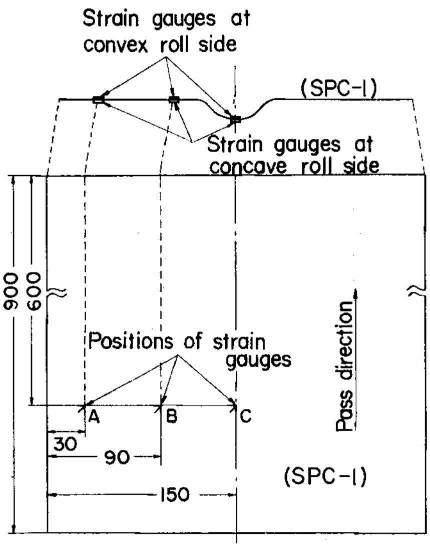


Fig. 14. Location of resistance wire strain gauges pasted on the surfaces of the specimen.

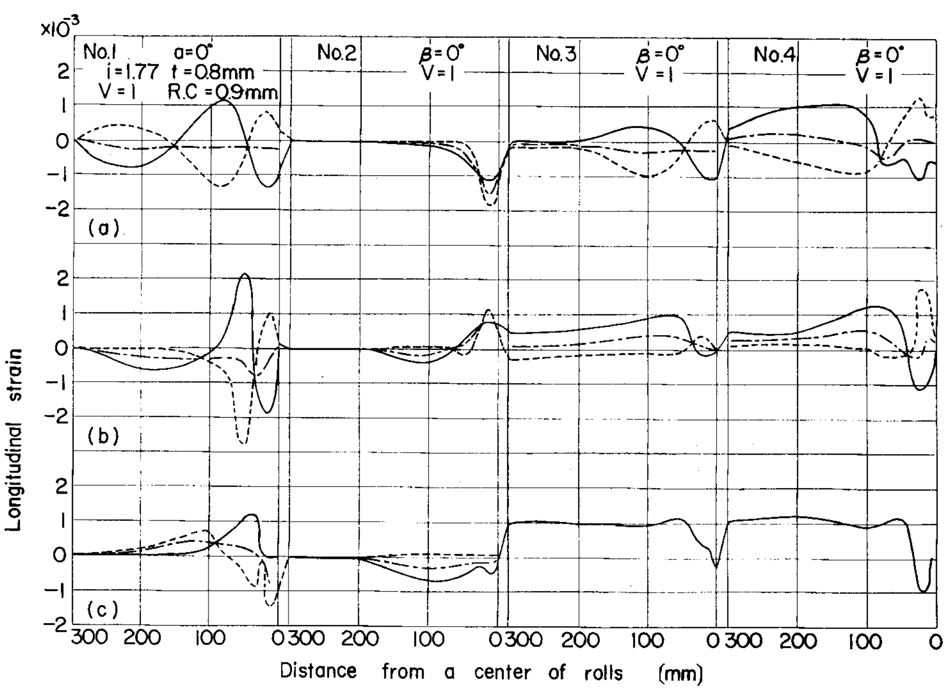


Fig. 15. Transition of longitudinal and its membrane strains through tandem roll mills in the case of standard pass-line $\beta=0°$ (Solid line: Surface strain at convex roll side, Dotted line: Surface strain at concave roll side, Broken line: Membrane strain).

$b/S=3.9$), as shown in Fig. 14.

As an example of the experimental results, Fig. 15, Fig. 16 and Fig. 17 show the transitions of three directional surface strains and membrane strains of the specimen ($t=0.8$ mm, $b/S=3.9$), with the distance from the center of rolls in each mill, where $V=1.0$ and $\beta=0°$. In these figures, the portions where the solid or dotted line does not exist are due to the broken lead wire of the electric resistance wire strain gauge during measurement.

From these figures, we can have the following observations. Namely, the deformation process of the specimen in the first roll mill is much the same as in a single stand roll forming as shown in Fig. 10. However, the change of the strains near the center of the rolls is stronger by the effect of tandem roll forming as compared with that in a single stand roll forming. Once the circular arc groove is formed in the first roll mill, the change of the strains of the specimen in both the second and the third mills is smaller than that in the first roll mill. Also, the forming process of the circular arc groove is smooth. In the fourth roll mill which transforms the circular arc groove into the trapezoidal groove, the change of the strains of the specimen near the center of rolls is somewhat strong. Further, from the transitions of the transverse and 45° directional strains, the forming of the bottom of the trapezoidal groove begins from a point about 50 mm before the center of rolls.

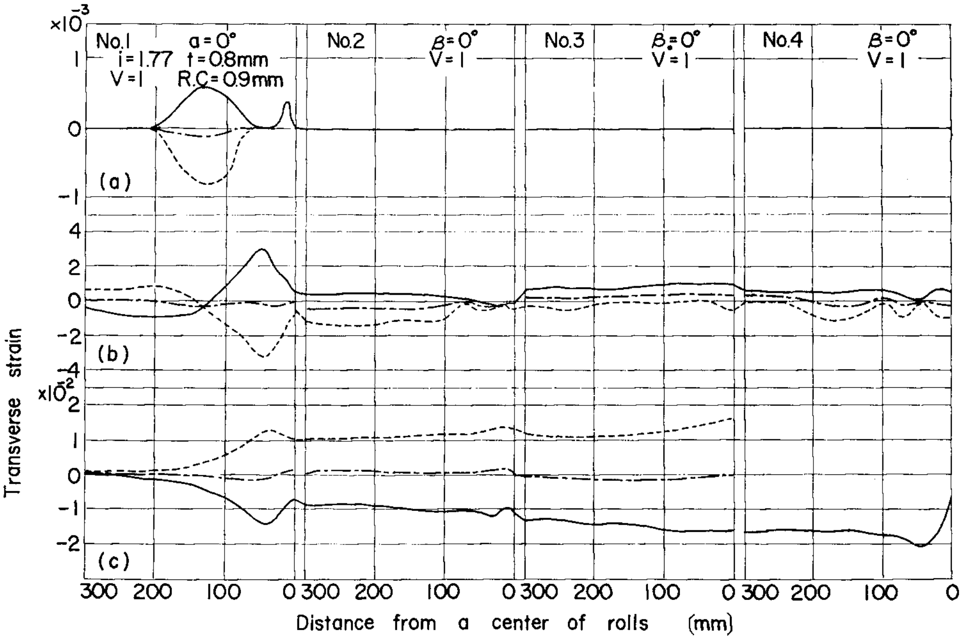


Fig. 16. Transition of transverse and its membrane strains through tandem roll mills in the case of standard pass-line $\beta=0°$.

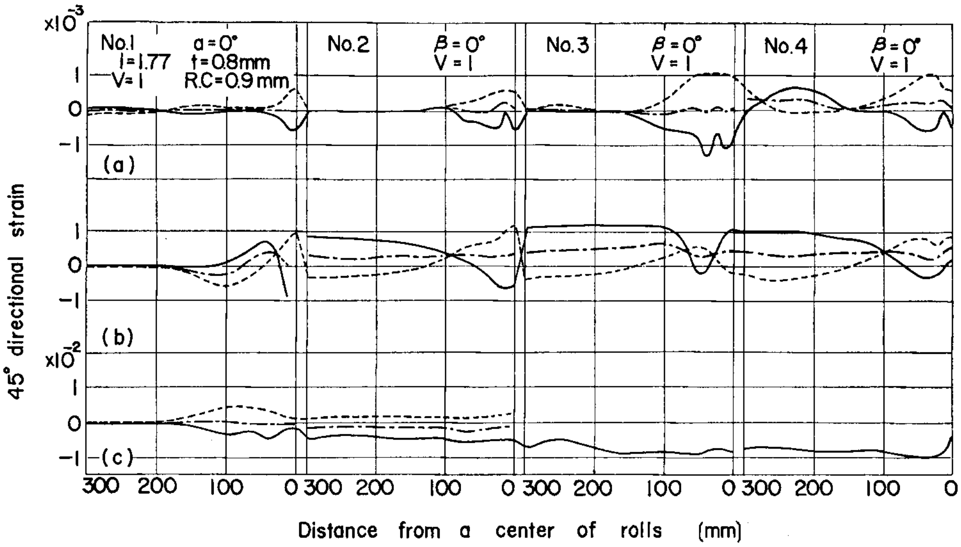


Fig. 17. Transition of 45° directional and its membrane strains through tandem roll mills in the case of standard pass-line $\beta=0°$.

From the observations of the transitions of the strains mentioned above, it is found that the transition of the strain is regular, though occasionally each strain changes strongly, and that the edge wave of the product cannot occur, as the membrane strain is within the elastic limit. Besides, it was confirmed that seven roll mills had to be equipped for the forming of a thick specimen by adding both two roll mills with circular arc profiles of the small pass height and one roll mill with a trapezoidal profile to this cold roll forming equipment.

7. Conclusion

Firstly, we discussed the longitudinal curvature and the transition of the strain of sheet steel in forming a circular arc groove with wide flanges by a single stand roll forming, and we obtained the following results.

(1) The value of the longitudinal curvature of the product is in proportion to 2.1 power of the thickness of the specimen and to several powers of the pass height.

(2) The value of the longitudinal curvature of the product increases with the inccrease in the width of the specimen for $b<2S$, and has an almost constant value for $b\geq 2S$, where S is the length measured along the roll profile.

(3) The value of the longitudinal curvature of the product is affected strongly by the inlet angle of the specimen to the rolling axis, and the inlet angle which minimizes this value exists.

(4) The transitions of both the three directional surface strains of the flanges

and longitudinal surface strain of the groove are sinuous and the bending is repeated. On the other hand, the transition of the transverse surface strain is comparatively simple.

(5) The so-called pre-deformation zone of the specimen before rolls is much affected by the width of the specimen, but it has little relation to the thickness of the specimen.

Secondly, we showed an example of the tandem roll forming of a trapezoidal groove according to the method of transforming a circular arc groove into a trapezoidal groove, and we obtained the following results.

(1) The finished product with less than 0.8 mm in thickness could be held within close dimensional tolerances by only one finished roll mill with a trapezoidal roll profile.

(2) The value of the membrane strain is small and within the elastic limit, and no edge wave of the finished product could be observed.

Acknowledgement

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