Study on the forward slip of cup with variable wall thickness during roll forming

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Abstract. Based on the principle of plastic forming, the metal flow of cup with variable wall thickness during roll forming is analyzed, and the formula of its coefficient of forward slip is derived. By comparing with the numerical simulation results, the correction formula of the coefficient of forward slip at the rim of roller is obtained. The correction formula is verified by experiment. The results show that the error between the theoretical and experimental value is 4.5%, and the agreement between them is good. This research provides a basis for the design of the roller groove for the roll forming of cup with variable wall thickness.

1. Introduction

Metal cup with variable wall thickness not only have extensive applications, but also need large scale production. Of parts such as drill pipe joints and projectile bodies, whose final shape or the shape in a certain step during the forming process needs to be a variable wall thickness. Cup with variable wall thickness usually is traditionally manufactured using the production process of plastic forming and then machining [1-6]. However, the material utilization rate is relatively low using this traditional production process.

In order to increase the material utilization rate of cup with variable wall thickness and meet the requirements of its production efficiency, a roll forming method is proposed and the schematic of roll forming is shown in Figure 1 [7-10]. At the time of roll forming, the punch is installed under the movable ram of the hydraulic press. The billet, which is pushed by the downwardly moving punch, makes the pre-forming rollers to rotate and the variable wall thickness of the cup is formed by the specific groove shape on the surface of the rollers. In order to avoid the formation of a thin flash, a triangular flash groove is designed between the adjacent pre-forming rollers (as shown in Figure 2). As a result, the metal that flows into the gap between the rollers will form a triangular flash, which can be eliminated by the shaping rollers installed below the pre-forming rollers. The shaping rollers rotate at an offset angle with respect to the forming rollers.

During the roll pre-forming process, due to the large deformation of metal, the speed of the metal flowing out of the roller is greater than the speed of the roller, which causes the arc length of the roller groove to be inconsistent with the axial dimension of the part after roll forming. During the roll shaping process, only a small amount of metal formed by the flash groove of pre-forming roller deforms, so the speed of the metal flowing out of the roller is nearly same as the speed of the roller, which causes the arc length of the roller groove to be nearly same with the axial dimension of the part.
after roll forming [9]. Therefore, precise design of the arc length for pre-forming roller is the key to ensure the axial dimension of the roll pre-formed parts. In this paper, the coefficient of forward slip ($S$), which is used for the design of the arc length of the pre-forming roller groove, is studied.

Figure 1. Schematic of roll forming   Figure 2. Schematic of flash groove on pre-forming rollers

2. Derivation of the coefficient of forward slip

2.1. Theory of forward slip

During roll forming, the metal flow direction in the deformed area is shown in Figure 3. In the horizontal direction, there is a divided plane $NN$, whose speed is equal to the axial speed of the linear velocity of the roller. Just like roll forging, this plane is called the neutral plane. The angle between the neutral plane and the centerline of the roller is called the neutral angle ($\phi_N$). The angle $\alpha$ is called bite angle. The area in front of the neutral plane is called the forward slip zone, in which the metal flow velocity is greater than the axial partial velocity of the roller linear velocity, that is, the metal flows forward relative to the roller and called forward slip. The forward slip causes the length of the part roll formed to be greater than the corresponding arc length of the roller. The coefficient of forward slip can be expressed by

$$S = \frac{L - L_n}{L_n} \times 100\% = \frac{V_1 - V_n}{V_n} \times 100\%$$  

where $L$ is the axial dimension of the part after roll forming, $L_n$ is the corresponding arc length of roller groove, $V_1$ is the speed of part at the outlet end, $V_n$ is the linear speed of roller at groove surface.

2.2. Calculation of coefficient of forward slip

According to the principle incompressibility, the volume of the metal passing through the cross section per unit time meets eq. (2)

$$A_n V_n \cos \phi_n = A_1 V_1$$  

where $A_n$ is the cross-sectional area of the cup at the neutral plane $NN$, $A_1$ is the cross-sectional area of the cup at the outlet end. They can be expressed as

$$A_n = \pi (r_0 + t_N)^2 - \pi r_0^2$$  

$$A_1 = \pi (r_0 + t_1)^2 - \pi r_0^2$$

where $r_0$ is the radius of punch, $t_N$ is the wall thickness of cup at the neutral plane, $t_1$ is the wall thickness of cup at the outlet end, $t_0$ the wall thickness of cup before roll forming.

The value of draught between the neutral plane and outlet end can be expressed by

$$\Delta t_N = R(1 - \cos \phi_n)$$
where $R$ is the radius of roller. It can be seen from Figure 3, the wall thickness of cup at the neutral plane can be expressed by

$$t_y = t_i + R(1 - \cos \phi_N)$$  \hspace{1cm} (6)

Eqs. (3), (4) and (6) are inserted into eq. (2), and the following eq. (7) can be obtained.

$$\frac{V_i}{V_N} = \frac{[2t_i + t_i + R(1 - \cos \phi_N)]/[4t_i + R(1 - \cos \phi_N)] \cos \phi_N}{(2r_i + t_i) \mu_i}$$  \hspace{1cm} (7)

If eq. (7) is inserted into eq. (1), the coefficient of forward slip can be expressed by

$$S = \frac{[2t_i + t_i + R(1 - \cos \phi_N)]/[4t_i + R(1 - \cos \phi_N)] \cos \phi_N}{(2r_i + t_i) \mu_i} - 1$$  \hspace{1cm} (8)

When the neutral angle $\phi_N$ is small, the following formula can be obtained.

$$1 - \cos \phi_N \approx \frac{\phi_N^2}{2}$$  \hspace{1cm} (9)

If eq. (9) is inserted into eq. (8), the coefficient of forward slip can be expressed by

$$S = \frac{(2t_i + t_i) \mu_i + (t_i + t_i) R \phi_N^2}{(2r_i + t_i) \mu_i} - 1$$  \hspace{1cm} (10)

2.3. Calculation of neutral angle

According to the balance between the force of the roller on the billet, the friction force (friction coefficient $\mu_1$) between the punch and the billet, and the friction force (friction coefficient $\mu_2$) between the roller and the billet, as shown in Figure 4, it can be obtained

$$\int_0^\alpha F\sin R = \int_0^\alpha F\mu_1 \cos R + \int_0^\alpha F\mu_2 \cos R - \int_\phi_0^\phi N F \mu_1 \cos R \cos R = 0$$  \hspace{1cm} (11)

After integration, eq. (11) can be expressed as

$$1 - \cos \phi_N + \mu_1 \sin \phi_N^\alpha + \mu_2 \sin \phi_N^\alpha - \mu_1 \sin \phi_\phi^\alpha - \mu_2 \sin \phi_\phi^\alpha = 0$$  \hspace{1cm} (12)

After calculation, eq. (12) can be expressed as

$$\sin \phi_N = \frac{1}{2} \sin \alpha - \frac{1 - \cos \alpha}{2(\mu_1 + \mu_2)}$$  \hspace{1cm} (13)

Since $\phi_N$ and $\alpha$ is small, the above formula can be simplified as

$$\phi_N = \frac{\alpha}{2} \left[ 1 - \frac{\alpha}{2(\mu_1 + \mu_2)} \right]$$  \hspace{1cm} (14)
2.4. Correction of the coefficient of forward slip
During roll forming, the radius, bite angle, and groove arc length of the middle and rim of the roller are different, so the coefficient of forward slip also is different. By comparing the theoretical coefficient of forward slip with that of numerical simulation results obtained by different process parameters, a correction formula of the coefficient of forward slip at the rim of roller can be expressed by

\[
S' = 2 \left\{ \frac{(2r_0 + t_f)\eta_0 + (r_0 + t_i)R\phi_0^t}{(2r_0 + t_i)\eta_0} - 1 \right\}
\]

(15)

3. Experimental verification

3.1. Experimental conditions
The diagrams of experimental billet and the cup with variable wall thickness to be formed by roll forming are shown in Figure 5, the material is 1060 pure aluminum. 3-D model of the roller for roll forming is shown in Figure 6. At the rim of the roller, the radius \( R \) is 156 mm, the arc length \( L_m \) is 65.35 mm and the bite angle is 0.227. Roll forming is performed on a hydraulic press (as shown in Figure 7). As this paper only studies the coefficient of forward slip during roll pre-forming, only the roll pre-forming equipment is installed on the hydraulic press, and the shaping equipment is not installed.

![Figure 5. Diagram of cup](image)

![Figure 6. 3-D model of roller](image)

![Figure 7. Equipment of roll pre-forming](image)

3.2. Experimental results
The billet for roll forming and the part roll formed are shown in Figure 8. The part roll formed was measured and the size \( L \) is 71.1mm. According to eq. (1), the experimental coefficient of forward slip can be calculated to be 8.8%, and the theoretical value obtained according to eq. (10) is 9.2%. The
The error between the theoretical and experimental value is 4.5%. It can be seen that the obtained formula for coefficient of forward slip is accurate.

![Figure 8. Billet and the part roll formed](image)

4. Conclusion
The formula of coefficient of forward slip for roll forming of cup with variable wall thickness is obtained. The error between the theoretical and experimental value is 4.5%, and the agreement between them is good. This research provides a basis for the design of the roller groove for the roll forming of cup with variable wall thickness.

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