Analysis on Stress Field of Asymmetrical Cold Ring Rolling for High-speed Rail Bearing Inner Ring

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Abstract. In this paper, the finite element model of asymmetric cold ring rolling for high-speed rail bearing inner ring is built by using ABAQUS software and the inner stress field of the ring metal during the whole cold ring rolling process is researched and analyzed, which reveals. The distribution of radial, axial, circumferential and equivalent stress at the bite rolling stage, the stable rolling stage and the fine rolling stage in the asymmetric cold rolling forming process for high-speed rail bearing inner ring were analyzed respectively. The stress in each direction of the ring was found to increase first and then decrease with each stage of cold rolling going. Finally, it tends to be stable. The stress on the contact area between the ring blank and the drive roll and the mandrel is obviously greater than that on the core of ring, and the stress in the core is more uniform.

1. Introduction

Ring cold rolling forming technology is an advanced manufacturing technology for the production of various seamless ring parts such as bearing rings, high-neck flanges, railway wheels and marine turbine rings [1,2]. It has been widely used in manufacturing fields such as automobiles, trains, ships, machinery manufacturing, aerospace, petrochemicals, and atomic energy because of its advantages of saving material, high processing precision, high reliability and high production efficiency [3]. Many scholars have done a lot of researches in this field. Hua et al. [4] conducted the finite element simulation on the cold ring rolling of the ring section of the groove ball by using ABAQUS software, studied the variation of roundness and optimized the size and process parameters of the ring blank. Yang et al. [5] studied the relationship between the ring radius expansion deformation and the press quantity of a typical profiled ring member which is a stepped ring ring during the cold roll forming process. Mao et al. [6] simulated and optimized the feeding speeds of a set of blanks and core rolls, analyzed and compared the effects of different width-radius ratios and feed speeds on the rolling force and rolling torque, and obtained the optimal parameters. Jin et al. [7] used the test to verify the reliability of the simulated cold ring rolling process. The simulation results were in good agreement.
with the test results, which verifies the rationality of the program on the optimized blank cold ring rolling. Xu et al. [8] proposed a new mathematical model for predicting the diameter expansion of the flat ring in the radial–axial rolling process. Li et al. [9-10] investigated deeply the effect of the mandrel and drive roll radius on uniformity of strain in cold-closed T-shaped ring rolling process.

2. Principle of cold ring rolling
Cold ring rolling technology is a kind of cold forming process that makes the inner metal material of the ring parts undergo plastic deformation with the help of the extrusion effect of drive roll and mandrel of cold rolling mill at room temperature. The drive roll is driven by the motor to rotate at a constant speed along its central axis, and the mandrel is moved along the radial direction of the ring in the radial direction by the pressing device of the cold ring mill. Under the combined action of friction and extrusion forces, the ring rotates and plastically deforms. At the same time, its diameter gradually increases and the wall thickness gradually decreases. During this period, the guide roll always adheres to the ring to ensure its roundness. When the diameter of the ring part gradually increases to reach the measuring roll at the predetermined position, the mandrel stops the radial linear feed motion, and finally the ring part falls from the cold ring rolling mill, and the entire cold ring rolling process ends. Figure 1 shows the basic working principle of ring during cold ring rolling.

![Figure 1. Basic working principle of ring rolling](image)

3. Finite element simulation of cold ring rolling

3.1. Material
High-speed rail bearings are subjected to very large radial load and road impact load, so service life and performance are required to be higher. GCr15 bearing steel is selected as material of high-speed rail bearing inner ring in this paper. The comprehensive property of GCr15 bearing steel is good, which has high hardness, good wear resistance, the uniform texture and high contact fatigue strength. The chemical composition and physical properties of GCr15 bearing steel are shown in Table 1 and table 2 respectively.

| Element | C    | Cr    | Mn    | P     | Si    | Ni    | Mo    | Cu    | S     |
|---------|------|-------|-------|-------|-------|-------|-------|-------|-------|
| Percentage (%) | 0.95–1.0 | 1.30–1.6 | 0.20–0.4 | ≤0.027 | 0.15–0.3 | ≤0.3 | ≤0.1 | ≤0.2 | ≤0.0 |
|          | 5 | 5 | 0 | 5 | 0 | 0 | 5 | 2 |
Table 2. Physical properties of GCr15 bearing steel

| Material | Density (g/cm³) | Thermal expansion (10⁻⁶/°) | Elastic modulus (GPa) | Poisson ratio | Hardness (HB) |
|----------|----------------|-----------------------------|-----------------------|--------------|--------------|
| GCr15    | 7.8            | 11                          | 208                   | 0.3          | 800          |

3.2. Finite element model

The finite element model of cold ring rolling for high-speed rail bearing inner ring is built which is based on ABAQUS software, as shown in Figure 2. The main process parameters of the finite element simulation are shown in Table 3.

Table 3. Process parameters for cold ring rolling of finite element simulation

| Process parameter                              | Value  |
|------------------------------------------------|--------|
| Driving roll speed (rad/s)                     | 16     |
| Mandrel first feed speed (mm/s)                | 1      |
| Mandrel sixth feed speed (mm/s)                | 0.2    |
| Conical roll speed (rad/s)                     | 29     |
| Friction factor between rollers and ring       | 0.5    |
| Network elements of ring                       | 12096  |

Figure 2. Finite element model of asymmetric cold rolling of high speed railway bearing inner ring

4. Finite element simulation results

4.1. Stress field of bite rolling stage

At the bite rolling stage of asymmetrical cold rolling for the high-speed rail bearing inner ring, the cold ring rolling has just begun. The inner wall surface of the ring blank and the outer surface of the mandrel are in close contact with each other, and the mandrel performs linear feed movement. The drive roll rotates around its center axis. Under the effect of friction force, the ring blank rotates. At the same time, the internal metal material undergoes plastic deformation and metal flow. The diameter of the ring gradually increases, and the rolling force increases slowly and is very unstable. The simulated results of the stress in radial, axial, and circumferential direction is presented as Figure 3.
It can be seen from Figure 3(d) that it is mainly manifested as the contact stress between the blank and the drive roll and the mandrel at the bite rolling stage. At the same time, it can be observed that the contact stress is mainly concentrated on the inclined step and the mandrel side of lardge end face of the blank , which is directly related to the shape of the blank. Since the blank is subjected to the pressure on the side of the inclined step of the drive roll, the opposite force is generated on the side of the mandrel. Figure 3(a) shows at the same place, there is a larger contact compressive stress , which indicates that the ring is radially compressed during the cold ring rolling. Figure 3(b) shows that the surface contact area exhibits axial compressive stress and is mainly concentrated on the side of the small end face, while the blank center is mainly axial tensile stress, which explains the axial elongation at the beginning of the rolling process. In addition, a slight “fish-tail” phenomenon can be observed on the side of large end face. Expect the contact compressive stress on the surface, the center of the ring is tensile stress as shown in Figure 3(c), which indicates that there is a tendency of circumferential expansion during bite rolling stage.

4.2. Stress field at stable rolling stage
At the stable rolling stage of the high -speed rail bearing inner ring, with the rotation of the drive roll and the continuous feeding of the mandrel, the plastic deformation and the circumferential flow of the metal material inside the blank are accelerated. This will result in increase of the diameter of the ring blank but the decrease of wall thickness of the ring blank. Since the ring blank has undergone stable elasto-plastic deformation, the rolling force gradually increases and reaches the maximum value, which is the main stage of the cold ring rolling for the high-speed rail bearing inner ring. Figure 4 shows the simulated results of the stress at the stable rolling stage in radial, axial, and circumferential direction.
Figure 4. Stress field at stable rolling stage (a) Radial stress, (b) Axial stress, (c) Circumferential stress, (d) Equivalent stress

From Figure 4(d), it can be observed that when it enters the stable rolling stage, the plastic deformation is the most severe, and the stress distribution of the entire section is uniform at the same time, indicating that the forming process in all areas is stable and the stress is uniform. Figure 4(a) shows that the compressive stress is dominant in the radial direction, and the concentration area of the compressive stress is basically the same as that of the bite rolling stage, and the compressive stress on the side of the large end surface of the drive roll is smaller. Figure 4(b) shows that the compressive stress is on the side of the small end face, the stress distribution of the contact surface is larger than that of the inner. The side of the large end face of the mandrel is mainly the compressive stress. This is due to side baffle of the mandrel limit axial broadening, which leads to the obstruction of the lateral metal flow and the increase of contact stress with the mandrel. It can be seen from Figure 4(c) that on the side of the drive roll in the circumferential direction, compressive stress is at the small end face and tensile stress is at the large end face, while it is opposite on the side of the mandrel. Observing the shape of the blank, it was found that the fish-tail that appeared on the large end face at the bite rolling stage gradually disappeared with the limitation of the baffle as the rolling progresses.

4.3. Stress field at fine rolling stage

At the fine stage of the asymmetrical cold ring rolling for the high-speed rail bearing inner ring, the rolling process comes to an end. With the stop of the linear feed movement of the mandrel, the mandrel is maintained at the position where the feed ends, and the ring continues to be pressed. The blank and the drive roll continue to rotate, and the blank and the mandrel are driven to rotate under the action of the friction force, and the guide roll also reaches the predetermined position and no longer follows. The effect of fine and returning round is achieved, and the forming precision of the cold ring rolling is improved. Figure 5 shows the simulated results of the stress at the fine rolling stage in radial, axial, and circumferential direction.
Figure 5. Stress field at fine rolling stage (a) Radial stress, (b) Axial stress, (c) Circumferential stress, (d) Equivalent stress

It can be observed from Figure 5(d) that since the mandrel stops feeding, the stress has decreased significantly compared with the main forming stage. At the same time, the stress distribution is similar to the former stages of the rolling process, presenting two stress concentrated areas. The stress concentrated area is mainly the severely deformed area on the side of the small end face and the side of the mandrel on the large end face. Comparing the three graphs in Figure 5(a), (b), (c) with the corresponding graphs in Figure 3 and Figure 4, it is found that the stress distribution at the fine rolling stage is basically the same, the stress is concentrated on the side of small end surface, and the side of large end surface close to the mandrel. However, the difference is that the magnitude of the stress is significantly decreased, and the distribution of stress is also more uniform. This shows that the stress and the tendency of plastic deformation is smaller at the fine rolling stage.

5. Conclusion

In this paper, the distribution of radial, axial, circumferential and equivalent stress at the bite rolling stage, the stable rolling stage and the fine rolling stage in the asymmetric cold ring rolling forming process for high-speed rail bearing inner ring were analyzed respectively.

(1) At the bite rolling stage, the rolling force of cold ring rolling increases slowly and is very unstable. The stress of the ring blank mainly concentrates on the top end of the outer wall of the ring blank and the inner bottom end, and gradually expands to the metal structure of the core.

(2) At the stable rolling stage of the high-speed rail bearing inner ring, the rolling force gradually increases and reaches the maximum value. The stress distribution of the ring blank is presented as tensile stress and relatively uniform. At this stage, the stress has penetrated into the core of the ring blank. This indicates that the diameter of the ring blank increases faster, the plastic deformation becomes more severe and has permeated through the entire blank, the stress in all directions shows an increasing trend.

(3) At the fine rolling stage, the stress distribution in each direction in the inner ring blank is more uniform, the equivalent stress value tends to be stable and shows a downward trend, and the degree of plastic deformation of the metal structure gradually weakens.

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