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Effect of Front Tension on Strip Rolling Analysed by Photo-Rheological Method*

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Formerly, the photo-rheological stress analysis was applied for finding stress distributions in the roll and strip specimens in strip rolling.

In the strip rolling, however, a method in which the strip is subjected to front tension with rolling torque has been applied for improving the process.

In the present paper, the photo-rheological stress analysis is applied to analyse the effect of front tension on the stress distribution in the roll and strip specimens.

As the result of analysis, the effect of front tension on the rolling appeared as follows:

- 1) on the roll specimen, the stress components in the specimen and the normal pressure on the contact surface decrease considerably with increase of the front tension.
- 2) on the strip specimen, though the effect of front tension does not appear so remarkably as in the roll, the residual stress after rolling fairly decreases with increase of the front tension.

1. Introduction

Strip rolling is one of the most important processes in plastic working and there are many theoretical investigations^{(1)~(4)} for finding the stress distribution of the contact surface concerning this process. However, the propriety of hypothesis used in their theoretical calculations has been ascertained only partly. Though some experimental investigations have been performed^{(5)~(6)} to find the roll pressure, the relations between their results and the corresponding actual stress states are not analysed sufficiently. The main reason for such situations seems to be due to the fact that any suitable method has not been developed yet for measuring the stress distributions in such cases.

In the model test, however, by means of the photo-rheological method⁽⁷⁾ proposed by one of the present authors, the stress state within a plastically flowing body in the plane strain state may be analysed with the same accuracy as in the photoelasticity. The present authors have already analysed many examples^{(8)~(9)} in the contact pro-

blem between elastic and plastically flowing bodies by using this method.

In the previous paper⁽¹⁰⁾, the above mentioned procedure was applied to the strip rolling process in the plane strain state, and the stress distributions on the contact surface as well as within the roll and strip specimens were investigated in detail.

In the strip rolling process, however, the front tension method^{(1)~(3)~(5)} in which the strip is subjected to the front tension as well as rolling torque has been proposed, and some advantages such as the reduction of roll pressure and the increase of strip velocity have been pointed out for this method. Moreover, a simple graphical method⁽¹¹⁾ has been proposed in order to apply these merits for practical working. However, on the relation between the stress distribution and the front tension in the strip rolling, any measurement has not been performed yet.

In the present paper, the effects of front tension on the stress distribution within the roll and strip in the rolling process are discussed regarding to the result of a model test in the plane strain state using the photo-rheological method.

2. Experimental apparatus

Figure 1 shows the apparatus, in which a

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device to give a front tension to the strip is attached to the apparatus same as that in the former experiment⁽¹⁰⁾. In the figure, P and T denote the front tension and rolling torque, respectively, loaded by means of dead weights. In order to restrict the deformation of strip in the plane strain state, the strip is constrained by a pair of thick glass plates on both sides of it. So that the glass plate may move vertically with the strip, they are supported by ball bearings on their outsides.

When the apparatus is immersed in an oil bath heated at 65°C, the strip specimen (celluloid) is softened and deforms plastically under the external loads, while the roll specimen (Araldite) is kept in a glassy elastic state. As the mechanical properties of celluloid are sensitive to temperature, the variation and non-uniformity of temperature in the specimens are kept within $\pm 0.05^\circ\text{C}$ by using a regulator of thermistor type. Accordingly, the contact surface between roll and strip is considered to be lubricated sufficiently.

3. Specimens

3.1 Roll specimen

The roll specimen was a segment of circular plate finished by the light cutting from an Araldite plate of 6 mm thick without any initial stress. The right side in Fig. 2 shows the geometry of the specimen used. As the result of calibration test using two uniaxial specimens cut out from the same Araldite plate as above, it was confirmed that the Araldite was kept in a glassy elastic state at 65°C. Moreover, Young's modulus and the fringe stress of the material at 65°C were

found as 234 kg/mm², and 0.966 kg/mm, respectively.

3.2 Strip specimen

The strip was finished by end-mill from a transparent celluloid plate of 6 mm thick and its size corresponding to the case of $r=19.6$ percent and $2R/H=40$ is shown in the left side in Fig. 2, where r denotes the reduction ratio $r=(H-h)/H \times 100\%$, R denotes the roll radius, H and h denote the widths of the strip before and after rolling, respectively. A square network with 0.5 mm spacing is incised on one surface of it, as shown in the figure.

The fundamental relations of the photo-rheological method in the plane strain state are as follows⁽¹²⁾;

i) loading process

$$\Delta\epsilon(t) = \frac{B_0}{2} \int_0^t \tau^\alpha \Delta\sigma(\tau) e^{(b/2)\Delta\sigma(\tau)} d\tau + \frac{\Delta\sigma(t)}{2G} \left[1 + \left\{ \frac{\Delta\sigma(t)}{2k} \right\}^{2n} \right] \dots\dots\dots (1)$$

$$N(t) = C_1 \Delta\sigma(t) + C_2 \Delta\epsilon(t) + C_3 \Delta\epsilon(t)^{3/2} + C_4 \Delta\epsilon(t)^2 \dots\dots\dots (2)$$

ii) unloading process

$$\Delta\bar{\epsilon}(t) = \frac{B_1}{2} \int_{t^*}^t (\tau - t^*)^\beta \Delta\bar{\sigma}(\tau) e^{(b'/2)\Delta\bar{\sigma}(\tau)} d\tau + \frac{\Delta\bar{\sigma}(t)}{2G'} - \frac{B_0'}{2} \int_{t^*}^t \tau^\alpha \Delta\sigma(\tau) e^{(b/2)\Delta\sigma(\tau)} d\tau \dots\dots\dots (3)$$

- ①: Supporting frame
- ②: Strip specimen
- ③: Roll specimen
- ④: Ball bearing
- ⑤: Glass plate
- ⑥: Heater
- ⑦: Oil bath

Fig. 1. Experimental apparatus

$v=0.2 \text{ mm/min}$
 $2R/H=40, r=(H-h)/H \times 100\%$

$r \%$	$H \text{ mm}$	$h \text{ mm}$	$2R \text{ mm}$
19.6	8.82	7.09	352.8

Fig. 2 Shapes and sizes of specimen

$\tilde{N}(t) = C_5 \Delta \sigma(t) + C_6 \Delta \varepsilon(t) \dots\dots\dots (4)$
 where $\Delta \sigma(t)$ and $\Delta \varepsilon(t)$ denote the principal stress and strain differences at time t , $N(t)$ is the fringe order at time t , t^* denotes the time t at the beginning of unloading, $\Delta \sigma(t) = \sigma(t) - \sigma(t^*)$, $\Delta \varepsilon(t) = \varepsilon(t) - \varepsilon(t^*)$, $\tilde{N}(t) = N(t) - N(t^*)$, and B_0 , α , b , G , k , n , B_1 , β , b' , G' , B_0' , C_1 , $\dots$ C_6 are the characteristic values depending on the

material and temperature and so on. The calibration test of celluloid was performed with uniaxial specimens under a combined loading of axial load and hydrostatic pressure for finding the above mentioned characteristic values. Though the characteristic values in the above relations are affected by the principal stress ratio σ_1/σ_2 , as an example, Table 1 shows the characteristic

Table 1 Characteristic values ($\sigma_1/\sigma_2 = -1$)

B_0	b	$-\alpha$	$2G$	n	k	B_0'	$2G'$	$-\beta$
1.45×10^{-4}	6.71	0.417	59.0	2.03	0.875	0.25×10^{-4}	132	0.514
b'	B_1	C_1	C_2	C_3	C_4	C_5	C_6	
5.94	1.3×10^{-4}	0.21	1.10	0.92	0.20	0.155	1.18

P=9 kg

Fig. 3 Isochromatic fringe pattern of the roll specimen (19.6%)

P=9 kg

Fig. 4 Isochromatic fringe pattern of the strip specimen (19.6%)

P=9 kg

Fig. 5 Isoclinic fringe pattern of the roll specimen (19.6%)

P=9 kg

Fig. 6 Isoclinic fringe pattern of the strip specimen (19.6%)

values for $\sigma_1/\sigma_2 = -1$ obtained by the calibration test.

4. Experimental procedure

An experiment was performed for the case of $2R/H=40$ and $r=19.6$ percent shown in Fig. 2, and the rolling torque T was selected such that the strip velocity at the entry to the roll might attain $V=0.2$ mm/min for the values of front tension $P=0, 3, 6$ and 9 kg, respectively. After the temperature of the oil bath was settled at the assigned value (65°C), the loads T and P were applied.

In the steady state of the rolling process, the isochromatic and isoclinic fringes were recorded photographically. The former was taken through a monochromatic filter of $5461 \text{ \AA}$, and the latter was recorded without filter and canceling the former with the use of colour film at a slight over-exposure. The deformed network on the strip was also recorded with them.

5. Experimental result

Figures 3 and 4 show some examples of the isochromatic fringe patterns of the roll and strip, respectively, for $P=9$ kg. Figures 5 and 6 show the corresponding isoclinic patterns. Figure 7 shows the relation between the rolling torque T and the front tension P obtained by the experiment.

6. Stress distribution in the specimens

Though the principal stress difference within the roll specimen can be found by the usual photoelastic method, the photo-rheological method⁽¹²⁾ must be used for finding that in the plastically flowing strip. Moreover, it should be

noted that the characteristic values contained in the fundamental relations of the photo-rheological method are affected by the value of principal stress ratio σ_1/σ_2 . In the previous paper⁽¹⁰⁾, an elaborate procedure taking account of the effect of principal stress ratio was performed. However, the difference between the result obtained by the elaborate method and its first approximation using only the characteristic values for $\sigma_1/\sigma_2 = -1$ was found to be very small. For this reason, in the present paper, the principal stress difference $\Delta\sigma$ was obtained by using the photo-rheological method⁽¹²⁾ with the characteristic values corresponding to $\sigma_1/\sigma_2 = -1$ shown in Table 1. As an example of the results obtained, Fig. 8 shows the distribution of $\Delta\sigma$ within the strip for $P=9$ kg.

The stress analysis within the roll specimen was performed by using the shear difference method with the isochromatic and isoclinic fringe patterns obtained by the experiment. At first, a vertical section having a distance $0.0315 R$ (R denotes the roll radius) from the surface at the end of horizontal diameter of roll was selected as a base section which intersects with the free surface of roll, as shown in Figs. 3 and 5. The interval from the surface to the section was divided equally into 7 parts with $0.0045 R$ in the x -direction, and sections dividing these parts were designated as Sections $x=0, 1, 2, \dots, 7$. In the y -direction, the sections having an interval $0.009 R$ were designated as Sections $y=28, 27, \dots, 0, \dots, -16$. The stress components were analysed first along section $x=1$, and those along each section parallel to the x -axis were found by means of the results obtained above. As an example of the results obtained, the stress distributions of Sections $y=10, 5, 0$ and -4 for $P=9$ kg are shown in Fig. 9 with the open circles. On the other hand, the stress components along the vertical sections crossing with the free surface may be obtained independently. The solid circles in the figure show the values of σ_y obtained in such a way. For comparison, the results for $P=0$ are also shown in the same figure with triangles, where the results shown with the open and solid circles were obtained in the same way as in the case of open and solid circles, respectively.

The stress components within the strip specimen may be obtained by the shear difference method from the isoclinic fringe pattern shown in Fig. 6 and the distribution of $\Delta\sigma$ shown in Fig. 8. As shown in Figs. 6 and 8, the X - Y coordinate system is entered in the strip, in which Sections $X=0, 1, 2, \dots, 8$ divide the half

Fig. 7 Relation between T and P

Fig. 8 Distributions of $\Delta\sigma$ (kg/mm²) in the strip specimen (19.6%)

width of the strip into 8 parts equally, and Sections $Y=0, 1, 2, \dots$ divide the strip in the Y -direction into the same distance as in the X -direction. The stress components were found first along Section $Y=12$, and those along Section $X=0$ were found by means of the above obtained results. Then, the stress components along sections parallel to the X -axis were found by using the values in Section $X=0$. Figure 10 shows, for example, the stress distributions in Sections $Y=14, 24, 39, 58$, and 82 for $P=9$ kg with the open circles. The solid circles in the figure show the values of σ_y obtained along the sections in the Y -direction by means of the values on $Y=12$, independently. For comparison, the results for $P=0$ are also shown in the same figure with triangles, where the results shown with

Fig. 9 Stress distributions within the roll specimen

Fig. 10 Stress distributions within the strip specimen

open and solid triangles were analysed in the same way as in the case of open and solid circles, respectively.

7. Stress distributions on the contact surface

The contact pressure σ_n and the frictional stress τ_n on the contact surface may be obtained from the values of σ_x , σ_y and τ_{xy} obtained above. Figures 11 and 12 show the stress distributions of σ_n and τ_n in the roll and strip specimens for each value of front tension P . In these figures, the solid line shows the results for $P=9$ kg, the dashed line for $P=6$ kg, the chain line for $P=3$ kg and the double dotted chain line for $P=0$. The symbol ϕ in these figures indicates the angle between the normal to the roll and x -axis, as shown on the roll side of Fig. 8.

8. Discussion and conclusions

In Figs. 9 and 10 showing the stress distributions within the roll and strip specimens, two kinds of values corresponding to the same stress components obtained along the different paths of numerical integration agree well with each other. This verifies the sufficient accuracy of the results obtained by the numerical procedure.

Comparing the circle with the triangle in Fig. 9 to discuss the effect of front tension P

for the roll specimen, the value of σ_x in each section fairly decreases with the increase of front tension P . The value of σ_y and the absolute value of τ_{xy} also decrease with the increase of P . Accordingly, it may be said that the stress distributions within roll are reduced considerably by the front tension P .

As for the strip specimen, the stress distributions in the cross sections before rolling (for example, section $Y=14$) are not affected by the front tension at all, as shown in Fig. 10. The value of σ_x and the absolute value of τ_{xy} in the cross sections passing through the contact surface are not so remarkably reduced as in the roll by the front tension, as shown in Fig. 9. Moreover, the effect of front tension on the distribution of σ_y becomes larger at the exit side than at the entry side. At a sufficient distance after leaving the contact surface, the sum of σ_y in any cross section of the strip must be equal to the front tension P . Since the mean value of σ_y becomes equal to zero after releasing the front tension

Table 2 Comparison of A and B with P

Front tension P kg	9	6	3	0
A kg	51.6	50.7	50.2	49.8
$B+P$ kg	48.6	47.9	47.5	46.9
$\frac{A-(B+P)}{A} \times 100\%$	5.8	5.5	5.4	5.8

Fig. 11 Stress distributions on the contact surface of the roll specimen

Fig. 12 Stress distributions on the contact surface of the strip specimen

P , it may be considered that the difference between the values of σ_y and their mean values represents the distribution of residual stress. On the other hand, in the case of $P=0$, the distribution of σ_y represents the distribution of the residual stress itself. Comparing both cases, it is concluded that the residual stress decreases with the increase of front tension P , as shown in Fig. 10(e).

As shown in Figs. 11 and 12, the values of the contact pressure σ_n in the roll and strip specimens remarkably decrease with the increase of front tension P . Such a trend appears stronger at the exit side than at the entry side, and stronger on the roll side than on the strip side. The variation of τ_n owing to the front tension is not so large as that of σ_n , and a slight decrease at the exit side and the movement of zero point toward the exit are recognized with the increase of front tension. From the above discussions, it becomes clear that the effect of front tension is useful for decreasing the values of σ_n and τ_n . Accordingly, it may be concluded that the method in which the strip is subjected to the front tension with the rolling torque is useful for improving the rolling process.

In the strip specimen, the sum of the components in the y -direction of σ_n and τ_n acting on the contact surface must be equal to the front tension P . Denoting the positive and negative values of the sum of the components as A and B , respectively, the results of the comparison of the values of A and B with P are shown in

Table 2.

As for the roll specimen, the value of the torque calculated from the difference of the areas shown in Fig. 11 for τ_n acting on the contact surface must be equal to the value of the torque given as the external load. In the experiment, these two values agree with each other within a few percent of errors for each value of front tension P .

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Discussion

A. SHINDO (Kobe University):

(1) In Figs. 11 and 12, I would like to ask whether both results ought to coincide with each other or not, and whether the difference between the value of τ_n is due to the effect of the lubricant being in the contact surface.

(2) What situation of the strip specimen do you think as the steady state?

Authors' closure

(1) In Figs. 11 and 12, though the corresponding values of σ_n must agree with each other, they do not always agree very precisely for within a few percent of errors in the analysis. As for τ_n , it may be supposed that the difference is due to the effect of the lubricant, as mentioned in

the previous paper⁽¹⁰⁾. This interpretation is more qualitative than quantitative in meaning.

(2) The situation may be found out from time dependent variation of the isochromatic fringe pattern. As shown in Fig. 2, the strip specimen has a leading part for guiding it correctly to the gap between the roll specimens. When the leading part passes through the roll specimens, the steady state is attained in reality. However, in the present paper, in order to analyse the stress state within the strip after leaving the roll as well as during rolling, we considered the steady state after leaving the leading part at a distance of 4 to 5 times of width of the strip specimen from the exit of roll.