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Modeling and development of technological modes for production of grinding balls of increased hardness and impact resistance

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Abstract. In order to substantiate the possibility of producing grinding balls of the 5th hardness group and to stabilize the production of balls of the 4th hardness group in an operating ball rolling mill, a series of theoretical and experimental studies were conducted. Based on the results of computer modeling of the production process of grinding balls with a diameter of 60 mm, the authors determined the patterns of formation of the metal stress state during cross-screw rolling of balls made of standard steel Sh2.3 and experimental economically alloyed steel Sh76KhF. A decrease in the temperature of billet discharge from the heating furnace within the permissible range of its change according to current technology (880 – 1000 °C) leads to a significant increase in stress intensity over the entire surface of the balls during rolling, which increases the load on the equipment of the rolling stand and wear of the roller calibers. Additionally, the simulation shows that after the end of rolling, there is a significant (up to 80 °C) temperature unevenness on the balls surface, which, however, is almost completely eliminated after the balls are cooled on the conveyor before quenching. In the case of rolling balls from the billets with a discharge temperature from a heating furnace of less than 980 °C, the balls surface temperature before quenching is lower relative to the recommended range, ensuring the production of products with specified properties, which is confirmed by metallographic and durometric studies. Based on the results of the conducted research, a new mode of grinding balls production was developed with the temperature of billet discharge from the heating furnace increased to 980 – 1030 °C. Pilot testing of the new rolling mode showed that its use guarantees producing grinding balls of the 4th hardness group according to GOST 7524 – 2015 in their production from standard steel Sh2.3 and producing balls of the 5th hardness group using the developed economically alloyed steel grade Sh76KhF. At the same time, balls made of both steel grades under consideration have increased impact resistance.

Keywords: grinding balls, cross-screw rolling, mathematical modeling, microstructure, hardness, impact resistance, chemical composition of steel

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Моделирование и разработка технологических режимов производства мелющих шаров повышенной твердости и ударной стойкости

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Аннотация. С целью обоснования возможности производства мелющих шаров 5-ой группы твердости и стабилизации производства шаров 4-ой группы твердости в условиях действующего шаропрокатного стана проведена серия теоретических и экспериментальных исследований. На основании результатов компьютерного моделирования процесса производства мелющих шаров диаметром 60 мм определены закономерности формирования напряженного состояния металла в процессе поперечно-винтовой прокатки шаров из стандартной стали Ш2.3 и экспериментальной экономнолегированной стали Ш76ХФ. Снижение температуры выдачи заготовок из нагревательной печи в рамках допустимого интервала ее изменения согласно действующей технологии (880 – 1000 °C) приводит к значительному увеличению интенсивности напряжений по всей поверхности шаров при их прокатке, что повышает нагрузки на оборудование прокатной клети и увеличивает износ калибров валков. Дополнительно проведенное моделирование показывает, что после окончания прокатки имеет место значительная (до 80 °C) неравномерность температур по поверхности шаров, которая, однако, практически полностью устраняется после подстуживания шаров на конвейере перед закалкой. В случае прокатки шаров из заготовок с температурой их выдачи из нагревательной печи менее 980 °С температура поверхности шаров перед закалкой является пониженной относительно рекомендуемого интервала, обеспечивающего получение продукции с заданными свойствами, что подтверждено металлографическими и дюрометрическими исследованиями. На основании результатов проведенных исследований разработан новый режим производства мелющих шаров с повышенной до 980 – 1030 °С температурой выдачи заготовок из нагревательной печи. Опытно-промышленное опробование нового режима прокатки показало, что его применение гарантированно обеспечивает получение мелющих шаров 4-ой группы твердости по ГОСТ 7524 – 2015 при их производстве из стандартной стали Ш2.3 и получение шаров 5-ой группы твердости при использовании разработанной экономнолегированной стали марки Ш76ХФ. При этом шары из стали обеих рассматриваемых марок обладают повышенной ударной стойкостью.

Ключевые слова: мелющие шары, поперечно-винтовая прокатка, математическое моделирование, микроструктура, твердость, ударная стойкость, химический состав стали

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Introduction

In recent years, domestic ball rolling production has seen a transition from manufacturing grinding balls from rejected billets of steels intended for various applications to the use of specialized ball steels. This shift is due to a significant increase in consumer requirements for the quality parameters of grinding balls, namely, hardness, wear resistance, and impact resistance. These changes in requirements have been reflected in the main regulatory document governing the production of this type of product. Compared to its previous version (GOST 7524–89), GOST 7524–2015 provides for the production of balls with high surface hardness and specified bulk (5th hardness group), and also expands the range of balls produced under the 4th hardness group (balls with high surface hardness and standardized hardness at a depth of 0.5 of the ball radius) (Table 1).

In addition, GOST 7524–2015 introduced, for the first time, the possibility of supplying grinding balls of the 4th and 5th hardness groups with controlled impact resistance.

A review of the literature shows a significant number of studies aimed at improving the chemical composition of grinding balls to enhance their performance characteristics. However, recommendations regarding both the list and concentration of alloying elements, as well as the carbon content in the steel, vary significantly. For example, the authors of study [1] developed a chromium–molybdenum steel of a provisional grade ShKhM with a carbon content of 0.69 %, chromium content of 0.56 %, and molybdenum content of 0.26 %. In [2], the feasibility of producing grinding balls of the 5th hardness group from an experimental medium-carbon steel alloyed with manganese (0.90 – 1.01 %) and chromium (up to 0.34 – 0.41 %) was substantiated. Researchers in [3] proposed two variants of hypereutectoid complex-alloyed steels for ball production. These steels have a carbon content of 0.9 – 1.2 % and are simultaneously alloyed with manganese (0.8 – 1.5 %), chromium (1.0 – 1.7 %), vanadium (0.15 – 0.25 %), and molybdenum (0.2 – 0.4 %) or nickel (0.4 – 0.6 %).

It should be noted that meeting the increased quality requirements for grinding balls requires not only the use of steels with an optimal chemical composition but also the improvement of rolling and heat treatment modes.

When determining the optimal temperature modes for rolling grinding balls, it is important to consider that

Table 1. **Analysis of changes in hardness requirements for grinding balls**

Таблица 1. **Анализ изменения требований к твердости мелющих шаров**

Ball diameter, mm	Minimum hardness by group, HRC						
	1	2	3	4		5	
	surface				at a depth of 0.5 radius	surface	bulk
GOST 7524–2015 requirements							
15 – 45	45	49	55	55	45	61	57
50 – 70	43	48	53	53	43	60	53
80 – 100	39	42	52	52	40	58	48
110 – 120	35	38	50	50	35	56	43
GOST 7524–89 requirements							
15 – 70	43	49	55	55	45	–	–
80 – 100	40	42	52	–	–	–	–
110 – 120	35	38	50	–	–	–	–

excessive increases in rolling temperature may adversely affect the internal structure of the balls, leading to the formation of porosity and internal cavities in the axial zone [4]. Conversely, reducing the rolling temperature inevitably increases the load on the equipment of the rolling stand due to the higher resistance of steel to plastic deformation. This effect has been observed across a wide range of steel grades, including stainless steels [5; 6], high-carbon steels [7; 8], steels for automotive and shipbuilding applications [9; 10], and ultra-high-strength steels [11]. In addition, changes in the rolling temperature mode can influence the subsequent quenching process, which, at the vast majority of modern ball rolling mills, is performed directly from rolling heat.

The heat treatment modes for grinding balls used at modern ball rolling facilities vary significantly in both their process design and the specific temperature–time parameters of the main stages. For example, at the ball rolling mill of JSC EVRAZ Nizhny Tagil Metallurgical Plant (EVRAZ NTMK), commissioned in 2017, a single-stage quenching mode has been successfully applied for producing balls of the 5th hardness group [12], whereas the new ball rolling mills at PJSC Severstal, commissioned in 2014 and 2017, employ a more complex mode involving interrupted quenching [13]. Both self-tempering in special containers (bunkers) and low-temperature tempering performed by heating and holding at a set temperature in dedicated heat treatment furnaces are used. According to various researchers [14 – 16], the recommended temperature for self-tempering ranges from 60 to 210 °C, with a process duration ranges from 12 to 24 h. Similarly, significant variations in recommended parameters are also observed for low-temperature tempering in dedicated furnaces. The optimal tempering temperature range lies between 160 and 300 °C, with a holding time of 2 to 10 h [17 – 19]. Some authors support the applicability of a non-standard mode known as *Quenching and Partitioning* (Q&P) [20] for grinding ball production. This mode was originally developed [21] and later validated by international researchers for the heat treatment of various steel grades [22 – 24]. Other foreign researchers [25; 26] have proposed recommendations for improving grinding ball heat treatment within standard technological frameworks. A number of studies have also reported on the potential effectiveness of using thermal cycling technology for grinding ball production [3; 27], which involves repeated quenching and tempering cycles.

Overall, there are substantial differences in approaches to optimizing the chemical composition as well as the rolling and heat treatment modes of grinding balls. Consequently, the recommendations proposed by individual researchers cannot be directly applied to improve production modes at a specific ball rolling mill without appropriate adaptation. This, in turn, necessitates additional research.

The objective of this study is to substantiate optimal production modes for grinding balls of the 5th hardness group in accordance with GOST 7524–2015, using economically alloyed steel under the conditions of an operating ball rolling mill. At present, this facility produces grinding balls of the 2nd, 3rd, and 4th hardness groups only.

Methodology and initial research conditions

The study was conducted under the conditions of the 40–100 ball rolling mill and consisted of two stages. At the first stage, mathematical modeling of the rolling and cooling processes of grinding balls prior to quenching was performed using the DEFORM software package. It is worth noting that in recent years, standard applied software packages such as DEFORM have been widely used by researchers as effective tools for optimizing rolling and heat treatment modes. Both domestic [28; 29] and international [30 – 32] studies have focused on modeling the stress–strain state of the metal during the rolling of balls using various roller caliber configurations, as well as simulating temperature field distribution during the thermomechanical processing of grinding balls [13; 33].

The second stage involved metallographic and durometric studies of full-profile ball samples (grinding balls cut into two equal halves) after quenching. An OLYMPUS GX-71 optical microscope was used for metallographic studies, and a TK-2M hardness tester was used for durometric studies.

The product range of the rolling mill under study includes grinding balls with diameters from 40 to 100 mm, produced from standard steel grades depending on ball diameter and hardness group (Table 2).

The production technology for grinding balls includes billet heating, rolling, cooling of the balls on a conveyor, followed by quenching in a screw drum and self-tempering in bunkers. The following key process parameters are regulated and actually controlled in the production flow: the temperature in the reheating furnace and the heating duration of the billets, the discharge temperature of the billets from the furnace, the duration of cooling of the rolled balls on the conveyor before quenching, the ball temperature before quenching, the cooling duration in the quenching device, and the temperature and duration of ball self-tempering.

As part of the present study, the production of grinding balls with a diameter of 60 mm was examined. The permissible ranges of technological parameters for this diameter do not depend on the steel grade. The main technological parameters for the production of 60 mm grinding balls are as follows:

Table 2. **Chemical composition of standard steels for production of grinding balls with a diameter of 60 mm**

Таблица 2. **Химический состав стандартных сталей для производства мелющих шаров диаметром 60 мм**

Steel grade	Hardness group	Ball diameter, mm	Chemical element content, wt. %							
			C	Mn	Si	Cr	Cu	Ni	S	P
							max			
Sh2.1	2, 3	40 – 60	0.60 – 0.69	0.60 – 0.70	0.20 – 0.30	–	–	–	0.025	0.03
Sh2.2	2, 3	70 – 100	0.70 – 0.80	0.60 – 0.70	0.20 – 0.30	–	–	–	0.015	0.02
Sh2.3	4	40 – 60	0.65 – 0.75	0.70 – 0.80	0.20 – 0.35	0.30 – 0.40	0.3	0.3	0.020	0.03
Sh2.4	4	70	0.65 – 0.75	0.70 – 0.80	0.20 – 0.35	0.35 – 0.45	0.3	0.3	0.020	0.03
Sh2L	4	80 – 100	0.65 – 0.75	0.70 – 0.80	0.20 – 0.35	0.50 – 0.60	0.3	0.3	0.015	0.02

Parameter	Value
Discharge temperature of billets from the furnace	880 – 1000 °C
Duration of ball cooling on the conveyor	95 – 100 s
Ball temperature before quenching	830 ± 30 °C
Time in the quenching screw drum	45 – 55 s
Ball self-tempering temperature, not less than	180 °C
Ball self-tempering duration, not less than	12 h

The choice of the research subject was determined by the highest rejection rate observed for grinding balls of this specific diameter and hardness group, along with their significant share in the overall product range.

In addition, sumulation was carried out for the production of 60 mm grinding balls made from a provisional steel grade Sh76KhF (steel grade 76KhF in accordance with GOST R 51685–2013, with a narrowed permissible range of chemical element variation) (Table 3). The selection of this steel grade is supported by the results of previous studies [34], which demonstrated the feasibility of producing grinding balls with high hardness and potentially high impact resistance using this material.

Results and discussion

The modeling results for the production of grinding balls from Sh2.3 steel, presented as the distribution of stress intensity across generalized surface zones, reveal a pronounced non-uniformity in stress levels (Fig. 1).

The highest stress intensity consistently occurs in the zones where the collar engages with the initial billet, reaching substantial values in these areas. Although the overall stress distribution patterns on the surface of grinding balls remain similar across different rolling temperature modes, it is important to note that reducing the discharge temperature of billets from the heating furnace to the lower limit of the permissible range (880 °C) leads to a significant increase in stress intensity compared to rolling at the upper limit (1000 °C). For instance, the peak stress at specific points of contact between the metal and the rolls reaches 400 MPa at a deformation temperature of 880 °C, whereas at 1000 °C, the corresponding local stresses do not exceed 325 MPa.

A similar pattern is observed for localized stress values in other surface zones of the balls, as well as for average stress values across generalized surface areas of the rolled balls. This, in turn, leads to a significant increase in rolling force (Fig. 2), causes accelerated wear of the rolls, and notably raises the risk of defect formation in the balls.

When rolling grinding balls from Sh76KhF steel, the surface stress patterns are similar to those described above for Sh2.3 steel (Fig. 1). At the same time, stress intensities – particularly in the local zones where the collar penetrates the billet – slightly exceed the corresponding values observed during rolling of balls made from Sh2.3 steel. This results in a corresponding difference in rolling force when producing balls from these two steel grades (Fig. 3).

Table 3. **Chemical composition of experimental economically alloyed steel**

Таблица 3. **Химический состав экспериментальной экономнолегированной стали**

Steel grade	Chemical element content, wt. %						
	C	Mn	Si	Cr	V	S	P
						max	
Sh76KhF	0.74 – 0.76	0.80 – 0.90	0.35 – 0.45	0.40 – 0.50	0.03 – 0.05	0.015	0.015
76KhF (as per GOST R 51685–2013)	0.71 – 0.82	0.75 – 1.25	0.25 – 0.60	0.20 – 0.80	0.03 – 0.15	0.020	0.020

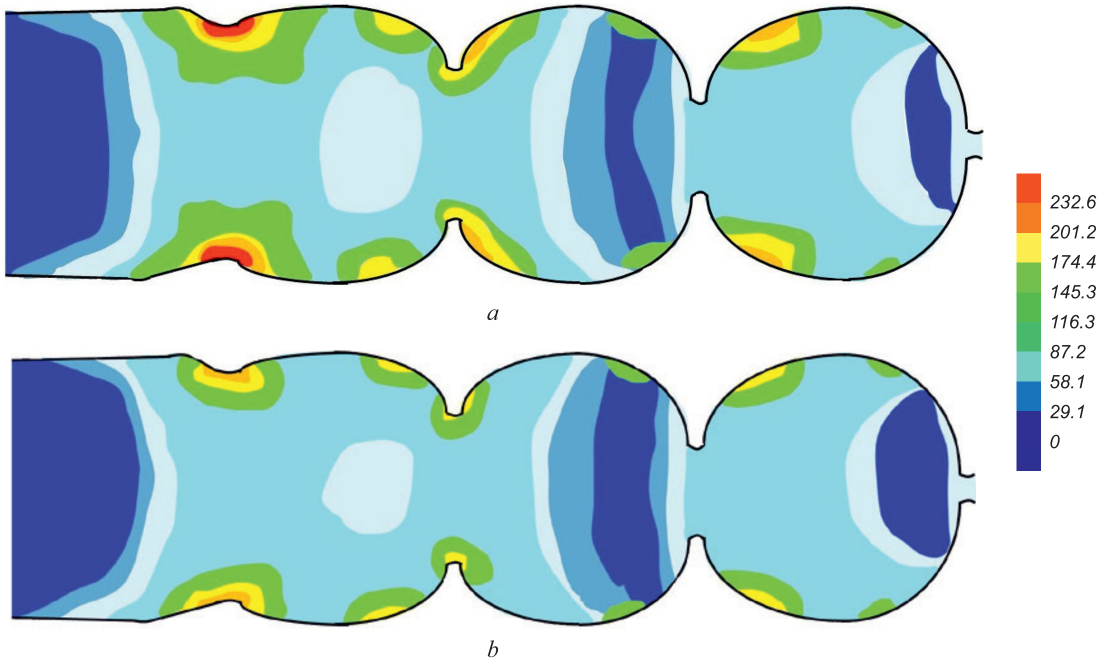

Fig. 1. Stress intensity distribution over the surface of grinding balls at their rolling temperatures of 880 (*a*) and 1000 °C (*b*)

Рис. 1. Распределение интенсивности напряжений по поверхности мелющих шаров при температуре их прокатки 880 (*a*) и 1000 °C (*b*)

Overall, the above data indicate that the current rolling temperature mode for grinding balls is suboptimal for both the production of 4th hardness group balls from standard steel and the production of 5th hardness group balls from Sh76KhF steel. It is therefore advisable to consider increasing the rolling temperature as a direction for process optimization.

As previously noted, the grinding ball production process at the rolling mill under consideration involves quenching directly from rolling heat, following intermediate cooling on a moving conveyor. Therefore, any changes to the rolling temperature mode must be considered comprehensively, taking into account their impact on subsequent heat treatment and on the overall performance of the rolling mill as a unified technological system.

To substantiate the feasibility of adjusting the rolling temperature, a simulation was carried out to model the surface temperature of the balls after rolling and prior to quenching, within the permissible ranges of rolling temperature and pre-cooling duration.

The modeling results (Table 4) show that the surface temperature of the balls drops by an average of 70 °C after rolling. At the same time, significant surface temperature unevenness of up to 50 °C is observed, regardless of the billet heating temperature. This variation is

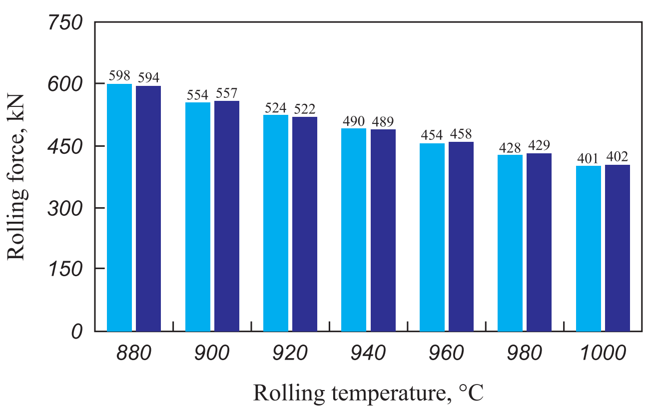

Fig. 2. Influence of the rolling temperature of grinding balls made of Sh2.3 steel on rolling force:
■ and ■ – fact and calculation

Рис. 2. Влияние температуры прокатки мелющих шаров из стали Ш2.3 на усилие прокатки:
■ и ■ – факт и расчет

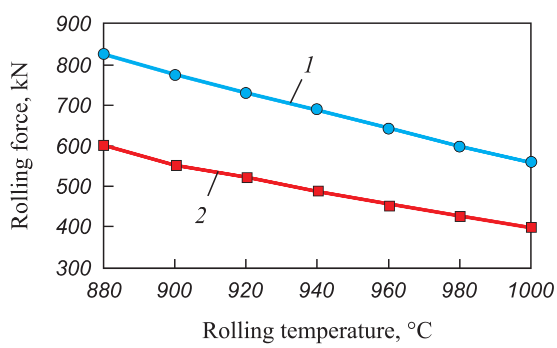

Fig. 3. Calculated values of rolling force of grinding balls made of various steels depending on rolling temperature:
1 – Sh76KhF; *2* – Sh2.3

Рис. 3. Расчетные значения усилия прокатки мелющих шаров из различных сталей в зависимости от температуры прокатки:
1 – Ш76ХФ; *2* – Ш2.3

mainly attributed to localized zones of elevated temperature at points of intense deformation – specifically where the collar penetrates the billet during rolling.

The modeling data show that after conveyor cooling, the surface temperature of the balls becomes almost uniform, regardless of the rolling temperature and cooling duration (Table 4). It is worth noting that at the minimum permissible rolling temperature, the surface temperature of the balls before quenching approaches the A_{C3} point for standard steel grade Sh2.3. In practice, quenching from this temperature does not ensure the formation of a homogeneous martensitic structure, nor does it provide the required levels of hardness and impact resistance. This has been confirmed by metallographic studies of grinding balls made from Sh2.3 steel currently in production, rolled at the lower end of the allowable temperature range. The microstructure of these balls after quenching reveals ferrite alongside martensite (Fig. 4), while both the surface hardness and the hardness at a depth of half the ball radius fall below the specifications for the 4th hardness group and correspond instead to the 2nd hardness group as per GOST 7524–2015 (Table 5).

Table 4. **Results of modeling the dynamics of temperature changes of grinding balls with a diameter of 60 mm during their rolling and cooling**

Таблица 4. **Результаты моделирования динамики изменения температуры мелющих шаров диаметром 60 мм при их прокатке и охлаждении**

Billet discharge temperature, °C	Ball surface temperature after rolling, °C		Cooling time, s	Ball surface temperature before quenching, °C		Required ball temperature before quenching / A_{C3} temperature, °C
	min	max		min	max	
880	792	833	95	758	774	800 – 860 / 760
1000	898	951	100	853	862	

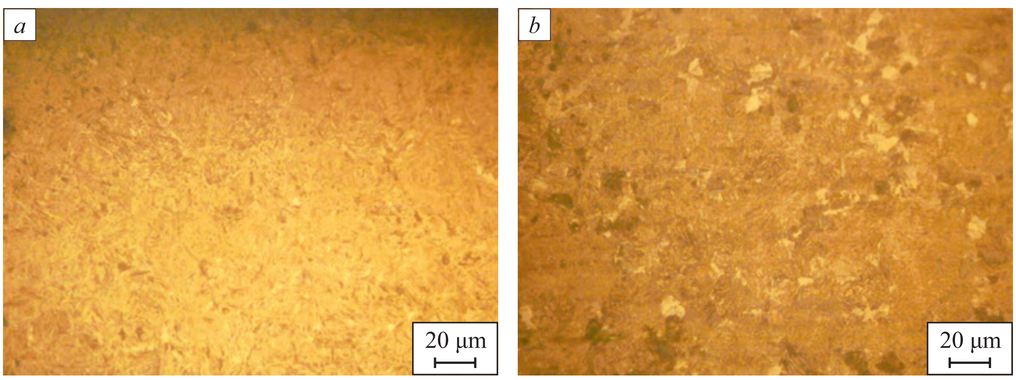

Fig. 4. Characteristic microstructure of grinding balls made of Sh2.3 steel on the surface (*a*) and at a depth of 1/2 of the ball radius at rolling temperature of 880 °C (*b*)

Рис. 4. Характерная микроструктура мелющих шаров из стали Ш2.3 на поверхности (*а*) и на глубине 1/2 радиуса шара при температуре прокатки 880 °C (*b*)

Table 5. **Quality indicators of grinding balls with a diameter of 60 mm made of Sh2.3 steel with varying rolling temperatures**

Таблица 5. **Показатели качества мелющих шаров диаметром 60 мм из стали Ш2.3 при варьировании температуры их прокатки**

Billet discharge temperature, °C	Typical microstructure of balls		Hardness of balls, HRC	
	surface	at 1/2 radius depth	surface	at 1/2 radius depth
880	martensite	martensite + troostite + ferrite	48 – 50	35 – 42
1000	martensite	martensite	54 – 56	47 – 49
2nd hardness group according to GOST 7524–2015			≥48	–
3rd hardness group according to GOST 7524–2015			≥53	–
4th hardness group according to GOST 7524–2015			≥53	≥43

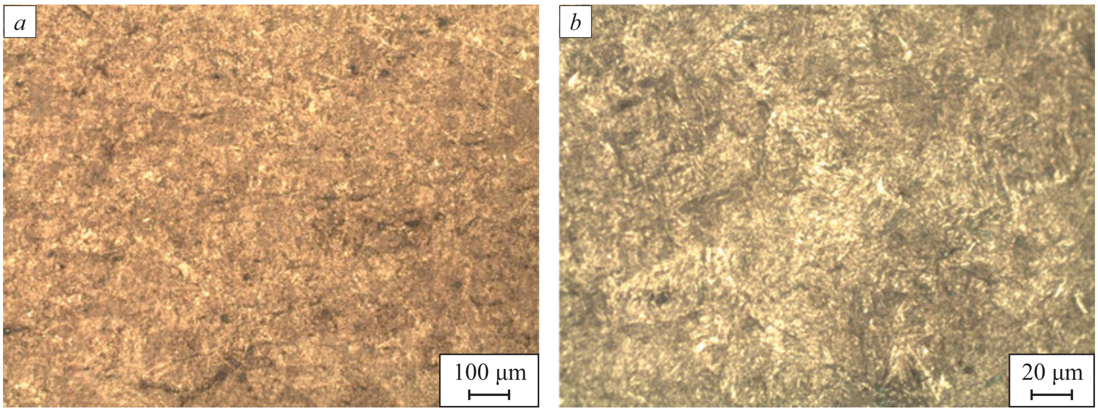

Fig. 5. Characteristic microstructure of grinding balls made of Sh2.3 steel on the surface (*a*) and at a depth of 1/2 of the ball radius at a rolling temperature of 1000 °C (*b*)

Рис. 5. Характерная микроструктура мелющих шаров из стали Ш2.3 на поверхности (*a*) и на глубине 1/2 радиуса шара при температуре прокатки 1000 °C (*b*)

Guaranteed compliance with the optimal pre-quenching temperature range for grinding balls, as determined through modeling, is achieved when rolling begins at a billet discharge temperature of 980 – 1000 °C. Metallographic analysis of grinding balls with a comparable chemical composition, rolled within this temperature range, revealed a fine acicular martensitic microstructure after quenching (Fig. 5). The measured hardness values correspond to the 4th hardness group (Table 5). Based on these results, the optimal billet discharge temperature range for rolling 60 mm grinding balls was established as 980 – 1030 °C.

Rolling of billets from 20 heats of the specified steel at the revised temperature range confirmed that the resulting balls fully meet the 4th hardness group requirements, while also demonstrating enhanced impact resistance. No macroscopic defects – such as porosity or internal voids – were found across the entire volume of the rolled balls. These findings are consistent with earlier research conducted at the Gur'evsky Metallurgical Plant, which showed that increasing the rolling temperature does not adversely affect the macrostructural quality [35; 36].

The impact resistance of the grinding balls is presented below.

Steel (billet heating temperature)	Share of balls that failed impact resistance test, %
Sh2.3 steel (880 – 1000 °C)	4.6
Sh2.3 steel (980 – 1030 °C)	2.7
Sh76KhF steel (980 – 1030 °C)	1.9

Further modeling of the temperature evolution in Sh76KhF steel grinding balls during rolling and pre-quenching cooling revealed trends similar to those observed for Sh2.3 steel.

Experimental production of grinding balls from Sh76KhF steel at elevated rolling temperatures confirmed that the balls meet the requirements of the 5th hardness group while exhibiting enhanced impact resistance compared to those made from Sh2.3 steel.

Thus, implementing the new rolling temperature mode ensures the consistent production of 60 mm grinding balls that meet the 4th hardness group requirements (GOST 7524–2015) when manufactured from standard Sh2.3 steel, and the 5th hardness group when using economically alloyed Sh76KhF steel. Moreover, the balls from both hardness groups demonstrate increased impact resistance.

Conclusions

Based on a set of theoretical and experimental studies, a new rolling temperature mode was developed for the production of grinding balls with increased hardness and impact resistance. Pilot testing of the proposed temperature mode conducted on an operational ball rolling mill confirmed that the resulting balls correspond to the 4th and 5th hardness groups in accordance with GOST 7524–2015 when produced from standard Sh2.3 steel and experimental Sh76KhF steel, respectively. A significant improvement in the impact resistance of these balls was also confirmed, compared to balls made from Sh2.3 steel under the standard rolling temperature mode.

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