Effect of the arc profile roll gap on forming results in flexible rolling process

Yi-xue Yang¹, Tian-peng Wang¹, Yi Li*¹
¹College of Mechanical Engineering, Jilin Engineering Normal University, Changchun, Jilin, 130052, China
*lyi15@mails.jlu.edu.cn, *Corresponding author’s e-mail: liyi6929@163.com

Abstract—Flexible rolling is a new-style process, it is suitable to produce the small batch and various size forming parts. In this paper, a new design scheme of roll gap was applied to form spherical surface. Two arc with different curvature radius are used as the upper and lower profile of the roll gap. Theoretically, the smooth and continuous arc can’t cause instability and wrinkling in the local area of sheet metal. Based on the process of flexible rolling, the finite element model was established, and the boundary conditions were determined. The forming process of spherical surface formed by arc profile roll gap was simulated. The results show that: By simulating forming process, the forming part is smooth without forming defects, the forming quality is better, it verifies the feasibility of the application.

1. Introduction
Metal curved parts are widely used in many fields such as automobile, airplane, ship and construction. In order to meet the diversity, low-cost and high-efficiency manufacturing of product demands in the manufacturing market, Li combined the cold rolling process with multi-point concepts and proposed the flexible rolling process [1]. The main forming tool of the equipment is a pair of flexible rolls, the roll profile can be changed by adjusting the control unit. Gong simplified the finite element model and studied the influence of roll stiffness on forming results [2]. Cai derived the bending theoretical formula of roll gap distribution [3-5]. On this basis, Wang conducted an in-depth analysis of the forming precision by numerical simulation [6]. In this paper, the effect of the arc profile roll gap on forming results in flexible rolling is studied by numerical simulation.

2. Methods
Figure 1 is the schematic diagram of equipment developed by Jilin University. Flexible roll has the characteristics of small deflection, high stiffness and small diameter, it can bend and reduce the sheet metal, and its profile distribution in the natural status is a line. After the roll gap distribution is configured, the upper roll presses down vertically based on the thickness reduction of the sheet metal, and the lower roll doesn’t move at this time. When the upper roll reaches the specified position, it catches the sheet metal with the lower roll and rotate around their respective central axes. In the feeding process, the sheet metal is bent by a pair of rolls with different curvature radius, transverse deformation is caused; Due to the uneven thinning along the roll gap, the transverse elongation distribution of sheet metal is also non-uniform and caused the additional stress, so the longitudinal bending deformation is obtained. When forming a spherical surface, the curvature radius of the upper flexible roll should be less than the one of the lower flexible roll, and the roll gap height gradually increases from the center to the left and right sides.
Figure 1. flexible rolling process schematic diagram.

Figure 2 shows a simplified model of flexible rolling process. Based on the characteristics of the uneven distribution of the arc profile roll gap and flexible rolls rotate around their own central axis, a discrete numerical modeling scheme is selected. In the modeling scheme, each flexible roll is divided into a series of short rolls to realize the characteristic of each short rotates around its own central axis, and the short rolls are arranged in the target curvature radius of the flexible roll profile, the whole process is simplified into a sheet metal and two flexible rolls composed by short rolls.

In this process, a pair of rolls contact the two surfaces of a sheet metal. The roll is a rigid body, and the sheet metal is a flexible body. Therefore, the surface of the roll with high stiffness is defined as the driving surface. The corresponding sheet metal surface is set as the driven surface. R3D4 quadrilateral shell element was used as the short roll mesh. Because the thickness of sheet metal needs to be analyzed, the C3D8R element of hexahedron with eight nodes is selected for the mesh, and the forming result with high precision can be obtained.

In order to get the similar result with the forming experiment, boundary conditions should be set for the finite element model. In the forming process, sheet metal only has displacement in the X and Z directions and rotation in the Y axis, so it is necessary to limit the displacement in the Y direction and rotation in the X and Z axes. The short roll only has displacement in the Z direction and rotation in the Y axis, so its displacement in the X and Y directions and rotation in the X and Z axes need to be limited.

By the comparative analysis of the results in experiment and numerical simulation (in Figure 3), it can be seen that the surface qualities of the forming parts are better, without defects, and the forming characteristics in the experiment and numerical simulation are almost same, so the numerical simulation has the feasibility of guiding the experiment.

Figure 2. The simplified model of flexible rolling process.

(a) In experiment (b) In numerical simulation

Figure 3. The forming parts in the experiment and numerical simulation.
3. Result

The reasonable distribution of roll gap profile is the basis to ensure the quality of forming parts. If the design is not proper, it can cause local regional instability and wrinkling. As shown in Figure 4a, the wrinkling position of spherical surface is mostly located in the middle. In this paper, a new method of roll gap design is used to form curvature surface. Two arc with different curvature radius are used as the upper and lower profile of the roll gap, theoretically, the smooth and continuous arc can’t cause instability and wrinkling in the local area. And the arc as the roll gap profile makes the roll profile adjustment process more rapid and simple. As shown in Figure 4c, based on the thickness distribution characteristics of spherical surface, the curvature radius of the upper roll contour ($R_T$) should be smaller than the one of the lower roll ($R_L$). At this time, the center of the roll gap height ($T$) is the lowest, while the two sides of the roll gap height ($T'$) is the highest. The forming part formed by the arc profile roll gap is shown in Figure 4b. It can be seen that the surface of the forming part is smooth without forming defects.

![Figure 4](image-url)  
(a) Forming part by improper roll gap  
(b) Forming part by arc profile roll gap  
(c) Arc profile roll gap  

Figure 4. The forming parts formed by different style roll gap.

The profile of the spherical surface formed by arc profile roll gap is shown in Figure 5. In the transversal and longitudinal, the profile curve is smooth and continuous, it indicates a better forming quality. Because of the transverse profile curve is in the same direction with the longitudinal profile curve, the forming part conforms to the feature of spherical surface.

![Figure 5](image-url)  
(a) Along the transversal  
(b) Along the longitude  

Figure 5. The profile distributions of spherical surface formed by arc profile roll gap

Figure 6 shows the plastic strain distribution of the spherical surface formed by arc profile roll gap. As shown in the figure, in the transverse direction (Y direction), as the roll gap distribution characteristics of the spherical surface, the plastic strain is the largest in the center of the forming part and the smallest on the both sides. In the longitudinal direction (X direction), when it closes to the front and back ends of the sheet metal, the plastic strain changes monotonously. When it is far from the ends,
the plastic strain gradually presents a continuous and stable trend. Therefore, the spherical surface can be divided into three regions in the longitudinal direction by plastic deformation, which are named as the front transition area (FTA), the stable forming area (SFA) and the back transition area (BTA). The plastic deformation in the transition area changes continuously and monotonously, because the additional stress caused by the longitudinal elongation is not enough to bend the sheet metal to the target shape in the area near the ends of the sheet metal. When it is far away from the ends, as the change of boundary constraints, there is enough additional stress to bend the sheet metal to the target surface, so the plastic deformation in the stable forming area is continuous and stable. The stable forming area is also the effective forming area, which is the effective part in the engineering application. Figure 7 shows the equivalent stress distribution of the spherical surface formed by arc profile roll gap. The equivalent stress distribution is not uniform in the transversal, and the general trend is that: the equivalent stress at the center of the sheet metal is largest and decreases gradually from the center to the both sides. It can be seen that the plastic strain and stress distribution characteristics are in accordance with the features of spherical surface.

Figure 7. The equivalent stress distribution of the spherical surface formed by arc profile roll gap.

The transverse thickness distribution of spherical surface is shown in Figure 8a. The maximum thickness is on the both sides and the minimum is at the center. The longitudinal thickness distribution is shown in Figure 8b. In the front transition area and back transition forming area, the thickness
presents a continuous monotonically changing trend, while in the stable forming area (SFA), the thickness distribution is basically stable and continuous.

Figure 8. The thickness distribution of spherical surface formed by arc profile roll gap.

Figure 9 shows the distribution of local bending deformation of spherical surface. Since the Gaussian curvature radius determines the local shape of the points in the surface, the change of surface shape can be reflected by comparing the Gaussian curvature radius of adjacent points. In the transverse direction, the bending deformation is basically in a stable distribution; in the longitudinal transition region, the bending deformation shows a monotonous gradual trend, while in the stable forming region, the bending deformation is stable and continuous. It can be seen that the bending deformation characteristics are different in different forming areas.

Figure 9. The local bending deformation distribution of spherical surface formed by arc profile roll gap.

4. Conclusions
In this work, the effect of the arc profile roll gap on forming results in flexible rolling process was studied by numerical simulation.

(1) The flexible rolling discretization modeling method is used to simplify the surface forming process and the boundary conditions are determined.

(2) A new design scheme of roll gap is applied to form spherical surface. Two arc with different curvature radius are used as the upper and lower profile of the roll gap, theoretically, the smooth and continuous arc can’t cause instability and wrinkling in the local area. By simulating the forming process, the forming part is high-quality without forming defects.

(3) Numerical simulation is carried out for the forming process of spherical surface. The forming results show that the forming part formed by arc profile roll gap has obvious bending deformation and continuous smooth surface. The transverse deformation is related to the roll gap. In the longitude, as the deformation characteristics, the forming part is divided into the front transition region, the stable forming region and the back transition region. In the transition region, the thickness distribution and local bending deformation are monotonic and gradual. In the stable forming region, the thickness and local bending deformation show a continuous and stable trend. So the feasibility of arc profile roll gap is verified.
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