Springback Analysis in Flexible-bending Process of Tubes

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Abstract. Flexible-bending, as a new bending technology, is widely used in the processing of profiles and tubes, especially in the production of small batches and multi-curvature. In flexible-bending process of tubes, the stress is complex and the springback problem exists which affects the forming accuracy and quality of bent tubes. In this paper, the springback is studied and solved by springback compensation by means of finite element numerical simulation and experimental verification. The results show that the wall thickness of tubes and the bending radii have important influence on springback. Springback compensation can effectively solve the problem of forming error caused by springback because that the forming radii after compensation can approach the target radius gradually. The experiments were carried out with flexible-bending equipment. The simulation results were in agreement with the experiments, which proved the reliability of the simulation.

1. Introduction

Because of the advantages of light weight and high strength, the demand and research of bent tubes are increasing. Traditional methods of bending tubes, such as rotary-draw-bending, bend tubes according to the shape of the die, which greatly affects the processing efficiency and production cost. Compared with traditional bending forming, flexible-bending has the advantage of processing different forming radii without changing the die. Murata [1-2] first proposed the flexible-bending method called MOS and designed the MOS equipment of bending tubes. Li Pengfei et al. [3-4] studied the flexible-bending of tubes and profiles of continuous varying curvature. Zhou Yongping [5-6] analyzed the elimination of forming defects of profiles and the residual stress of bent tubes in flexible-bending process. The process of flexible-bending of tubes involves material nonlinearity, geometric nonlinearity and boundary-condition nonlinearity. The stress state and deformation situation are complex, which often cause forming defects such as springback. In this paper, the springback defect is studied by numerical simulation and experimental verification and the corresponding solutions are put forward.
2. The principle of flexible-bending
Figure 1 shows the principle of flexible-bending. The forming device mainly consists of a pusher, a guiding device, a bend die and a bearing. Among them, the guiding device is fixed on the workbench, the pusher feeds the tube along the workbench direction (Z direction), the bearing can move on the plane (XY plane) vertical to the workbench to drive the offset of the die, the bend die is embedded in the bearing which can move along with the bearing and rotate at a certain angle under the action of the tube and bearing. Before the bending, adjust their centers so that they are on the same horizontal line and then the tube is penetrated into the guide and die. In the bending process, move the bearing to make the die shift some distance and rotate at a certain angle, and then feed the tube constantly to complete the continuous forming. The forming radius of the tube is determined by the die offset and different bending radii can be realized with different offset, so we can achieve the flexible-bending.

![Figure 1. Schematic diagram of flexible-bending.](image)

In the process of flexible-bending of tubes, the horizontal distance between the right side of the guiding device and the geometric center of the bending die is \( L \), the offset of the bending die along the Y direction is \( H \). The theoretical bending radius is \( r \) and the theoretical bending angle is \( a \).

According to the geometric relationship in the diagram, the \( r \) and \( a \) can be obtained

\[
r = \frac{L^2 + H^2}{2H}
\]

\[
a = \arctan \frac{H}{L}
\]

From the formulas and related geometric relationships, It can be seen that when \( H \) increases keeping \( L \) unchanged or \( L \) decreases keeping \( H \) unchanged, the theoretical bending angle \( a \) increases, which means that the corresponding theoretical forming radius \( r \) decreases.

3. Finite element model
In this paper, ABAQUS/explicit is used to simulate the process of flexible-bending. Figure 2 shows the finite element model. In order to facilitate calculation, the bearing, the bend die, the guide and the pusher are set as rigid bodies divided into R3D4 rigid body elements; the tube is set as a deformable body with the diameter of 12 mm and the thickness of 1 mm and is divided into C3D8R solid elements in the simulation. The material of the tube is 304 stainless steel and the related material parameters are as follows: density is 7930 Kg/m\(^3\), elastic modulus is 204 Gpa, yield strength is 205 Mpa and Poisson's ratio is 0.25. Considering friction, the friction coefficient at contact surfaces is 0.2.
4. Analysis of numerical simulation results

4.1 Analysis of springback

In order to explore the influence of wall thickness and bending radii on springback, we simulated the bending effect of different wall thickness and different bending radii. For facilitating the analysis, we use the radii difference ($\Delta r$) of before and after springback to express the springback amount.

Figure 3 shows the changing tendency of $\Delta r$ along with the wall thickness when the diameter $D = 12$ mm and theoretical bending radius $r = 81.25$ mm. It can be seen that $\Delta r$ decreases rapidly and then tends to be stable with the increase of wall thickness. This is because the tube body volume increases and the proportion of plastic deformation increases, which weakens the springback. As shown in Figure 4, the springback under different bending radii is obtained when the outer diameter $D = 12$ mm and the wall thickness $t = 1$ mm. The radii difference $\Delta r$ increases with the increase of bending radii and they show a linear relationship. This is because that the effect of elastic deformation increases with the increase of bending radii, which makes the springback phenomenon obvious.

4.2 Springback compensation
In this paper, springback compensation is used to solve the forming error caused by springback. Springback compensation is giving bending compensation in the opposite direction of springback so that the forming radius after unloading is close to the target curvature radius.

Figure 5. Schematic diagram of springback compensation.

Figure 5 is a diagram of springback compensation in flexible-bending process. O and H represent the center of the bending die and the offset of the die respectively when forming the target radius according to the theoretical formula; O'and H1 are the corresponding position and the offset of the die respectively when springback compensation is applied. In this paper, we set the theoretical bending radius (r=81.25 mm) of L= 20 mm and H=2.5 mm as the target curvature radius. According to formulas, the bending compensation is carried out by increasing the offset of the die while keeping L=20 mm. Considering Δr when r=81.25 mm, take the increase of die offset (ΔH ) as 0.6, 0.7, 0.8, 0.9, 1 and 1.1 mm and the corresponding die offset (H) is 3.1, 3.2, 3.3, 3.4, 3.5 and 3.6 mm.

The numerical simulations were calculated and the bent tubes after springback compensation were obtained. The nodes were extracted from the outer surface of the inside of bent tubes, and the radii of the neutral layer of the bent tubes were measured and calculated. Figure 6 shows the node shape of outer surface of the inside of bent tubes. Figure 7 shows the radii of the neutral layer under different bending compensation. It can be seen that with the increase of the offset of the die, the forming radius decreases and the corresponding bending compensation increases. When H is smaller meaning less
bending compensation, the forming radius after unloading is larger than the target curvature radius; when $H$ is larger meaning more compensation, the forming radius after unloading is smaller than the target curvature radius. This phenomenon makes the forming radius approach the target radius continuously and then the gap becomes larger. At the same time, it shows that there is a value of $H$ which can make the bent tube produce a suitable bending compensation and make the forming radius coincide with the target curvature radius.

Because we adjust the bending degree by increasing $H$, so the amount of springback compensation is expressed by $\Delta H$. The springback compensation of different wall thickness with diameter $D=12$ mm and bending radius $r=81.25$ mm was studied. The $\Delta H$ under different wall thickness is shown in the figure 8. It can be seen that with the increase of wall thickness, the $\Delta H$ decreases rapidly and then tends to be gentle. This is because springback amount decreases with the increase of wall thickness and the corresponding bending compensation shows the same trend. The springback compensation of different bending radii was studied when diameter $D=12$ mm, wall thickness $t=1$ mm and $L=20$ mm. Figure 9 shows the springback compensation under different bending radii. It can be seen that with the increase of bending radii, the $\Delta H$ increases and there tends to be a linear relationship between them. This is because the larger the bending radius is, the larger the springback amount is and the corresponding bent tubes need more bending compensation.

5. Experiment
In this paper, the flexible-bending forming equipment developed by Jilin University independently was used for experiments. Figure 10(a) and 10(b) are flexible-bending equipment and experimental results of springback compensation respectively.
After the experiment, the forming radii of the neutral layer of the bent tubes were measured. As shown in Figure 11, the relationships between the experimental results, simulation results and the target radius are discussed. It can be seen from the figure that there is a certain deviation between the experimental results and the simulation results, which is due to factors such as friction and clearance. The experimental results are in agreement with the simulation results and also show a trend of approaching the target radius and then the gap becomes larger. It shows that bending compensation in the opposite direction of springback can make the forming radii approach the target curvature radius and effectively solve the problem of forming error caused by springback.

6. Conclusion

In the process of flexible-bending, there is forming springback. We studied it and put forward the method of springback compensation to solve it.

(1) There is springback defect for 304 stainless steel tubes in flexible-bending process. The wall thickness and bending radii have important influence on springback. With the increase of wall thickness, the springback gradually decreases and then tends to be stable. The springback increases linearly with the increase of bending radii.

(2) By means of springback compensation, the forming radii can be close to the target radius, which can effectively reduce the forming error caused by springback and improve the forming accuracy. The experimental results validate the effectiveness of the method of and the reliability of the simulation.

(3) With the increase of wall thickness, the amount of springback compensation $\Delta H$ decreases rapidly and then the trend becomes gentle. With the increase of bending radii, the amount of springback compensation $\Delta H$ increases linearly.

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