Theoretical study of the process of balls rolling with a diameter of 40 mm on a ball rolling mill

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Abstract. The following calibration scheme for rolling round steel is used for producing thermally hardened grinding balls with a diameter of 40 mm at JSC SSGPO for 320 variety rolling mill: a round billet with a diameter of 40 mm is produced from the initial billet of 120×120 mm. In the last developed scheme the square billet 150x150 mm is used as an initial billet for whole mill where the round steel with diameter of 40 mm is obtained from the above mentioned billet and then this round steel is used for production of balls with a diameter of 40 mm. Computer simulation of the ball rolling process in the Simufact Forming program was performed. The results of strain state distribution showed that the maximum processing level in the surface layers of balls is observed, while the stress state distribution showed that in the surface layers prevail high compressive stresses up to -400 MPa. Such stress-strain state leads to formation of gradient structure in the ball cross-section, where the surface layers will have more high mechanical properties. That is the most optimal result for details worked in condition of high values of friction.

1 Introduction

The worldwide coronavirus pandemic has a negative impact on almost all sectors of the economy, including the extractive industry. Therefore, declining prices for ore raw materials are forcing subsurface users to look for new innovative ways to extract and enrich ore raw materials with reduced costs. At the initial stage, the process of mining and processing different ores has a lot in common, regardless of the metal extracted from the ore. So after extraction from the ground, before enrichment, any ore must be crushed and grinded. Grinding, as the final stage of ore preparation before enrichment, is carried out in mills of various designs using in most cases grinding balls. During this process, due to the abrasive action of the milled material on the grinding balls, they wear out and are irretrievably consumed in the process of grinding raw materials (wear on average is 0.5-2 kg/t). According to various estimates, the cost of purchasing grinding balls is from 15 to 35% of the total technological costs of the respective industries. As a result, rapid wear of grinding balls leads to a significant increase in the total cost of crushing and grinding, which is about 60-70% of the cost of processing raw materials.

Often arising losses are associated not only with increased consumption of grinding balls and decrease in indicators of the efficiency of the milling equipment due to frequent outages, and deterioration of product quality due to the increase of iron content in the final product. The same problem is also relevant when using mills for grinding raw materials in the production of cement and energy. Thus, the problem of increasing the resource of steel grinding balls is very relevant. Therefore, the solution to this problem is promising not only for Kazakhstan, which is among the world leaders in the production of ores of various metals, but it is actively developed in many developed countries of the West and the Asia-Pacific region, which also produce minerals. It is the introduction of innovations in the extraction and processing of ores that will allow mining companies to maintain the profitability of their enterprises even in the conditions of crisis caused by various factors, including the coronavirus pandemic.

One of the most promising technologies for producing steel grinding balls is the screw rolling technology, where steel balls are produced on a screw rolling mill [1-3]. According to this technology, the rolling process of balls is carried out from a round bar billet using two rolls with screw calibers. For single-pass
calibration, one ball is rolled for each revolution of the rolls. For multi-pass calibration, the number of balls coming out of the rolls per revolution is equal to the number of passes of the screw gauge. When leaving the rolls, the balls are intensely cooled in water and hardened, which ensures sufficient wear resistance of the balls in mills for grinding ore at processing plants. This technology is currently used for the production of grinding balls at the metal rolling plant of JSC "Sokolov-Sarybai Mining Production Association" (SSGPO). For these purposes, the SHPS 30-60 ball rolling mill is used, which is focused on the production of grinding balls with a diameter of 30 to 60 mm made of carbon, alloy and spring steel. The billet for rolling is a round hot-rolled steel rod with a length of 3 to 5 m, obtained by hot rolling at the variety rolling mill 320 of the same enterprise.

At present time, the following calibration scheme for rolling round steel is used for producing thermally hardened grinding balls with a diameter of 40 mm at JSC SSGPO for the 320 long-range rolling mill: a round billet with a diameter of 40 mm is produced from the initial billet of 120×120 mm [4]. But when analyzing the technical and economic indicators of this rolling scheme at the metal rolling plant of JSC "SSGPO", it was revealed that in this case there will be an undeveloped potential for the production capacity of the long-range rolling mill 320.

Therefore, we have developed a new calibration of rolls for rolling round steel No. 40 from a billet with a cross section of 150 x 150 mm in the conditions of mill 320 of JSC "SSGPO" [5]. This increased the total number of passes from 9 to 11, and evaluation of the appropriateness of the emerging values of the power parameters of permissible values (for the exception of equipment failure), and also conformity assessment of the shape and size of the final profile plant requirements (to prevent defects of the geometry of the rental). The research carried out in [5] proved that the proposed calibration for the production of round steel with a diameter of 40 mm fully meets the technical parameters of the long mill 320.

2 Scheme of balls rolling

This work is devoted to the development and calculation of calibration rolls for rolling balls with a diameter of 40 mm on a ball rolling mill in the conditions of JSC "SSGPO", obtained from the original cylindrical billet with a diameter of 40 mm, as well as computer modeling of this rolling process.

Rolling on a ball rolling mill is carried out between two rolls that rotate in one direction, and on the barrels of which screw calibers are cut. The axes of the rolling rolls of this mill are inclined at a slight angle to the axis of the rolled billet, which ensures the axial feed of the cylindrical billet in the rolls. In the rolls, the rotating initial billet is compressed by the gauge edges and takes the form of a ball connected by a jumper to the rest of the billet. With further progress in the rolls, the ball is calibrated and completely separated from the original cylindrical billet.

In this process the deformation zone has two main sections [6]:

- forming section, where the workpiece is compressed with a change in the shape and size of the screw edge;
- finishing section, where the shape and size of the edges remain unchanged, and compression is carried out by ovalizing the workpiece.

Ball forming is carried out by the edges of the rolls, the height of which gradually increases. To simplify the calibration calculation and roll manufacturing, it is assumed that the height of the gauge edge changes according to the law of a straight line. For a normal rolling process, the profile and dimensions of the forming section of the gauge are calculated in such a way that the following two main provisions are observed during the compression of the workpiece [7]:

1) the volume of metal compressed in the gauge must remain constant throughout the forming process;
2) changing the profile and size of the gauge edge must correspond to the stretching of the compressed workpiece.

According to the first provision, it is necessary that the volume of some part of the billet captured by the rolls remains unchanged as it passes through the remaining sections of the caliber. In this case, there will be no excess of metal at any time of rolling. When an excess of metal appears, the geometric shape of the ball is distorted and voids may form in the axial zone of the workpiece. The presence of a small excess of metal is allowed only at the beginning of the caliber, when the edge is still relatively low and does not prevent the displacement of metal from the caliber.

The second provision is that the normal formation of the bowl shape, the stretching of compressed zone should conform to the changing shape and sizes of caliber edge. In the case of balls rolling, the length of the compressed jumper must be equal to the width of the straight section of the caliber edge. If the change in the width of the caliber edge is less than the draw of the compressed billet, the metal will move away from the edge, and a roll will form on the surface of the billet, which will roll out in the film when the...
The billet is further compressed. If the change in the width of the caliber edge is greater than the workpiece stretching, then axial tensile stresses occur in the compressed jumper, which can lead to a break in the jumper. Thus, to fulfill both the first and second conditions, the edge on different sections of the caliber must have a strictly defined thickness. In this regard, the forming section of the caliber has a variable cutting step.

When developing the roll calibration, we decided to use the calculation algorithm, which is described in detail in [8-9]. In this case, the initial data for calibration of rolls are the technical characteristics of the rolling mill, the size of the rolls, and the diameter of the resulting grinding ball. The main dimensions of the rolls of the rolling mill are shown in figure 1.

![Figure 1. Basic elements of rolls calibration of for balls rolling: \(h_a\) and \(a_a\) – height and width of the edge; \(r_a\) and \(R_K\) – the radii of the jumper and caliber; \(C_a\) and \(S_a\) – width of the spherical and cylindrical sections of the caliber](image)

Ball calibration calculation is performed for the left roll, since the calibration of the right roll is almost the same. The only difference is that after cutting the edges of the right roll, it is cut in height by a certain amount. The initial data for calculating the calibration of the rolls of the SHPS 30-60 rolling mill are: ball diameter \(d_B = 40 \text{ mm}\); rolls diameter \(d_r = 300 \text{ mm}\). At the same time, when calculating and constructing the calibration of rolls, it is necessary to follow the design recommendations given in table 1.

### Table 1. Initial data for calibration calculation

| \(d_B, \text{ mm}\) | \(d_r, \text{ mm}\) | Length of caliber, deg | \(2r, \text{ mm}\) | Edge size, mm |
|---|---|---|---|---|---|
| \(d_W, \text{ mm}\) | \(\alpha_{\text{total}}\) | \(\alpha_{\text{fin}}\) | \(h_{\text{on the capture}}\) | \(w_{\text{on the finishing section}}\) | \(w_{\text{on the section 270° of capture}}\) |
| 40 - 50 | 180 - 300 | 900 - 1080 | 540 - 720 | 3.0 – 3.2 | 2.5 - 3.8 | 3.7 - 5.4 | 2.0 - 2.4 |
| 60 - 80 | 280 - 460 | 1080 - 1350 | 630 - 810 | 3.6 - 5.0 | 4.4 - 4.5 | 5.8 - 8.4 | 3.0 |
| 100 - 125 | 550 - 690 | 1260 - 1350 | 630 - 810 | 6.0 | 5.4 | 9.0 - 11.0 | 3.5 - 4.0 |

According to GOST 7524-2015 "Hot-rolled steel balls for ball mills" we choose the nominal diameter of the ball for subsequent calibration of the rolls, taking into account the permissible deviations. We accept \(d_B = 40 \text{ mm}\), the permissible deviation of the diameter is ±2 mm. Then the diameter of the workpiece is \(d_w = d_B / \eta_0 = 40 / 1.03 = 38.8 \text{ mm}\), where \(\eta_0\) is the coefficient that takes into account the radial growth of the ball size during rolling (we take \(\eta_0 = 1.03\)).

According to the regulations, the balls are rolled from a 40 mm blank. Then the diameter of the ball will be equal to:

\[
d_B = d_w / \eta_0 = 40 / 1.03 = 41.2 \text{ mm. (1)}
\]

Diameter of caliber

\[
d_c = d_B \cdot \eta_t = 41.2 \cdot 1.013 = 41.7 \text{ mm. (2)}
\]
where $\eta = 1.013$ - coefficient that takes into account the temperature expansion of the metal.

Minimum width of the edge

$$a = 0.04R_c + 1.3 = 0.04 \times 20.85 + 1.3 = 2.1 \text{ mm},$$

(3)

where $R_c = d_c / 2$ - radius of caliber, mm;

Initial height of the edge

$$h_0 = 1.5 + 0.07(R_c - 10) = 1.5 + 0.07(20.85 - 10) = 2.3 \text{ mm};$$

(4)

Minimum radius of the jumper

$$r = 1 + 0.04(R_c - 10) = 1 + 0.04(20.85 - 10) = 1.4 \text{ mm};$$

(5)

Width of the edge before cutting

$$a_{cut} = 4 + 0.14(R_c - 10) = 4 + 0.14(20.85 - 10) = 5.5 \text{ mm}. $$

(6)

The length of the caliber (the number of turns) is conventionally measured in degrees of sweep of the helix. For the beginning of the caliber (0°), the center of the radius of the caliber is taken, located on a straight line passing along the end of the shaft from the exit side of the finished ball. When rolling balls, we follow the recommendations of table 1 and set the total length of the caliber $\alpha_{TOTAL} = 900^\circ$, the length of the forming section $\alpha_f = 270^\circ$ and the dividing section $\alpha_{FIN} = \alpha_{TOTAL} - \alpha_f = 900 - 270 = 630^\circ$. We divide the length of the gauge into equal sections; for preliminary calculation, the split angle $\Delta\alpha = 90^\circ$ is sufficient. The radius of the jumper at the end of the forming at $\alpha = \alpha_f - \Delta\alpha$ is determined from the ratio

$$r_{cut} = r + \frac{R_c - h_0 - r}{\alpha_f} \Delta\alpha = 1.4 + \frac{20.85 - 2.3 - 1.4}{270} = 7.1 \text{ mm}$$

(7)

Changing the height of the edge when the roll is rotated by $90^\circ$:

$$\Delta h = r_{cut} - r = 7.1 - 1.4 = 5.7 \text{ mm}.$$ 

(8)

For each angle of rotation of the rolls from $\alpha_{TOTAL}$ to $\alpha_f$ at interval $90^\circ$ the height of the edge:

$$h_{\alpha_{FIN}} = h_\alpha + \Delta h = h_\alpha + 5.7.$$ 

(9)

where $h_\alpha$ - current height of the edge, mm.

While the jumper size on the finishing section $\alpha_{FIN}$ will be $r = 1.4$ mm, the radius of the bridge on the molding section is determined by the formula

$$r_{\alpha_{FIN}} = r_\alpha + \Delta h = r_\alpha + 5.7.$$ 

(10)

Determine the width of the spherical section of the caliber from the expression

$$C_\alpha = \sqrt{R_c^2 - r_\alpha^2} = \sqrt{20.85^2 - r_\alpha^2}.$$ 

(11)

So cut the jumper begins during the ball forming, then take the width of the spherical segments plot it on the angle of rotation of the roll $\alpha_{FIN}$ pre-finishing area of the caliber, i.e. $C_{cut} = C_{FIN}$. The main calibration calculations are shown in table 2.

**Table 2. Calculation data for rolls calibration of ball rolling with a diameter of 40 mm**

| $\alpha$, ° | 900 | 810 | 720 | 630 | 540 | 450 | 360 | 270 |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|
| $h_{\alpha_{FIN}}$, mm | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 |
| $r_{\alpha_{FIN}}$, mm | 18.5 | 18.5 | 18.5 | 18.5 | 18.5 | 18.5 | 18.5 | 18.5 |
| $C_\alpha$, mm | 9.6 | 16.4 | 19.6 | 20.8 | - | - | - | - |

### 3 FEM simulation

Based on the above calibration calculations of the SHPS 30-60 ball rolling mill, a computer simulation of balls rolling process with a diameter of 40 mm was carried out in the Simufact Forming program. The original billet had a diameter of 40 mm and a length of 150 mm. When modeling in the Simufact Forming software package, the following conditions and assumptions were accepted:
- material of the workpiece in the initial state (before deformation) was isotropic and there were no initial stresses and deformations;
- grid of 250,000 hex-type finite elements was created on the workpiece; the average length of the element face was 1.3 mm;
- material used in the simulation – AISI 1065 steel corresponding to 65G steel, the hardening curves were taken from the Simufact Forming library;
- initial temperature of the workpiece was assumed to be equal to 1150 °C, there was deformation heating and heat transfer between the workpiece, the tool and the environment;
- material model of the initial billet was assumed to be elastic-plastic;
- friction coefficients between the tool and the workpiece were selected based on recommendations from [6] and assumed to be equal to 0.5 at the contact of the workpiece with the rolls;
- roll rotation speeds were taken from the characteristics of the 320 mill.

In addition to these conditions, which are common to many metal forming processes modeling programs, the key features of the Simufact Forming complex were also used. In particular, the option of plotting coons surfaces was activated to improve the construction of a finite element grid on the curved surface of a round billet. Figure 2 clearly shows the difference between grid construction in the programs Deform and Simufact Forming. The grid in Deform is rougher, and the surface is not a circle, but a polyhedron (figure 2a). In Simufact Forming, by calculating the geometry, the final elements are curved to take the shape of an arc (figure 2b).

![Figure 2. Building a hex grid in Deform and Simufact Forming](image)

As a result, a model of balls rolling from a round billet was obtained (figure 3 a), in which the first ball billet is not fully formed due to tightening (figure 3b). The rest of the blanks are solid balls with a diameter of 40 mm. To study the stress-strain state (SSS), the parameters "effective plastic deformation" and "average normal stress" were considered.

![Figure 3. Model of ball rolling with a diameter of 40 mm](image)

When studying the strain state, its extremely uneven distribution over the section of the workpiece was noted (figure 4a). The central layers of the workpiece (0÷20% of the radius) receive almost no increase in deformation. Here the level of strain reaches 2.3÷2.5. In the intermediate layers (20÷70% of the radius), the effective plastic deformation is much higher, the level of strain reaches 3÷10. This is due to the fact that the metal in this zone, in contrast to the center of the workpiece, moves along a circular trajectory of the ball gauge more intensively. In the surface layers (70÷100% of the radius), the most intensive development of effective plastic deformation is observed, and at a distance of 95÷100% of the radius, the values of strain are the maximum, about 30÷33. This is due to the fact that the surface layers are subjected not only to the most intense deformation during the formation of the ball, but also to subsequent surface processing, after the ball is formed.
When studying the stress state, it was noted that the uneven distribution of the average normal stress across the section of the workpiece has a certain tendency (figure 4b). The central layers of the workpiece (0÷20% of the radius) are subjected to tensile stresses, but their value is small, about 0÷55 MPa. In the intermediate layers (20÷70% of the radius), there are no tensile stresses, only compressive stresses act here, their values are at the level of 0÷116 MPa. This is due to the fact that the metal in this zone, moving along the trajectory of the gauge, is more exposed to normal stresses. In the surface layers (70÷100% of the radius), only compressive stresses act, their values reach ~460 MPa. This sharp increase in normal stress is a consequence of the fact that the surface layers are most affected by normal stresses from the deforming caliper.

Analysis of the resulting force during balls rolling showed that the force graph is non-monotonic. The peaks that correspond to the rolling of individual balls are clearly visible, with the maximum force value in each peak corresponding to the moment when the jumper is cut. At the same time, the general nature of the graph is increasing, which is directly related to the filling of ball gauges with deformable metal. Thus, figure 5 shows three peaks: the first peak is the forming of 1st ball in the caliber (the force value is about 120 kN), the second peak is the forming of 2nd ball (force is approximately 160 kN), the third peak is the forming of 3rd ball (force is about 180 kN), the moment is shown in figure 3a.

4 Conclusions

The results of theoretical studies of the balls rolling process with a diameter of 40 mm at the SHPS 30-60 ball rolling mill in the conditions of the Sokolov-Sarybai Mining Production Association, including the results of computer modeling in the Simufact Forming software complex, have allowed to more fully study the production technology of grinding balls using screw rolling.

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