Experimental and numerical study of cold helical rolling of small-diameter steel balls

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Abstract
Cold helical rolling (CHR) is one of the most effective ways to produce small-diameter steel balls. In this study, one kind of work hardening model was established and implemented into Simufact 15.0 to investigate the work hardening phenomenon in the cold forming process. Firstly, based on the helical rolling theory, a set of finite element (FE) simulations was developed. The influence of CHR parameters, including the starting height of convex rib, forming area length, and rolling inclination angle, on the forming process was studied via simulation. Furtherly, the CHR process experiment and FE simulation were carried out; the results showed that the FE simulation was in good agreement with the experimental results and consistent with the predicted value of the theoretical calculation. Finally, the evolution of effective strain, effective stress, rolling force, work hardening, and microstructure during the cold helical rolling of Φ 5.2-mm steel balls was investigated via FE. As a result, the evolution trend of hardness was consistent with that of dislocation density, indicating that the model is credible. Besides, the microstructure of the steel ball at different positions further verified this point.

Keywords Helical rolling · Cold forming · Work hardening · Small-diameter steel balls

1 Introduction
Bearings are widely used in various fields of modern industrial technology and are a kind of key basic parts of the assembly manufacturing industry. As one of the key components of bearings, steel balls have a direct impact on the dynamic performance, reliability, and life of the bearing. For the forming of small-size steel balls (SSSB) (whose diameter is < 20 mm), there are two methods: cold forging and helical rolling (HR) [1]. Compared with cold forging, the main advantages of HR are the high utilization rate of raw materials (no pole and ring belt of the formed balls), small machining allowance, high production efficiency, closer metal streamline inside the rolled workpiece, and low cost [2]. Therefore, HR process is gradually being widely used to produce SSSB.

The HR process was firstly proposed in USSR. Since then, many scholars have carried out in-depth and meaningful work on the HR, which effectively improves the quality of rolled products. For the HR process, the HR rollers play an important role in the HR process, which directly affect the quality of formed parts. Therefore, many scholars have done a lot of research on the design of HR rollers. Pater et al. [3] proposed a new metal forming technique based on wedge rolling, which is helical-wedge rolling (HWR). They put forward the design method of rollers and HWR process, and the process parameters that influence the HWR process were discussed by FEM. Finally, its correctness was verified by experiment. Moreover, they [4] established a numerical model to study the influence of flange shape on the HWR process. The effective strain, damage function, force, and torque of three types of flange rollers were studied to optimize the roller shape. Based on the envelope theory, Yang et al. [5] proposed a mathematical model to design the helical rollers for HR process. Wang et al. [6] introduced a new method for groove design in the CHR process of steel balls, and the steel balls produced by new rollers were better and the material utilization is greater than that produced.

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by conventional rollers. In the study of Tomczak et al. [7], a modified method for sizing of helical impressions was proposed. Based on FEM, the geometry of formed balls, metal flow, and rolling force were compared between the HR process used modified roller and traditional roller. And the results showed that the modified roller was better than the traditional roller.

The forming process of steel balls has been reported in many articles. Huo et al. [8] studied the forming process of bearing steel balls with a diameter of 30 mm during warm skew rolling. They developed a multiaxial constitutive model to predict the microstructure evolution. Then, experimental and simulation results verified the availability of constitutive model. Gontarz et al. [9] investigated the influence of forming zone length on the helical rolling process and analyzed the distribution of effective strain, damage criterion, and temperature numerically. Chyla et al. [10] studied the difference between conventional helical rolling and a modified rolling method (helical rolling with helical rolls) based on the FEM. The results showed that the modified rolling method has obvious advantages in effective strain, mean stress, and tool wear compared with the traditional methods. The cold forming process of steel balls was investigated by Cao et al. [11], and they clarified the distribution and evolution of strain, stress, and damage during CHR. In summary, with the help of FEM, a large number of scholars have carried out in-depth and meaningful work on roller design [12] and HR process optimization [13, 14], which have effectively improved the quality of rolled products.

Most of the research mentioned above focuses on the hot forming of steel balls. However, for the forming process of SSSB, the temperature of the workpiece will drop rapidly due to the small size of rolled piece, so hot forming is not an ideal method. Compared with hot forming, cold forming has the advantages of economy, high efficiency, and good surface quality. Therefore, cold forming will be an ideal way to manufacture small size parts. One of the most critical issues of cold forming is work hardening, which will affect the forming process and quality of parts. During the cold forming process, the main hardening mechanism is dislocation slip [15]. Therefore, the density of dislocation can intuitively reflect the degree of work hardening of the workpiece. Lindroos et al. [16] studied the relationship between surface load, work hardening and material removal of high-strength steel. The results showed that surface work hardening can improve the wear resistance of steel, but the increasing work hardening rate cannot promote the improvement of wear resistance. Shterner et al. [17] explored the work hardening behavior of high manganese TWIP steel; it was found that the work hardening behavior at room temperature will give the steel excellent comprehensive mechanical properties. For steel balls, a higher degree of hardening will make them have good mechanical properties, which can effectively improve the quality and service life of steel balls. Consequently, in the cold forming of steel balls, work hardening is an important parameter that reflects the quality of parts.

In this paper, the CHR process of SSSB with a diameter of 5.2 mm was investigated. Firstly, a dislocation-based hardening model was established and implemented into Simufact 15.0. On this basis, the FE model of CHR was established. Then, the influence of CHR process parameters on the quality of SSSB was discussed. Finally, combined with the FEM and experiments, the forming mechanism and evolution of effective stress, strain and dislocation density were explored in the process of CHR.

2 Numerical simulation and experiment arrangement

2.1 Dislocation density–based hardening model

The resistance of dislocation slip of metal deformation is mainly the lattice resistance. The shear stress required for dislocation slip in the crystal is Peierls-Nabarro stress, which is the power of dislocation to overcome the resistance of slip system, and the equation is given as:

\[
\tau_{p-N} = \frac{2G}{1-\nu} \exp\left(-\frac{2\pi a}{(1-\nu)b}\right) \tag{1}
\]

where \(G\) is the shear modulus, \(\nu\) is the Poisson’s ratio, \(a\) is the distance of slip plane, and \(b\) is the magnitude of the Burgers vector. In addition to overcome the driving force of dislocations, the plastic deformation of metals is also hindered by dislocation increments and the stacking groups of dislocation, so the flow stress of single crystal is [18]:

\[
\tau = \tau_{p-N} + aGb\sqrt{\rho} \tag{2}
\]

where \(\rho\) is dislocation density. The equivalent stress of polycrystalline can be expressed by Taylor equation [19]:

\[
\sigma = M\tau \tag{3}
\]

where \(M\) is the grain Taylor factor. The relationship of dislocation density and equivalent stress is considered as:

\[
\sigma = M(\tau_{p-N} + aGb\sqrt{\rho}) \tag{4}
\]

The stress–strain relationship of material after annealing is based on the Hensel-Spittel rheological plastic model:

\[
\sigma = A \cdot \dot{\varepsilon}^{m_1} \cdot \varepsilon_p^{m_2} \cdot \dot{\varepsilon}_p^{m_3} \tag{5}
\]

where \(\varepsilon_{eq}\) is the equivalent strain, \(\dot{\varepsilon}_{eq}\) is the equivalent strain rate, \(T\) is the temperature. \(A, m_1, m_2,\) and \(m_3\) are the fitting
parameters, as listed in Table 1. Combined with (4) and (5), the dislocation density can be expressed as:

\[
\rho = \left[ \frac{A \cdot e^{m_1 T} \cdot \varepsilon_p^{m_2} \cdot e^{m_3 \tau_{p-N}} - M \cdot \tau_{p-N}}{M a G b} \right]^2
\]

For the convenience of expression analysis, normalized dislocation density is introduced [20, 21]:

\[
\bar{\rho} = 1 - \frac{\rho_i}{\rho}
\]

where \( \rho_i \) is the initial dislocation density and \( \rho \) is actual dislocation density. The normalized dislocation density varied from 0 (initial state) to 1 (saturation state).

In this paper, the material of the workpiece is GCr15 bearing steel, the shear modulus of GCr15 is 81839.44 MPa, Poisson’s ratio is 0.283, and the value of the Burgers vector is \( 2.48 \times 10^{-8} \) cm. In general, the value of Taylor factor \( M \) is set as 3.01 [22]. The Peierls-Nabarro stress of GCr15 is about 62.837 MPa, and the chemical compositions of GCr15 are listed in Table 2.

### 2.2 FE modeling of CHR process

The FE model of CHR is established within the FE software Simufact 15.0, as shown in Fig. 1. CHR rollers and guide plates are set as rigid bodies due to their low elastic and plastic deformation compared with the workpiece. The workpiece is assumed to be a uniform and isotropic plastic body, hexahedral elements are used for mesh generation, and the total number of elements is 13464. The Coulomb friction model is used in this paper, the friction coefficient between the rollers and workpiece is 0.2 and the friction coefficient between the guide plates and workpiece is 0.1, respectively [23]. The detailed parameters of the simulation are listed in Table 3. In addition, the parameters of the CHR dies are listed in Table 4.

### 2.3 Experiment arrangement

To study the cold forming process of steel balls, a laboratory CHR mill is used, as shown in Fig. 2. The CHR mill is

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Table 1 The fitting results of parameters

| A       | \( m_1 \) | \( m_2 \) | \( m_3 \) | \( m_4 \) |
|---------|-----------|-----------|-----------|-----------|
| 1060.94 | -0.00107  | 0.22064   | 0.01122   | 0.00066   |

Table 2 Chemical compositions of GCr15 (wt %)

| C       | Si    | Mn   | Cr   | Mo   | P    | S    | Ni   | Cu   | Fe   |
|---------|-------|------|------|------|------|------|------|------|------|
| 0.95~1.05 | 0.15~0.35 | 0.25~0.45 | 1.4~1.65 | \( \leq 0.1 \) | \( \leq 0.25 \) | \( \leq 0.3 \) | \( \leq 0.3 \) | \( \leq 0.25 \) | Bal  |
driven by two servo motor systems. Before the experiment, the left roller deflects upward at a certain angle $\alpha$ along the axis, while the right roller deflects downward at the same angle. During the CHR process, two CHR rollers rotate clockwise simultaneously and drive the workpiece forward, and the workpiece forms steel balls under the extrusion of the groove. The speed of the CHR mill is set as 40 Rpm. The CHR rollers and two guide plates are illustrated in Fig. 2. In this paper, the influence of the number of roller grooves on the forming process is ignored. Therefore, in order to improve production efficiency, double groove rollers are used in the experiment, while single groove rollers are used in FEM.

### 2.4 Measurement

To accurately measure the diameter of steel balls, connecting neck and the roundness of steel balls, an HD CCD microscope with an accuracy of 0.01 μm was used. Moreover, to verify the correctness of the constitutive model, the hardness of different sections was measured to reflect the evolution of dislocation density. Firstly, the experimental steel balls were cut into two parts. Subsequently, the sample surface was ground using waterproof abrasive paper, and then the sample surface further polished using a polishing machine with abrasive pastes. Finally, the VTD512 Vickers hardness tester was used to measure the hardness of the longitudinal section and cross-section of SSSB. Five points on the longitudinal section and four points on cross-section were selected, and the hardness of each point was measured three times, the average value was taken as the final hardness value.

### 3 Effect of CHR parameters on forming process

The CHR forming process of steel balls is continuous partial plastic forming, and the main deformation is axial elongation and radial compression. Figure 3 gives the CHR forming process of SSSB. As the figure show, during the knifing stage, under the action of CHR dies, the workpiece diameter decreases continuously, the connecting neck is gradually elongated, and the metal on both sides of the convex rib forms an arc. Then, the adjacent convex ribs are gradually closed after one circle of the rollers. At the same time, the metal in the closed area is extruded by the convex ribs on the left and right sides, and the groove is filled slowly. In the sizing stage, steel balls are formed and the surface is further refined to improve the size and shape accuracy.

#### 3.1 Effects of starting height of convex rib on forming process

The height and width of the convex rib are basic parameters of CHR rollers, which affect the selection of other parameters, especially the impact on the forming process of steel balls. The influence of starting height of convex rib on the forming process is shown in Fig. 4. At first, the

| FE Parameters (unit)   | Values |
|------------------------|--------|
| Speed of roller (Rpm)  | 40     |
| Initial temperature of workpiece (°C) | 20 |
| Initial diameter of workpiece (mm) | 5.0 |
| Friction factor (workpiece and rollers) | 0.2 |
| Friction factor (workpiece and guide plates) | 0.1 |
| Initial element number of workpiece | 13,464 |

| Parameters (unit)          | Values |
|---------------------------|--------|
| Diameter of roller (mm)    | 110    |
| Groove radius (mm)         | 2.6    |
| Length of groove (°)       | 1080   |
| Length of sizing area (°)  | 450    |
| Connecting neck diameter in sizing area (mm) | 1 |
| Basic lead (mm)            | 6.703  |
| Width of convex rib at starting position (mm) | 1 |
| Convex height of starting position (mm) | 0.5 |
| Width of convex rib in sizing area (mm) | 1.6 |
| Convex height in sizing area (mm) | 2.1 |

Fig. 2 Laboratory CHR mill and CHR rollers

Table 3 Parameters of FE simulation

Table 4 The parameters of the CHR rollers

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starting height of convex rib is set to 0.7 mm. When the workpiece rotates for the first circle, it will be severely necked due to the extrusion of the convex rib. A large number of metal materials accumulated near the connecting neck, which is marked by the yellow line in Fig. 4. As the rolling process going on, the metal materials produced by the accumulation flow to both sides rapidly, forming grooves on both sides of the convex rib, which will seriously affect the quality of steel balls. Considering the causes of defects, the starting height of the convex rib is changed to 0.5 mm. It is found that due to the reduction of convex rib starting height, the radial reduction of the workpiece is decreased during the first circle, and the deformation is relatively gentle. The accumulation of materials is greatly reduced, and the metal flow tends to be uniform.

### 3.2 Effect of forming area length on forming process

The length of the forming area directly affects the change rate of convex rib height. The change rate of convex rib height increase with the decrease of the length of forming area. As shown in Fig. 5, when the total spiral length of convex rib is 810°, the length of the sizing area of CHR die is 450°, the length of forming area is 360°, and the height of the convex rib gradually increases from 0.7 to 2.1 mm. Because of the short length of forming area, causing a higher speed of the workpiece shrinkage in the radial direction, and the axial extension rate of the connecting neck is also fast. Therefore, the workpiece and the dies are gradually separated during the forming process. When the total spiral length of roller convex rib is 1080°, the total length of the spiral in the forming area is 630° and the height of the convex rib of CHR die is from 0.5 to 2.1 mm, there is no separation phenomenon. The workpiece fits perfectly with the rollers and improves the processing quality. Therefore, for the CHR process of steel balls, a longer forming area length is beneficial to reduce the occurrence of defects and improve the quality of steel balls.

### 3.3 Effect of rolling inclination angle on rolling force

Figure 6 illustrates the evolution of rolling force and rolling torque at different inclination angles in the CHR process. After the first knifing stage, the rolling force at different angles has little difference. Because the workpiece is in the first deformation stage, and the rolling inclination angle and spiral angle are different when the front of the rollers is knifing, so the change of inclination angle has little effect on it. In the subsequent knifing stage, when the roll inclination angle is 1.3°, the rolling force and rolling torque are the smallest, and the fluctuation of the rolling force and rolling torque is also small. Under this condition, the inclination angle of the dies is equal to the spiral angle of the sizing area, steel balls rolling in the groove, and the pressure of the inner wall of the grooves on steel balls is small. When the inclination angle is 2°, it can be seen that the rolling force and torque data are the largest among the four conditions, and the oscillation is also serious. Due to the deviation between the inclination angle and the spiral angle in the sizing area of rollers is greater, so the pressure on steel balls from the inner wall of the grooves is large too. In summary, as the deviation between the rolling inclination angle and spiral angle of the rollers sizing area increases, the rolling force and torque increase, and the fluctuations increase too.

It is can be seen that the rolling force and rolling torque increase sharply in each knifing stage. In the smooth rolling stage, the material at each position of the workpiece...
gradually fits the inner wall of the groove. Due to the larger deformation, the temperature at the connecting neck rises, resulting in a reduction in deformation resistance. Therefore, the rolling force decreases slowly, and rolling torque tended to be gentle and slightly decreases until the next convex rib start to knife into the workpiece. As new parts of the workpiece continue to enter the dies, and the part previously contacting with rib is still in the forming stage, resulting...
in the accumulation of rolling force and torque. Therefore, after three cycles, the peak value of the rolling force and torque becomes larger and larger. Besides, the fluctuation of rolling force and rolling torque is more and more intense, which is due to more steel balls are involved in rolling. Consequently, the larger contact areas between the dies and the rolled piece, the worse rolling stability and the larger fluctuation of the rolling force energy.

### 3.4 Effect of rolling inclination angle on work hardening

The distribution of normalized dislocation density in different sections is shown in Fig. 7. When the roller inclination angle is 1.3°, the dislocation density field has fewer layers from left to right, and the span is small. Moreover, the dislocation density in most areas is high and uniform. When the inclination angle is 1°, 1.6°, and 2°, the distribution of dislocation density field is multi-layered, and the dislocation range is large. Compared with the initial state, the dislocation density in the center of steel balls has almost no change. The reason is that under the action of rollers, the axial component velocity of the circular motion velocity of rollers rotation does not match the push of groove to steel balls. The velocity mismatch results in the extrusion of the convex rib on steel balls, which makes the degree of work hardening near the two poles higher.

In the cross-section of steel balls, it can be seen that when the roller inclination angle is 1.3°, the work hardening of steel balls after cold rolling is obvious and uniform. While in other conditions, there is almost no work hardening in the center. Moreover, the distribution of dislocation density field is uneven and the hardening layers are thin, which will be far from meeting the use conditions of steel balls.

### 3.5 Effect of rolling inclination angle on strain and stress

Figure 8 shows the distribution of effective plastic strain and effective stress in different inclination angles. When the inclination angle is 1.3°, the distribution of equivalent strain of steel balls is more uniform, and it is umbrella-shaped at the connecting neck. Moreover, the equivalent stress of two poles of steel balls is low, and there is no large stress concentration area except the connecting neck. While in other working conditions, the strain distribution at the connecting neck is fishtail-shaped with a central depression and divergent around. With the increase of inclination angle, the stress concentration area on the left side of the steel ball gradually decreases, and gradually increases on the right side of the steel ball. Under the condition of α = 1.3°, there is almost no stress concentration area in the steel ball. If the stress concentration area on the left or right side of steel ball is large, it indicates that the steel ball is in close contact with the inner wall of the groove. Such conditions will increase the friction between the steel ball and rollers, and the surface quality of steel balls will be affected.

### 4 Results and discussion

#### 4.1 Comparison of experiment and simulation

Based on the above results, α=1.3° was selected as the rolling inclination angle. Then, the CHR experiments were carried out with the CHR mill and rollers shown in Fig. 2, and the results are shown in Fig. 9. Five steel balls are selected to measure their diameter and the diameter of connecting neck and compared with the simulation results. It can be seen that the steel balls are regular spherical and with good surface...
Fig. 7 Distribution of normalized dislocation density in the (a) outer contour, (b) longitudinal section, (c) cross-section.

Fig. 8 The distribution of (a) effective plastic strain, (b) effective stress.
quality. The experimental and simulated ball contours are in good agreement. Besides, compared with the target part, the diameter difference of experiment and simulation results are 0.034 mm and 0.036 mm, which is much smaller than the required error value of 0.1 mm, indicating that the simulation results are in good agreement with the experiment results, and both consistent with prediction value.

To further verify the experimental and simulation results, reverse checking software Geomagic Qualify was used to compare the difference between the simulation result and a 5.2-mm-diameter standard part established by Creo 4.0. The results are shown in Fig. 10. S1, S2, and S3 are XY, XZ, and YZ sections, respectively. The error values of the three sections are similar, which fluctuated around −0.013 to 0.042 mm, and the average error value of the three sections is 0.027 mm. Therefore, it could be considered that the simulation results are reliable.

Figure 11 gives the comparison between the experimental steel ball and the standard part outline. It can be seen that the overall dimensions are in good agreement. However, there are some defects in the range of 210–270°, the maximum value of defects is 59.81 μm, and the allowable error value of the actual part is 0.1 mm, so these errors can be ignored. Through the roundness calculation formula $P = \frac{\sum r}{N \cdot R}$, the roundness of Φ 5.2 mm steel balls is 1.022. Therefore, the size of the experimental parts meet the dimensional accuracy requirements.

4.2 Evolution of effective strain

Figure 12 shows the evolution of effective plastic strain in the CHR process. During 0.1 s, the workpiece begins to enter the CHR rollers, and the connecting neck is compressed radially and extended axially. At the moment of 1.5 s, the first steel ball enters the closed area. When the
workpiece is extruded by both sides of the convex rib, the spherical shape gradually appears. It can be seen that the contact part of the convex rib is the largest part of deformation. Before 4 s, the largest deformation degree of the steel balls is the two-pole position. Due to the contact area between the bottom of the groove and the steel ball is small, the deformation of the equator of steel balls is slight. At the time of 4 s, the first steel ball is formed and enters the sizing area; the deformation degree of the center of steel balls is similar to the equatorial position. In the sizing area, the strain field of steel balls is distributed in a band from left to right.
Figure 13 presents the distribution of effective stress at the time of 2.6 s and 4 s. Figure 13a shows the effective stress distribution of the outer contour, and Fig. 13b shows the effective stress distribution of the longitudinal section. The effective stress of the contact part between steel balls and die groove is the largest, followed by the connecting neck and equatorial area, and the center of steel ball is the smallest. Although the deformation of the connecting neck is largest, however, the temperature rise caused by deformation reduces the deformation resistance of the metal; therefore, the stress value is not the largest.

The triaxial stress state in the rolling process is also analyzed, and the results are shown in Fig. 14. As the figure shows, during the CHR process of steel balls, the surface of connecting neck and the two poles of steel balls are always under pressure. However, the center of the steel ball...
is always in a three-direction tension state. Such continuous action of three-direction tensile stress can easily lead to internal rarefaction. Because the metal axial flow is caused by the extrusion of convex ribs during the rolling process, the center of connecting neck is in a tension state. Moreover, due to repeated tensile and compressive stress, the surface of steel balls is strengthened, and the hardness of the spherical surface increase after rolling, which is the work hardening phenomenon.

4.4 Work hardening

Figure 15 shows the distribution of normalized dislocation density in the CHR process. It can be seen that the normalized dislocation density is distributed in layers. Moreover, the surface hardening layer is parallel to the equator and gradually decreases from two poles to the equator. Similarly, the degree of hardening is reduced accordingly. Therefore, the two poles of formed steel balls must be the position with the greatest degree of hardening. In Fig. 15b, the dislocation density near the first connecting neck on the right side is the largest, and the position near the two poles has a larger dislocation density compared with other regions. The degree of hardening near the equator of steel balls is the same, and the overall dislocation density is the same in the cross-section, as shown in Fig. 15c.

Figure 16 illustrates the hardness of different positions in the longitudinal section and cross-section. The initial hardness of GCr15 is 232HV, and the hardness of the steel ball center is slightly larger than that of the workpiece. In the longitudinal section, the hardness gradually increases with the increase of the position number. While in the cross-section, the hardness varies slightly at different positions, but all belong to the same level. The changing trend of hardness is consistent with the evolution trend of dislocation density, indicating that the hardening model is credible.

In the observation of microstructure, the sample after the hardness test is used and polished to the mirror surface again. Then, an alcohol solution containing 4% of nitric acid (volume fraction) is used to corrode the sample. Subsequently, an optical microscope is used to observe the microstructure, and the results are illustrated in Fig. 17. As the figure shows, the microstructure is granular pearlite; that is, spherical carbides are distributed on the ferrite matrix. From position 1 to 5, as the deformation increases, the granular carbides are refined gradually. Because of
the increase of dislocation density and the precipitation strengthening of second phase, the hardness of the sample at different positions gradually increases. Besides, the refined granular carbides can enhance the precipitation strengthening effect of second phase. And the dispersed small carbide particles will pin the dislocations and increase the deformation resistance, so the hardness of position 5 is the largest.

4.5 Evolution of grain size

Figure 18 gives the evolution of GCr15 grain size before and after CHR process. It can be seen that the initial average grain size of GCr15 is uniform, and the average grain size is 13 μm. In the formed steel ball, the average grain size in the center of the ball is 10 μm, which is almost the same as that of the original material. The reason is that the deformation here is small, the grain is slightly refined compared with the original material, while the average grain size of the part with the edge close to the connecting neck is 6 μm. Compared with the ball center, the plastic deformation here is larger, and severe plastic deformation will refine the grain, so the grain refinement phenomenon is more obvious here.

5 Conclusion

In this paper, FE simulations and experiments were conducted to investigate the CHR process of small steel balls with a diameter of 5.2 mm and the following conclusions are drawn:

(1) The parameters of the CHR rollers have a great influence on the forming process of steel balls. A higher rib height will lead to seriously affect the formation of steel balls. When the inclination angle is 1.3°, the strain and stress fields are uniform. Moreover, the total dislocation density of the formed steel balls is large and uniform, which indicates that the work hardening phenomenon of the steel ball is obvious after cold rolling, and the strength and hardness of steel balls are effectively improved. In other cases, the overall inhomogeneity of the equivalent strain field and the equivalent stress field of steel balls is obvious, and the rolling force and torque are also increased, which will affect the forming performance of steel balls.

(2) The counter of steel balls obtained from simulation agrees well with the experiment and also the diameter of the balls and connecting neck are consistent with
the theoretical prediction, which indicates that the FE results are credible.

(3) The equivalent strain and stress at the two poles of steel balls are larger, while the center of steel balls is the smallest. The two poles of steel balls are the positions where the degree of hardening is the greatest, and the dislocation density gradually decreases from the poles of steel balls to the equatorial due to the gradual decrease of strain. The results of the Vickers hardness test show that the hardness trend of the steel ball is consistent with the trend of the numerical simulation dislocation density distribution graph, which verifies the accuracy of the cold work hardening mathematical model. Moreover, with the increase of deformation, the granular carbides and grain size are refined gradually, which will further enhance the mechanical properties of the material.

**Author contribution**  Shengqiang Liu: software, investigation, validation, methodology, writing—original draft. Jinping Liu: project administration, supervision, funding acquisition. Hao Xu: supervision, writing—reviewing and editing. Zhipeng Wang: methodology, writing—reviewing and editing. Jinxia Shen: writing—reviewing and editing. Baoyu Wang: administration, supervision, funding acquisition.

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**Declarations**

**Ethical approval**  This article does not contain any studies with human participants or animals performed by any of the authors.

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**Fig. 18** Evolution of grain size of steel balls. a original material. b ball center. c the edge of steel ball near the connecting neck.
Informed consent  All the authors listed have approved the manuscript that is enclosed.

Consent to participate  Applicable.

Conflict of interest  The authors declare no competing interests.

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