Cross-Sectional Shapes of Corner Zones of Hexagonal Steel Pipes Formed by Extroll-Forming Mill with Expanding Inner Idler Rolls*

Takuo Nagamachi¹, Yoshitomi Onoda², Sadao Kimura³ and Takeo Kitawaki³

¹Department of Mechanical Engineering, Tokushima University, Tokushima 770-8506, Japan
²Department of Mechanical System Engineering, Yamanashi University, Yamanashi 400-8511, Japan
³Toyo Superior Steel Tube Works Ltd., Osaka 550-0005, Japan

Keywords: roll forming, tube forming, extroll-forming, round welded steel pipe, hexagonal pipe, non-driven grooved rolls

To improve the cross-sectional shapes (outer curvature, wall thickness change) of the corner zones of hexagonal steel pipes (168.0, 170.0 and 173.0 mm wide, STK400) formed by an extroll-forming mill, an expanding-type forming tool with six idler rolls is introduced into the groove of No. 1 grooved rolls to impose peripheral bending on the portions of the round pipes (outer diameter \(D_0 = 190.7\) mm, wall thickness \(t_r = 4.6\) mm) that correspond to the corner zones of the finished products. Characteristics of the cross-sectional shapes of the corner zones of the hexagonal pipes are investigated with respect to the nose radius of the inner roll and the degree of corner bending by the inner rolls, and compared with the results obtained by conventional extroll-forming. The results show that a hexagonal steel pipe with a small outer radius at each corner zone can be manufactured using a pair of inner idler rolls with a small nose radius.

(Received November 14, 2003; Accepted January 19, 2004)

1. Introduction

Extroll-forming is a method of forming square or deformed pipes from round pipes. In the extroll-forming, round pipes are placed into the grooves of tandem non-driven grooved rolls, and they in process receive external constraints from each set of grooved rolls. Their peripheral length is reduced, sides are bent back, and corner zones are bent. In the formation of a polygonal pipe having a blunt angle between adjacent sides, priority is given to reducing peripheral length rather than to corner zone forming, because the forming roll produces large peripheral compression strength. Therefore, forming a polygonal pipe having corners of a small radius of curvature is known to become more difficult as the number of sides increases.

The authors have proposed a forming process for re-forming a round pipes to a square steel pipe. In this process, an inner expanding-type forming mill having a set of four small-diameter rolls is introduced into the grooves of outer four grooved rolls to re-form a round pipe both from inside and outside. Introducing the inner rolls was verified to suppress the wall thickness at the corner zones of a re-formed square steel pipe (product) rather greatly and to reduce the internal and external radii of curvature at the same time.¹,²

Therefore, to make the corner zones of a polygonal steel pipe sharper, in this study the inner roll method was applied to the re-forming of a hexagonal steel pipe, and a forming experiment was performed with an experimental machine. In addition, some conditions of forming were simulated by rigid-plastic FEM in order to survey pipe strains.

This study reports the results of investigating how extroll-forming with inner rolls would affect the cross-sectional shapes at the corner zones of a hexagonal steel pipe, and compares the results with those of ordinary extroll-forming.

2. Experiment and Calculation Method

Figures 1(a) and (b) illustrate the extroll-forming process with inner rolls and the ordinary extroll-forming process respectively. The extroll-forming mill employed in this study is of the four-rolls type with upper and lower rolls and two side rolls. The upper and lower rolls have V-shaped grooves.

The extroll-forming with inner rolls shown in Fig. 1(a) is called Case 1, and ordinary extroll-forming shown in Fig. 1(b) is called Case 2. In both cases, the forming processes performed with No. 1 to No. 3 forming rolls are referred so as No. 1 to No. 3 forming processes.

Figure 2 shows the expanding-type forming tool having a set of six inner rolls used for No. 1 forming process in Case 1, and Fig. 3 shows the geometrical arrangement of the forming tool and No. 1 non-driven grooved roll. In this study, the inner rolls are set into the groove of No. 1 non-driven grooved roll by aligning the central position (lengthwise (z) direction) of the inner rolls with that of No. 1 non-driven grooved roll.

Table 1 lists the cross-sectional dimensions and main mechanical properties of the round pipe used in both Cases 1 and 2.

Figure 4 shows the conditions of forming for No. 1 forming process in Case 1. The nose radii \(R_n\) of the inner roll were set to 5.0 and 7.5 mm, and the strokes \(S_p\) from the internal position of the round pipe were set to 2.0 and 3.0 mm (expansion rates \(\xi\) 2.2 and 3.3%).

Figure 5 and Table 2 give the main notations and dimensions of the No. 1 to No. 3 non-driven grooved rolls used in both Cases 1 and 2.

Table 3 gives the cross-sectional dimensions \((A)\) of the hexagonal steel pipe (product), the set distances \((H_T\) and \(H_S\)) of the groove of No. 1 to No. 3 forming rolls from the center of figure, and the schedule of reduction \(r_i\) of the outer diameter of the round pipe. Using the forming conditions \(r_1 = 12.7\%\) \((A = 168.0\) mm), rigid-plastic FEM simulation of the forming processes is executed along with the forming.

---

*This Paper was Originally Published in Japanese in the Journal of ISTRP, 43 (2002) 1157–1161
experiments of Case 1 and Case 2. The calculation procedure and the boundary condition setting method for the simulation are the same as those used for FEM simulation of the wall-thickening behavior in the extroll-forming of a square steel pipe.3)

3. Results and Discussion

3.1 Cross-sectional Shape of Pipe Formed by No. 1 Forming Rolls

The cross-sectional shape of pipe formed by No. 1 forming rolls (grooved rolls and inner rolls) in Case 1 is compared with that of pipe formed by ordinary forming in Case 2.

Figure 6 shows notations representing the cross-sectional shapes of pipes formed by each set of forming rolls. The corner zone at 30 degrees up on the x-axis (flange positions of the upper, lower, and side rolls) is called Corner 1, and that on the y-axis (throat position of the upper and lower rolls) is called Corner 2. Points U, V, and W represent contacts (shoulders) with the grooved rolls adjacent to Corner 1 and Corner 2.

Table 1 Cross-sectional dimensions and mechanical properties of tested circular pipe.

<table>
<thead>
<tr>
<th>Material of circular pipe</th>
<th>Initial wall thickness $t_0$/mm</th>
<th>Initial external diameter $D_0$/mm</th>
<th>Yield stress $\sigma_y$/MPa</th>
<th>Strain hardening exponent $n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>STK400</td>
<td>4.6</td>
<td>190.7</td>
<td>422</td>
<td>0.163</td>
</tr>
</tbody>
</table>

thickening behavior in the extroll-forming of a square steel pipe.3)

3. Results and Discussion

3.1 Cross-sectional Shape of Pipe Formed by No. 1 Forming Rolls

The cross-sectional shape of pipe formed by No. 1 forming rolls (grooved rolls and inner rolls) in Case 1 is compared with that of pipe formed by ordinary forming in Case 2.

Figure 6 shows notations representing the cross-sectional shapes of pipes formed by each set of forming rolls. The corner zone at 30 degrees up on the x-axis (flange positions of the upper, lower, and side rolls) is called Corner 1, and that on the y-axis (throat position of the upper and lower rolls) is called Corner 2. Points U, V, and W represent contacts (shoulders) with the grooved rolls adjacent to Corner 1 and Corner 2.

Figure 7 shows the measured cross-sectional profile of pipe formed by No. 1 forming rolls in Case 1 where Roll 1 ($R_p = 5.0$ mm) is used as the inner roll and that in Case 2. For both Corner 1 and Corner 2, the internal and external faces at the center of a corner zone project further in the direction of expansion, and the shoulder positions (Points U, V, and W) are closer to the center of the corner zone as the expansion rate $\xi$ becomes greater. A similar tendency is observed when
the inner roll is Roll-2 ($R_p = 7.5$ mm). For effective expansion by the inner rolls in Case 1, the corner zone should be given greater expansion than the projection of the internal face at the center of a corner zone in Case 2, with no inner rolls. In this study, therefore, $C_24_{m1}$ and $C_24_{m2}$ determined from $l_1$ and $l_2$ are defined as the required minimum expansion rates, and $C_22_{m}$ as shown in Fig. 8 is defined as the effective expansion rate. Under experimental conditions employed in this study, the required minimum expansion rates were $C_24_{m1} = 1.5\%$ and $C_24_{m2} = 1.4\%$.

Figure 9 and Fig. 10 show the influences of effective expansion rate ($C_22_{m}$) by the inner roll on the relative radius of outer curvature ($C_26_{OC1} = t_0$, $C_26_{OC2} = t_0$) and on the increasing rate of wall thickness ($C_22_{TC1}$, $C_22_{TC2}$) at the center of each corner zone (Corner 1, Corner 2) of pipe formed by No. 1 forming rolls, where $t_0$ is the wall thickness of round pipe. The conditions of forming in the case that the horizontal axis is $C_22_{m}$ are those in Case 2.

The effective expansion rate by inner rolls has the following relationship with the relative radius of outer curvature and the increasing rate of wall thickness of pipe formed by No. 1 forming rolls. The values of $C_26_{OC1}$ and $C_26_{OC2}$ change from...
Cross-sectional shapes of corner zones of hexagonal steel pipes formed by Extroll-forming mill with expanding inner idler rolls

Fig. 6 Notations representing cross-sectional shapes of corners of pipe formed by No. 1 forming rolls.

Fig. 7 Effect of expansion rate (ξ) on cross-sectional profiles of pipe formed by No. 1 forming rolls (Inner roll: Roll-1). Symbol (O, △, □) shows contact point (U, V, W) adjacent to corner.

Fig. 8 Definitions of required minimum expansion rate (ξm1, ξm2) and effective expansion rate (ξ).

Fig. 9 Effect of effective expansion rate (ξ) on relative radius of outer curvature (ρOC1/t0, ρOC2/t0) of pipe formed by No. 1 forming rolls.

Fig. 10 Effect of effective expanding rate (ξ) on increasing rate of wall thickness (TC1, TC2) of pipe formed by No. 1 forming rolls.
positive to negative values, indicating a decrease in wall thickness. These tendencies are explained with the peripheral strain at the center of a corner zone calculated by rigid-plastic FEM illustrated in Fig. 11. As shown in Fig. 11(a), the internal and external peripheral strains ($\varepsilon_X$) become high with an increase of $\xi$, especially, the external elongation strain ($\varepsilon_X$) becomes rather high. This causes the peripheral membrane strain ($\varepsilon_{MX}$) to change from compression strain to elongation strain, as shown in Fig. 11(b). In other words, increases in these peripheral strains reduce the wall thickness at the center of a corner zone. However, the peripheral bending strain ($\varepsilon_{bX}$) becomes high with an increase in $\xi$. This corresponds to the tendency where the radius of curvature decreases at the center of a corner zone.

The influences of the nose radius $R_p$ of the inner roll in Case 1 are as follows. The values of $\rho_{DC1}/l_0$, $\rho_{DC2}/l_0$, $T_{C1}$, and $T_{C2}$ with Roll 1 of $R_p = 5.0$ mm are small as compared with those values with Roll 1 of $R_p = 7.5$ mm.

When Corner 1 and Corner 2 are compared, in both Case 1 and Case 2 $\rho_{DC1}/l_0 < \rho_{DC2}/l_0$ and $T_{C1} > T_{C2}$ under any condition of forming.

### 3.2 Cross-sectional shape of products

The cross-sectional shape of a product formed by inner roll in Case 1 is compared with that formed by ordinary forming in Case 2.

Figure 12 shows the measured cross-sectional profile of products in the cases. The internal and external faces at each corner zone (Corner 1 and Corner 2) of a product in Case 1 effectively show the more effective expansion by the inner roll in the No. 1 forming process and project further than those of a product in Case 2. As the expansion rate ($\xi$) by the inner roll increases, the projections grow and the shoulder positions (Points U, V, and W) are close to the center of each corner zone. Products of $r_3 = 9.71\%$ and $11.5\%$ with Roll 2 serving as the inner roll show a similar tendency.

Figure 13 and Fig. 14 show the influences of effective expansion rate ($\xi$) on the relative radius of outer curvature ($\rho_{OC1}/l_0$, $\rho_{OC2}/l_0$) and the increasing rate of wall thickness ($T_{C1}$, $T_{C2}$), in relation to the wall thickness $l_0$ of round pipe at the center of each corner zone (Corner-1, Corner-2). The conditions of forming when the horizontal axis is $\xi = 0$ are those employed in Case 2.

The effective expansion rate by the inner roll has the following relationship with the relative radius of outer curvature and the increase rate of wall thickness of pipe formed by No. 1 forming rolls. As shown in Fig. 13, the influences of bending by the inner roll in the No. 1 forming process mentioned in Fig. 9 are observed in the $\rho_{DC1}/l_0$ and $\rho_{DC2}/l_0$ values of a product at given reduction $r_3$, being diminished with an increase of $\xi$. These values become smaller as the reduction $r_3$ becomes larger. When $r_3 = 12.7\%$ and $\xi = 1.7$ to 1.8%, the values are 1.32 to 1.56, indicating a rather sharp corner zone. A similar tendency was obtained in relation to the internal radius of curvature at the center of each corner zone of a product. When $r_3 = 9.71\%$ as shown in Fig. 14(a), $T_{C1}$ and $T_{C2}$ become small with an increase of $\xi$, because of the wall thickness reducing effect of the inner roll mentioned in connection with Fig. 10. When $r_3 \geq 11.5\%$ as shown in Figs. 14(b) and (c), $T_{C1}$ and $T_{C2}$ become large with an increase of $\xi$, showing the opposite tendency. The reason can be explained with the peripheral strain at the center of each corner zone of a product calculated by rigid-plastic FEM shown in Fig. 15. When $r_3$ is large, the corner zone size (size between shoulders) and the radius of external curvature at the center of each corner zone become rather small with an increase of $\xi$ (see Fig. 12 and Fig. 13). Accordingly, the internal peripheral strain $\varepsilon_X$ (compression strain) at the overlap between the peripheral compression strain by bending and the compression strain by reduction changes
rather high as compared with the external strain $\varepsilon_X$ (elongation strain). As shown in Fig. 15(b), the absolute value of peripheral membrane strain $\varepsilon_{nx}$ (compression strain) becomes high with an increase in $\xi$. In other words, the increase in wall thickness at the center of each corner zone is mainly attributable to an increase in the absolute value of peripheral compression strain.

The influences of the nose radius $R_p$ of inner roll in Case 1 are such that for a given $\xi \rho_{\text{OC1}}/t_0$, $\rho_{\text{OC2}}/t_0$, $T_{C1}$, and $T_{C2}$ are smaller when the inner roll is Roll 1 of a small nose radius than when the inner roll is Roll 2 of a great nose radius.

When Corner 1 and Corner 2 are compared, in both Case 1 and Case 2 $\rho_{\text{OC1}}/t_0 < \rho_{\text{OC2}}/t_0$ and $T_{C1} > T_{C2}$ under any condition of forming.

4. Conclusions

(1) A regular hexagonal steel pipe (product) reformed from a round pipe by extroll-forming with inner rolls has corners zones of a rather smaller radius of external curvature than found in a product re-formed by ordinary extroll-forming. Within the range of this study, the radius of external curvature at the center of a corner decreases as effective expansion rate increases, as the nose radius of inner roll becomes small, and as the product reduction becomes large.

(2) The increase rate of wall thickness at each corner zone of
a product decreases with an increase in effective expansion rate by the inner roll when the product reduction is small but increases when the product reduction is large. The increase rate of wall thickness at each corner zone of a product decreases with a decrease of the nose radius of the inner roll. (3) Under any condition of forming, the radius of external curvature at the center of a corner is smaller for a corner zone at the throat of a V-shaped upper or lower roll than for a corner zone at the flange, but the increase rate of wall thickness is greater.

**REFERENCES**