IMPLEMENTATION OF PRODUCING STEEL GRINDING BALLS USING SIX-START HELICAL CALIBRATED ROLLS

Shakhobutdinov Rustam[1] [0009-0007-8666-8042] and Karimova Anorgul[1] [0000-0002-0668-3653]
[1]Tashkent State Technical University named after Islam Karimov
E-mail: karimovaanorgul@tdtu.uz

Abstract - This paper explores the production of steel grinding balls used in the mining and metallurgical industries through the hot rolling process. Calculations were performed for hot rolling 40 mm diameter steel balls. Calibration calculations were carried out to produce the transverse screw-calibre rolls used in steel ball rolling. Based on these calculations, mathematical models describing the motion of the cams used to cut the rolls were developed. These models were based on the design of rolls with six-start screw gauges with shifted groove centres. The solutions of these models were analysed in MathCAD, and 3D models of the cams were created with KOMPAS software. To analyse the calibration results, 3D models of the six-start screw-calibre rolls were developed. Using these results, the feasibility of manufacturing cams for cutting ball rolling rolls on the screw-cutting lathe was determined. These cams were machined using a CNC milling machine. Based on the calibration calculation results for balls with a diameter of 40 mm, analytical expressions were developed to describe the variation of the neck radius and volume formed in the raw material. Based on both theoretical and experimental research aimed at increasing productivity in the hot rolling of 40 mm steel balls, a manufacturing process for six-start screw-calibre rolls were successfully implemented at the Ball Rolling Section of Joint Stock Company “Uzmetkombinat”. This technology led to a 15–20% increase in productivity and reduced metal consumption for the rolls used to produce 40 mm steel balls by 1.2–1.4 times.

Keywords: Steel ball, Ball rolling mill, Ball rolling roll, Linear guide, Cam, Screw gauge.

1. Introduction

In the mining industry, steel grinding balls are used for crushing ore and mineral products. Steel grinding balls can be produced through casting, stamping (forging), and rolling methods. Steel grinding balls produced using these methods differ from each other in terms of structure, wear resistance, and impact resistance. To alter the microstructure of the steel balls, their hardness is increased by storing them under specially designed conditions for each alloy. Steel balls produced through the casting method are made by pouring the metal into moulds. The hardness of steel grinding balls produced using this method is very low, and their productivity in manufacturing is also low. Steel grinding balls produced by the stamping method have higher hardness compared to those produced by other methods; however, their manufacturing productivity is lower. The production of steel grinding balls through hot rolling is one of the most convenient and efficient methods. However, since the production of steel grinding balls via hot rolling is a very complex technological process, theoretically analysing this issue is somewhat difficult. To produce steel grinding balls through hot rolling, special ball rolling mills are used. The technological process is mainly carried out by processing raw materials heated to a specified temperature using a transverse screw rolling method. The rolling process is carried out using two calibrated transverse screw rolls rotating continuously in opposite directions, along with two linear guides that provide the supporting function.

The production technology for grinding steel balls using the hot rolling method was initially implemented by conducting practical experiments.

The development of computer technology and the advancement of capabilities for modelling metal forming processes have served as the foundation for the development of theoretical research in this field. Over past periods, numerous research studies have been conducted by several scientists, and based on practical achievements, critical issues related to cross-helical rolling mills have been resolved.

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Furthermore, solutions have been identified for the design and calculation tasks involved in producing round periodic sections, ribbed and profile tubes, gears, thread forms, steel balls, and small cylindrical billets [1]. For these tasks, the technical and economic efficiency of the considered mills, as well as the directions for their development and implementation, are indicated.

For the production of steel balls using the rolling method, the calibration calculation for balls with a diameter of 125 mm is provided in article [2].

Article [3] uses a 3D model based on the pass surface equation to conduct a numerical simulation of the skew rolling process for 21.6 mm diameter aluminium balls, obtaining the resulting stress and strain distributions.

Using computer modelling, article [4] simulates the rolling of precisely weighted 93 and 125-mm-diameter steel balls and analyses the stress intensity, stress tensor components, and average normal stress at points along the rolling axis.

Article [5] by authors Pater Z. and Saanouni K. presents the results of a numerical analysis for the helical rolling process of a 25 mm diameter workholding bolt using multi-wedge tools.

In articles [6-9], the calculation of roll calibration for the hot rolling of grinding steel balls is presented. The calculations were performed using a method that generates continuous curved profiles by employing helical grooves with a variable lead. Mathematical models for the cam used to machine rolling mill rolls on screw-cutting lathes, as well as mathematical models capable of determining the variable lead at any arbitrary value of the roll's angle of rotation, have been developed. In this process, accounting for the roll's angle of rotation is certainly considered crucial. In addition, the fact that the screw calibres on the rolling rolls have a variable pitch is of great importance. Issues related to the influence of the variable pitch of the rolls on the rolling process and the quality of the manufactured product are discussed in papers [10-12].

Using a three-dimensional finite-element model, study [13] characterized the stress, strain, and deformation of the workpiece material during skew rolling. The analysis concentrated on a representative cross-section, paying special attention to the billet's centre, edge, and mid-radius points.

In the monograph [14], the author investigated the problem of modelling the kinematics and dynamics of a cam mechanism system used for cutting screw guides in steel ball rolling. Theoretical and practical solutions to this problem were established. Furthermore, mathematical models describing the phase angles of the cam motion were developed. The loads on the links of the cam mechanism were determined, taking into account the variable forces acting on the cam's pusher. The monograph also provides the groove design calculation for two-start screw-guide rolls used for rolling 70 mm diameter steel balls.

Theoretical and experimental results for rolling 30 mm grinding balls were obtained by Tomczak J. and other authors [15]. Numerical analysis of the process was performed using the finite element method in the Simufact Forming software. Articles [16-18] by authors Tomczak J., Pater Z., and other authors present the selected numerical and experimental results of a skew rolling process for producing steel balls using helical tools.

The formation of balls during the rolling process was examined from a geometric standpoint by Yang S-C. and Chen C-K. [19]. Their work proposes a simplified method for studying the formation of steel ball shape in the skew rolling process.

Agrawal P. and other authors analysed issues related to the rolling process [20]. This article briefly presents information on the achievements reached over many years and on problems related to rolling processes. Initially, detailed information is provided about rolling processes based on traditional and general techniques. In addition, an outline of various rolling techniques, such as thread rolling, incremental rolling, and shape rolling, as well as advanced techniques, including corrugated rolling, riblet rolling, and symmetric and asymmetric rolling, is presented and discussed in detail with their merits, demerits, and applications.

Article [21] by Nayzabekov A. and other co-authors presents a preliminary calculation of the calibration rolls for rolling balls with a diameter of 40 mm in a rolling mill, Joint Stock Company "Sokolov-Sarbai Mining Production Association", which are to be produced from round workpieces with a diameter of 40 mm.

As is known, the raw material for producing grinding steel balls via the rolling method is heat-treated in the rolling mill workshops [22-24]. Ball rolling mills consist of a mill housing, drive mechanisms, and special individual rolling units. The rolls are the main working components of a ball rolling mill and are part of these special individual units (Figure 1).

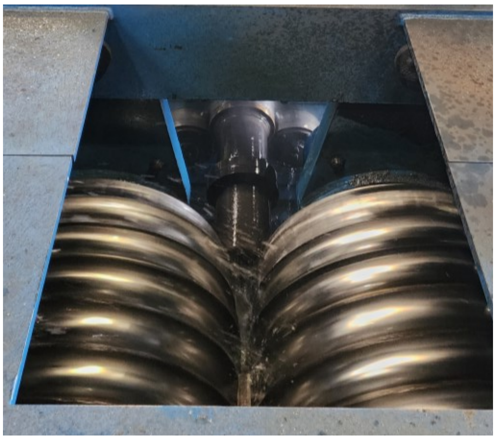

Figure 1: General view of ball rolling mill rolls

Ball rolling mill rolls perform a complex technological process involving the plastic deformation of a metal billet. During the metalworking process, the rotating rolls are subjected to significant pressure that arises from deforming the metal billet (Figure 2).

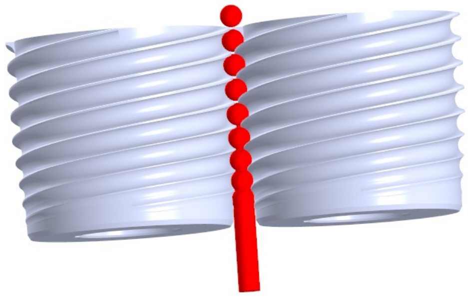

Figure 2: Ball rolling process

Rolls are bodies consisting of cylindrical and truncated conical parts with a diameter D_{roll} and a length L_{roll}, which are in direct contact with the metal billet during the rolling process. Their barrel has helical grooves with a displaced centre and a variable pitch.

In the manufacture of ball rolling rolls, screw calibres with variable pitch are produced using screw-cutting lathes equipped with special copying devices [25]. In this process, it is considered appropriate to use flat cams installed in the copying mechanism. One of the primary tasks in preparing these cams is to develop analytical expressions that determine their theoretical profiles and to create mathematical models describing the displacement of the cam centres.

The initial data required for developing the calibration are primarily based on the technical specifications of the rolling mill. Ball rolling rolls, manufactured according to precise dimensions, are installed in the mill's cassettes. To distinguish between the two rolls, they are referred to as the right roll and the left roll. The right and left rolls are cut according to different diameters and screw gauge profiles.

The general conclusions drawn from the scientific and practical studies on the hot rolling process presented in the articles analysed above indicate that, in addressing ball rolling problems, the theoretical aspects of using multi-start screw-calibrated rolls have not been fully considered. In order to examine the aspects that were not addressed in the analysed publications, the main objective of this article was defined as solving the problem of producing steel balls with a diameter of 40 mm using six-start screw-calibrated rolls. In this context, the 80–120 ball rolling mill was selected as the research object, which provides significant opportunities for increasing productivity in ball production when multi-start screw-calibrated rolls are employed.

2. Methods

It is known that the main working components of the ball rolling mill are the right and left rolls, as well as the top and bottom linear guides. The high-precision manufacture of these working components is one of the key factors in the ball rolling process.

This article presents the calibration calculations for the rolls used in rolling steel grinding balls with a diameter of 40 mm.

80–120 ball rolling mills were selected for conducting the experimental processes. These mills are primarily designed for rolling balls with diameters ranging from 80 mm to 120 mm. The key aspect of this research, representing its scientific novelty, is that the main objective was to roll smaller-diameter balls on a mill intended for large-diameter ball production. The ball rolling process is carried out by hot rolling of metallic billets heated to a temperature of 1000–1050 °C. In this process, the principal technical parameters of the ball rolling mill and the arrangement of the rolls within the mill are of critical importance (Figure 3).

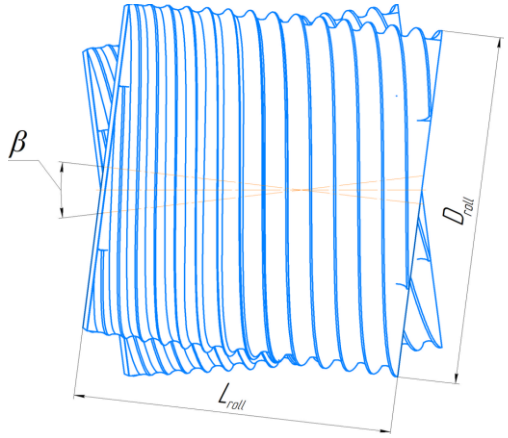

Figure 3: Arrangement of rolls in the ball rolling mill

The basic technical characteristics of the ball rolling mill are as follows: Nominal diameter of the rolls – 700 mm; Working part length of the rolls – 600 mm; Feed angle – 0° - 7°; Radial pressure of the metal on the roll – no more than 700 kN; Rolling torque per roll – no more than 25 kN·m; Rotational speed of the working rolls – 60 - 90 rpm.

The cutting of ball rolling rolls is performed on a screw-cutting lathe equipped with a special copying device designed for machining surfaces with screw grooves having a displaced center. In this process, the transmission ratio of the copying device is determined as follows [14]:

$$u_{c.d} = u_{w.g} \cdot u_{c.g} = 35 \cdot 1,643 = 57,5 \qquad (1)$$

where $u_{w.g}$ is the transmission ratio of the worm gear, and $u_{c.g}$ is the transmission ratio of the cylindrical gear.

When developing the calibration for six-start screw-calibre rolls, it is necessary to consider the standard dimensions of the grinding steel balls. GOST 7524–2015 is an interstate standard issued by the Interstate Council for Standardization, Metrology and Certification, which specifies the technical requirements for grinding steel balls [26]. In the production of grinding steel balls, it is necessary to ensure that the main characteristics and calculated parameters conform to the standard requirements. Table 1 presents the primary characteristics for grinding steel balls with a diameter of 40 mm.

Table 1. Ball size and limit deviations

Designated diameter, *mm*	Nominal diameter, *mm*	Deviation, *mm*
40	41,5	±2,0

Table 2 below presents the calculated parameters for grinding steel balls with a diameter of 40 mm.

Table 2. Calculated parameters of grinding balls

Designated diameter, *mm*	*Calculated nominal parameters*			
	Surface area, *cm²*	Volume, *cm³*	Mass, *kg*	Number of balls per tonne
40	54,0	37,4	0,294	3401

For rolling balls with a diameter of 40 mm, the diameter of the screw gauge is taken as $D_{calibre} = 42\,mm$ in accordance with the GOST 7524–2015.

When developing the calibration of six-start screw-calibre rolls for rolling balls with a diameter of 40 mm, the radius of the screw gauge is taken as $R_{calibre} = 21\,mm$, and the number of starts in the screw grooves is taken as $n = 6$.

Taking into account the thermal expansion coefficient of the metal, the initial diameter of the ball is determined as follows:

$$D_{b.d} = \frac{D_{calibre}}{\eta_\tau} = \frac{42}{1,013} = 41,461\,mm \qquad (2)$$

where $\eta_\tau = 1,013$ is the thermal expansion coefficient of the metal during rolling.

Considering the radial expansion coefficient of the ball volume, the initial diameter of the raw material is determined as follows:

$$D_{billet} = \frac{D_{b.d}}{\eta_0} = \frac{41,461}{1,03} = 40,2534\,mm \qquad (3)$$

where $\eta_0 = 1,03$ is the coefficient of radial growth of the ball dimensions during rolling.

To determine the lead of the screw-cutting lathe, the interchangeable gears are adjusted. The lathe is set up using the machine's specifications. In this case, the lead of the lathe used for cutting six-start screw-calibre rolling rolls is determined as follows [14]:

$$T_{lathe} = 2T_M \cdot \frac{z_2}{z_1} = 242,(42)\,mm/rev \qquad (4)$$

where $T_M = 80\,mm/rev$ is the metric lead of the screw-cutting lathe, and $z_1 = 66$, $z_2 = 100$ are the numbers of teeth of the lathe's interchangeable gears.

When determining the total length of the screw gauge, the screw thread is conventionally measured in degrees. The total length of the screw gauge on the ball rolling roll is determined as follows:

$$\varphi_{general} = \frac{\pi \cdot l_{lathe}}{T_{lathe}} = 1024°39' \qquad (5)$$

where $l_{lathe} = 690\,mm$ corresponds to the travel length of the cutting tool for one full rotation of the cam in the screw-cutting lathe device. This value is determined based on the lathe's parameters through the adjustments performed.

Taking into account the roll length and the radius of the screw gauge, the total calculated length of the screw gauge on the ball rolling roll is determined as follows:

$$\varphi_{total\,cal.} = \frac{\pi \cdot (L_{roll} + R_{calibre})}{T_{lathe}} = 922°11'6'' \qquad (6)$$

Based on expression (6), the working length of the screw gauge on the ball rolling roll was selected as $\varphi_w = 900°$.

The initial length of the working part of the ball rolling roll is determined as follows [14]:

$$L_w = \frac{\varphi_w}{\pi} \cdot T_{lathe} - R_{calibre} = 585,(06)\,mm \qquad (7)$$

Based on the parameters of the screw-cutting lathe, the initial length from the front of the ball rolling roll to the start of the screw thread is determined as follows:

$$L_{initial} = L_{roll} - L_w = 14,(93)\,mm \qquad (8)$$

where $L_{roll} = 600\,mm$ is the length of the ball rolling roll.

The primary step in cutting the rolls is determined by the sections of the screw gauges with displaced centres, based on the dimensions of the flanges.

The variation of the necks formed on the raw material is determined as follows:

$$R_n(\varphi) = R_{calibre} - H(\varphi) \tag{9}$$

where $H(\varphi)$ is the variation in the heights of the flanges on the rolls.

The width of the hemispheres of the screw gauge on the rolls is determined by the following expression:

$$C(\varphi) = \sqrt{R_{calibre}^2 - (R(\varphi))^2} \tag{10}$$

The main pitch $T_{main}(\varphi)$ for cutting screw gauges with displaced centres of the grooves is determined as follows:

$$T_{main}(\varphi) = 2 \cdot C(\varphi) + B(\varphi) \tag{11}$$

where $B(\varphi)$ is the variation in the thickness of the flanges on the ball rolling rolls?

To ensure the condition of constant volume, the volume of metal in any cross-section of the gauge is calculated using the following formula [1]:

$$V_{total} = V_\alpha + V_{C\alpha} + V_{S\alpha-360^\circ} + V_{\alpha-360^\circ} + V_{C\alpha-360^\circ} \tag{12}$$

where V_C is the volume of metal in the hemispherical part of the gauge, V_α is the volume of metal in the neck formed on the raw material, and V_S is the volume of metal corresponding to the cylindrical part of the rolling roll.

The total volume of the ball and the neck formed from the rolled raw material is calculated as follows:

$$V_{total} = \frac{4\pi R_{calibre}^3}{3} + \pi B_r \left(\frac{360^\circ}{n}\right) \cdot \left[R_{n.r}\left(\frac{360^\circ}{n}\right)\right]^2 \tag{13}$$

where B_r is the length of the neck formed on the raw material, and $R_{n.r}$ is the radius of the neck formed on the raw material.

It should be noted that the diameters of the right and left rolls are different, and for the case under consideration, their values are determined as follows:

$$D_{right} = 690\,mm, \quad D_{left} = 684,7\,mm \tag{14}$$

Thus, the calibration of the ball rolling rolls is determined using the analytical expressions presented above. Based on these analytical expressions, numerical calculations are performed, taking into account the main parameters of the ball rolling mill.

3. Results

Below, the most important and essential parameters required for manufacturing the rolls, calculated based on the main working components of the ball rolling mill, are presented in the form of graphs and tables.

Using the calculations presented above and the expression (12) for determining the total volume, the result $V_{total} = 38826,7\,mm^3$ is obtained.

Based on expressions (1)–(13) given in the article, the calculations were performed in MathCAD, and the program was used to generate the necessary graphs for developing the calibration of the six-start screw-calibre rolls (Figures 4–7).

Using expression (9), the graph showing the variation in the radii of the necks formed on the raw material during the rolling process relative to the right and left rolls is determined.

Figure 4 presents the variation graph of the radii of the necks formed on the workpiece during rolling. This figure indicates that, for rotation angle values in the range $0 \le \varphi_w \le 900^\circ$, the radii of the necks formed on the raw material vary between $19,7\,mm \ge r_n \ge 0$. During rolling, the billet is positioned between two rolls — the right and the left. The origin of the coordinate system corresponds to the moment when the billet is gripped by the rolls, at which the neck radius is 19,673 mm. As the rolls rotate through an angle of 390 degrees, linear reduction of the billet occurs, decreasing the neck radius to 4,352 mm. Considering the different diameters of the rolls, the neck radius relative to the left roll remains constant, whereas the neck radius relative to the right roll continues to decrease as the rolls rotate from 390 degrees to 525 degrees, reaching 1,7 mm. At this stage, the neck between the forming balls fractures and separates.

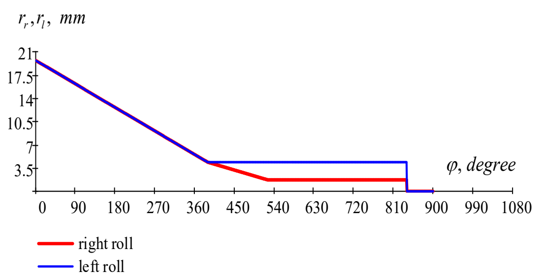

Figure 4: Graph of the variation of radius in the necks formed on the raw material.

Figure 5 shows the graph of the variation in the metal volume in the necks formed on the rolled raw material. This figure illustrates that for rotation angles of the screw gauge is in the range $0 \le \varphi_w \le 900^\circ$, the metal volume in the necks formed on the raw material varies within $4965\,mm^3 \ge V_\alpha \ge 0$.

Since the diameters of the right and left rolls are different, the metal volume in the necks formed on the raw material also takes on different values. Since the forming sections of the ball-rolling rolls are identical in their geometric parameters, the metal volume during the formation of the neck changes according to the pattern shown in Figure 4. When the rolls rotate through an angle of 390 degrees, the metal volume changes along a curved-line law, decreasing from 4965,7 mm^3 to 286,05 mm^3. The remaining angle of roll rotation within one cycle is 510 degrees, during which the formed neck will have different radii relative to each roll and, consequently, different volumes. Theoretically, the neck volume, relative to the roll with the smaller diameter, remains constant at 286,05 mm^3 during this period. Relative to the roll with the larger diameter, as the roll rotates to 525 degrees, the neck volume decreases from 286,05 mm^3 to 270,97 mm^3 and then remains constant. In practice, at this moment the neck between the forming balls fractures and separates.

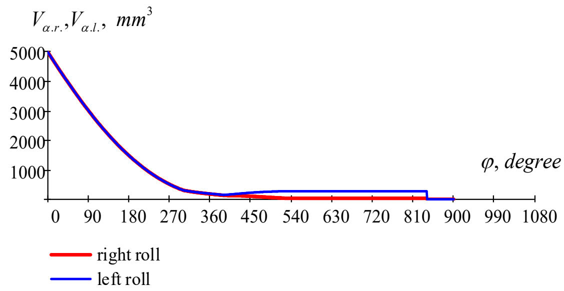

Figure 5: Graph of the variation in metal volume in the necks formed on the raw material.

Figure 6 shows the graph of the variation in metal volume in the hemispherical part of the screw gauge. From this figure, it can be seen that for rotation angles of the screw gauge in the range $0 \le \varphi_w \le 900°$, the metal volume in the hemispherical part of the screw gauge varies within $19395\,mm^3 \ge V_C \ge 0$. These values differ for the right and left rolls. On the forming sections of both ball-rolling rolls, the volume of metal in the hemispheres changes according to a curvilinear law, increasing from 9763,1 mm^3 to 19383 mm^3. These values are reached when the rolls rotate through an angle of 390 degrees, after which the final volume remains constant for the roll with the smaller diameter. For the ball-rolling roll with the larger diameter, the volume of metal in the hemispheres continues to increase from 19383 mm^3 to 19395 mm^3 until the rolls rotate through an angle of 480 degrees. Within these intervals, the cylindrical billet undergoes transformation into a spherical shape. The subsequent roll rotation, which completes the cycle, is intended for finishing the spherical product.

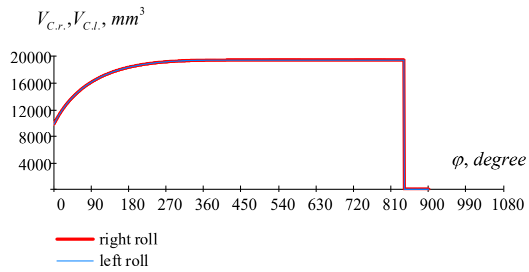

Figure 6: Graph of the variation in metal volume in the hemispherical part of the screw gauge

Figure 7 shows the graph of the variation in metal volume corresponding to the cylindrical part of the rolling roll. This figure presents the changes in metal volume in the cylindrical part of the roll for rotation angles of the screw gauge in the range $0 \le \varphi_w \le 900°$. From the graph, it can be seen that the volume variation $V_{S.r}$ for the right roll and $V_{S.l}$ for the left roll takes different values. At the beginning of the forming section of the roll, a cylindrical portion is used between the two hemispheres depending on the number of starts of the screw calibre, the total volume of which, combined with the volumes of both hemispheres, equals the volume of the finished ball. Given that the roll features six-start screw calibres, the formation of the cylindrical portion begins when the rolls have rotated 360°/6=60°. As shown in the graph, the volume of the cylindrical portion decreases from 10070 mm^3 to zero as the roll rotates from 60 degrees to 340 degrees, at which point the ball is fully formed.

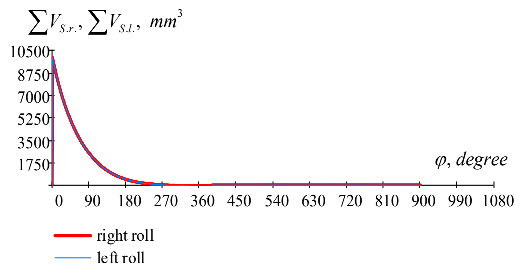

Figure 7: Graph of the variation in metal volume corresponding to the cylindrical part of the rolling roll

In the screw-cutting lathe, it is necessary to determine the control parameters for cutting six-start screw-calibre rolls with shifted groove centers. In this process, parameters such as the values of the variable pitch between the screw gauges, the widths of the cylindrical parts formed between the hemispheres of the gauges, the heights of the roll flanges, and the thicknesses of the roll flanges are identified.

For the problem considered in this study, the pitches of the screw gauges and the widths of their cylindrical parts were calculated, and the results are presented in tabular form (Table 3).

Table 3. Control parameters of the screw gauges

Screw rotation angle, degrees	Pitch of the screw gauges, mm	Width of the cylindrical part of the screw gauges, mm
60	45,7	0
120	91,4	0
180	137,0	0
240	183,0	0
300	228,3	0
360	274,0	0
420	319,0	0
480	363,0	0
540	405,3	0
600	445,8	0,07
660	484,9	0,3
720	521,8	1,1
780	555,8	2,9
840	586,2	7,3
900	612,3	-

The values of the heights and thicknesses of the helical wedges on the right and left rolls were determined based on the screw's rotation angle (Table 4).

Table 4. Control parameters of the helical wedges of the roll

Screw rotation angle, degrees	Right roll		Left roll	
	the height of the helical wedge, mm	the thicknes s of the helical wedge, mm	the height of the helical wedge, mm	the thickness of the helical wedge, mm
60	19,30	3,78	16,65	4,55
360	19,30	3,78	16,65	4,55
420	18,41	3,46	16,65	4,10
480	17,24	2,62	16,65	2,99
540	15,46	1,82	15,47	1,94
600	13,11	1,56	13,11	1,56
660	10,75	2,32	10,76	2,32
720	8,39	2,95	8,39	2,95
780	6,04	3,46	6,04	3,46
840	3,68	3,84	3,68	3,84
900	1,32	4,08	1,32	4,08

Based on the calculation results, the cutting of the ball rolling rolls was carried out on the screw-cutting lathe, and the six-start screw-calibre rolls were manufactured (Figure 8).

Figure 8: Six-start screw-calibre roll

Using the manufactured rolls, it became possible to produce 40 mm diameter grinding steel balls by the rolling method.

Steel grinding balls with a diameter of 40 mm were produced on the ball rolling mill using six-start helical-calibre rolls (Figure 9).

Figure 9: Grinding steel balls

The produced 40 mm diameter steel grinding balls were analyzed and tested under laboratory conditions. The inspection results confirmed that the balls complied with the GOST 7524–2015 [26].

4. Discussions

The process of rolling steel balls using six-start screw-calibrated rolls is a highly complex process. Developing a model for this technological process and carrying out the calibration calculations for the rolls is essential. The most important aspect of the problem presented in this article is that the issue of increasing productivity through the production of small-diameter balls using a mill designed for rolling large-diameter balls has been solved. This, in turn, distinguishes it from other scientific studies on rolling balls using rolls with a small number of screws starts due to its inherent complexity [6-9].

In paper [27], the author presents an innovative process for the screw rolling of balls. This process employs spiral rolls, the design of which makes it possible to form spherical balls from a cylindrical bar by hot rolling. As is well known, when a billet acquires a spherical shape between ball-rolling rolls, it simultaneously undergoes rotational and translational motion. During the rotational motion of non-cylindrical billets, additional forces arise, which can lead to damage to the ball-rolling rolls and the linear guides. Taking this into account, in the present study a round billet with diameter D_{billet}, produced by the conventional method on a section rolling mill, was adopted as the initial workpiece.

Based on the numerical results and experimental findings presented in this article, and taking into account the main parameters of the ball rolling rolls, the design possibilities for the working part structures of the linear guides that direct the raw material were developed.

5. Conclusions

In conclusion, it should be noted that the mining and metallurgical industry holds strategic importance for the economy and serves as a foundation for the development of many sectors. The production of grinding steel balls is an essential part of advancing the mining-metallurgical industry. In this article, the calibration calculations for rolls used to produce 40 mm diameter grinding steel balls by the rolling method were developed. Based on the results of these calibration calculations, the rolls were manufactured, making it possible to produce 40 mm diameter grinding steel balls.

Based on the results of the theoretical and experimental studies conducted, the following general conclusions were drawn:

- in accordance with GOST 7524–2015, a calibration technology for six-start screw-calibrated rolls with displaced groove centres was developed for rolling steel balls with a diameter of 40 mm;
- in order to determine the design and technological dimensions of the ball rolling rolls, mathematical expressions describing their geometric parameters were developed, and based on these expressions, the design of six-start screw-calibrated rolls intended for rolling 40 mm diameter steel balls on the 80–120 ball rolling mill was prepared;
- the hot rolling method using six-start screw-calibrated rolls was implemented in industrial production at the Ball Rolling Division of Joint Stock Company “Uzmetkombinat”, and as a result of applying this technology, the productivity of manufacturing steel balls with a diameter of 40 mm increased by 15–20%.

References

[1] Tselikov A.I., Barbarich M.V., Vasilchikov M.V., Granovskiy S.P. & Zhukevich-Stosha E.A. (1971). Special rolling mills. *Moscow: Metallurgy*. (p. 336). (In Russ.).

[2] Peretyat’ko V.N., Klimov A.S. & Filippova M.V. (2013). Roll pass design of a ball-rolling mill. Part 2. *Izvestiya. Ferrous Metallurgy*. 2013;56(6): (pp. 16-20). (In Russ.) https://doi.org/10.17073/0368-0797-2013-6-16-20

[3] Shi Xiao-min & Wang Bao-yu (2012) Numerical simulation of Al ball forming process in skew rolling. *Materials Science Forum* (pp. 151-154). https://doi.org/10.4028/www.scientific.net/MSF.704-705.151

[4] Filippova M.V., Temlyantsev M.V., Peretyat’ko V.N. & Prudkii E.E. (2017). Mathematical modeling of balls rolling. *Izvestiya. Ferrous Metallurgy*. 2017;60(7): (pp. 516-521). (In Russ.) https://doi.org/10.17073/0368-0797-2017-7-516-521

[5] Pater Z. & Saanouni K. (2016). "FEM Analysis of the Multi-Wedge Helical Rolling Process for a Workholding Bolt", *MATEC Web of Conferences*, Vol. 80, (p. 13001). https://doi.org/10.1051/matecconf/20168013001

[6] Shakhobutdinov R.E. (2021). Calibration of ball rolls with two-way screw calibres with an offset centre of grooves for rolling steel balls with a diameter of 70 mm according to GOST 7524-2015. Message 1. *Theoretical and practical journal «KB» (Roll Pass Design Bureau).* ISSN 2308-6440. Issue 18. Publication date: 30/06/2021. (pp. 25-29). (In Russ.)

[7] Shakhobutdinov R.E., Begimov N.N., & Khodjibekov T.D. (2021). Calibration of ball-rolling rolls with two-way screw calibres with an offset centre of streams for rolling steel grinding balls with a diameter of 70 mm according to GOST 7524-2015. Message 2. *Theoretical and practical journal «KB» (Roll Pass Design Bureau).* ISSN 2308-6440. Issue 19. Publication date: 30/12/2021. (pp. 16-21). (In Russ.)

[8] Shakhobutdinov R.E., Khodjibekov T.D., Nosirov T.N., & Khurramov D.Kh. (2022). Features of calibration of ball-rolling rolls with super-entry screw calibres. Message 1. *Theoretical and practical journal «KB» (Roll Pass Design Bureau).* ISSN 2308-6440. Issue 19. Publication date: 30/06/2022. (pp. 23-26). (In Russ.)

[9] Shakhobutdinov R.E., Khodjibekov T.D., Nosirov T.N., & Khurramov D.Kh. (2022). Features of calibration of ball-rolling rolls with super-entry screw calibres. Message 2. *Theoretical and practical journal «KB» (Roll Pass Design Bureau).* ISSN 2308-6440. Issue 21. Publication date: 30/12/2022. (pp. 19-23). (In Russ.)

[10] Shu Ch., Wang J. Shu X. & Tian D. (2019). Influencing Factors of Void Closure in Skew-Rolled Steel Balls Based on the Floating-Pressure Method. *Journals Materials. Vol.* 12, *Issue* 9. 1391. https://doi.org/10.3390/ma12091391

[11] Rubcov V.Ju., Shevchenko O.I., Spirina A.S. & Pankova N.A. (2020). Research into in-service deterioration of ball-rolling rolls. *IOP Conference Series: Materials Science and Engineering* 966 (1): 012069, (p. 6). https://iopscience.iop.org/article/10.1088/1757-899X/966/1/012069

[12] Shi X., Wang B. & Li Z. (2010). Optimization of Pass Parameters on Two-Grooves Skew Rolling for Al ball. *Key Engineering Materials*. 419-420: (pp. 313–316). https://doi.org/10.4028/www.scientific.net/KEM.419-420.313

[13] Haibo Yang, Lijie Zhang & Zhenghaun Hu. (2012). The Analysis of the Stress and Strain in Skew Rolling. *Advanced Materials Research (Volumes 538-541)*. (pp. 1650-1653) https://doi.org/10.4028/www.scientific.net/AMR.538-541.1650

[14] Shakhobutdinov R.E. (2024). Theoretical and applied fundamentals of cam mechanisms used in ball rolling production. *Monography. Tashkent*, (p. 152). (In Russ.)

[15] Tomczak J., Pater Z. & Bartnicki J. (2013). Skrew Rolling of Balls in Multiple Helical Impressions. *Archives of Metallurgy and Materials*, 58(4). (pp. 1071-1076). https://www.researchgate.net/publication/275992088

[16] Tomczak J., Pater Z. & Bulzak T. (2018). The Effect of Process Parameters in Helical Rolling of Balls on the Quality of Products and the Forming Process. *Journal of Materials* 2018, *Vol*. 11, *Issue* 11, 2125. (p. 15). https://doi.org/10.3390/ma11112125

[17] Pater Z., Tomczak J., Bartnicki J., Lovell R.M. & Menezes P.L. (2013). Experimental and numerical analysis of helical-wedge rolling process for producing steel balls. *International Journal of Machine Tools and Manufacture*. *Vol.* 67, (pp. 1-7). https://doi.org/10.1016/j.ijmachtools.2012.12.006

[18] Tomczak J., Pater Z. & Bulzak T. (2014). Designing of screw impressions in the helical rolling of balls. *Archives of Civil and Mechanical Engineering. Vol.* 14. *Issue* 1. (pp. 104-114). https://doi.org/10.1016/j.acme.2013.07.004

[19] Yang S-C. & Chen C-K. (2001). The surface geometry of rollers with skew rolling of steel balls. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*. 2001;215(5):523-532. https://doi.org/10.1243/0954406011520922

[20] Agrawal P., Aggarwal S., Banthia N. Suraj Singh U., Kalia A. & Pesin A. (2022). A comprehensive review on incremental deformation in rolling processes. *Journal of Engineering and Applied Science*. 69, 20. https://doi.org/10.1186/s44147-022-00072-w

[21] Naizabekov A., Lezhnev S., Stepanov E., & Panin E. (2018). The development of calibration for the rolling balls of diameter 40 mm in conditions of JSC "SSGPO". *International scientific Journal "Machines. Technologies. Materials." Vol. 12, Issue 1, (pp. 16-18)* https://stumejournals.com/journals/mtm/2018/1/16

[22] Liu W., Wang B. & Zhou J. (2025). Investigation on deformation characteristics of warm helical rolling process of steel balls and influence of rolling parameters on forming process. International scientific Journal "Materials Today Communications" *Vol*. 49, (p. 113888) https://www.sciencedirect.com/science/article/abs/pii/S2352492825024006

[23] Baidin V.V. & Umanskii A.A. (2025). Modelling and development of technological modes for production of grinding balls of increased hardness and impact resistance. International scientific Journal *"Izvestiya Ferrous Metallurgy" Vol.* 68, *Issue* 3. (pp. 218-227) https://doi.org/10.17073/0368-0797-2025-3-218-227

[24] Rubcov V.J. & Shevchenko O.I. (2020). Development of new roll pass designs for ball-rolling rolls with continuously variable parameters. *IOP Conference Series: Materials Science and Engineering* 966 (1), 012070, (p. 6). https://iopscience.iop.org/article/10.1088/1757-899X/966/1/012070

[25] Khasanov, S., Mardonov, U., Ongboyev, A., & Ismatov, M. M. (2024). Influence of a magnetic field on HSS tool wear/life and the intensity of external machining environments in turning. *International Journal of Mechatronics and Applied Mechanics*, (16), 163-170. https://doi.org/10.17683/ijomam/issue16.19

[26] GOST 7524-2015. Milling steel balls for ball mills. Specifications, (2016). Moscow: *Standartinform* (p. 20). (In Russ.)

[27] Pater Z. (2016). Analysis of Helical Rolling Progress of Balls Formed from a Head of a Scrapped Rail. *Research Journal, "Advances in Science and Technology", Volume 10, No. 30,* (pp. 110-114).