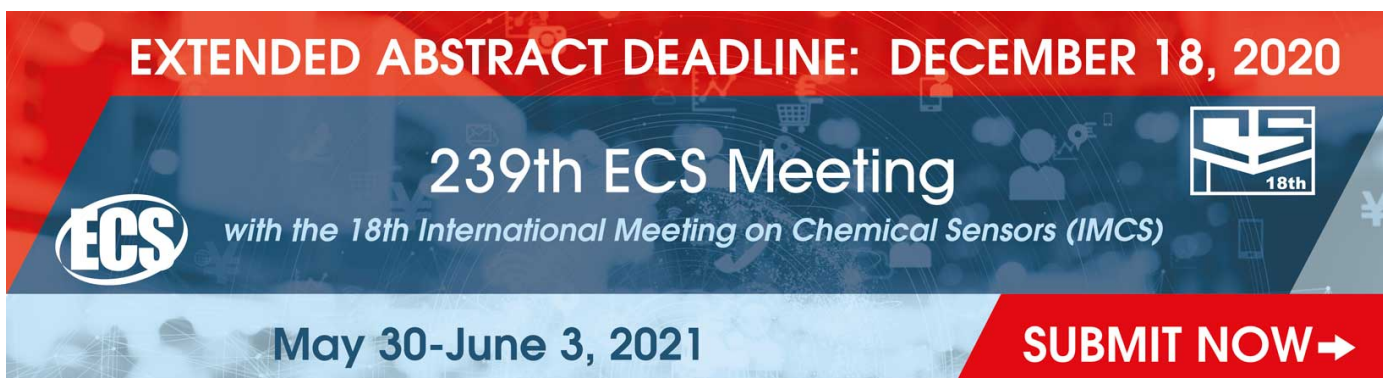


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# Analysis of the main trends in the development of the production of grinding balls in Russia and abroad

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**Abstract.** The article presents the results of the analytical review of the main trends in the grinding balls production in Russia and foreign countries. It is shown that grinding balls of domestic production have lower performance characteristics in relation to foreign counterparts, which is due to the technological features of their production, including the use of unalloyed steels with high hardenability and rejected billets of steels for other purposes (in most cases, rail steels), non-optimal technology of heat treatment. Based on the analysis, a list of promising areas for the development of domestic production of grinding balls that contribute to the competitiveness of this type of product in the domestic and foreign sales markets is determined. These areas include: increase in the share of rolled balls from alloy steels and cast balls from alloy cast irons, improvement of the technology of balls heat treatment and usage of new specialized steel grades for their production.

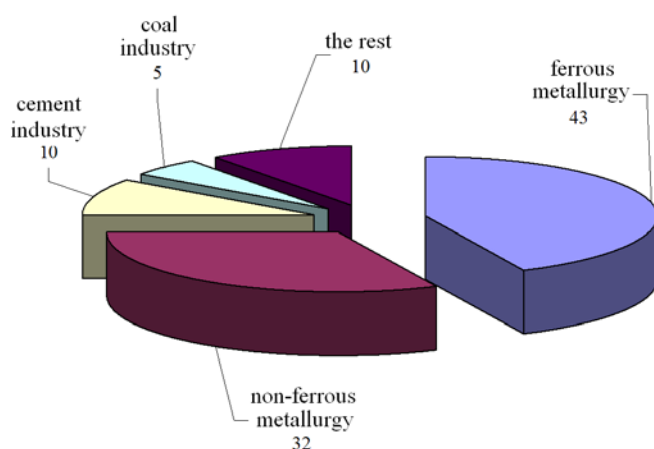
## 1. Introduction

Currently, over 2 billion tonnes of raw materials are crushed in various industries annually. At the same time, drum mills are mainly used for grinding, and balls, cylinders made of steel and cast iron are used as the grinding medium. The global production and consumption of grinding media is about 3 million tonnes per year. At the same time, the main consumers are the USA and Canada (about 20%), CIS countries (about 16%), China, and Australia.

The most common type of grinding media is grinding balls, due to their significant competitive advantages relative to other types of grinding media [1]. In particular, the specific consumption of grinding balls is 20–40% lower compared to cylpebs, which is explained by a much lower probability of a split during operation due to the absence of “stress edges” (angles) [2]. There is an improvement in the quality of grinding of crushed raw materials and an increase in the productivity of mills [3].

The volume of consumption of grinding balls in Russia is estimated at 250 thousand tonnes per year, while the main consumers of this type of product are the mining, metallurgical and cement industries (figure 1).





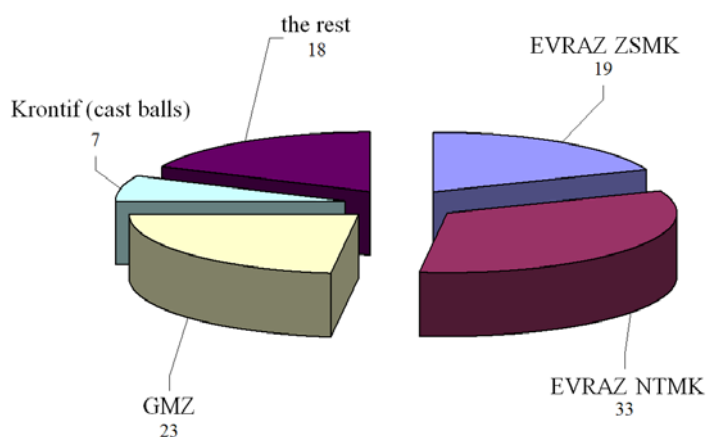
**Figure 1.** Consumption pattern of grinding balls in Russia.

The severe operating conditions of grinding balls, consisting in periodic shock loads, abrasive wear, determine the following requirements for their quality [4]: high hardness and strength, increased resistance to abrasion, resistance to splitting and chipping. Increase in the service life of the balls is an important task, since the cost of grinding media is about 30% of the cost of the grinding process. In addition, in the event of premature wear and cracking of the balls, not only their specific consumption increases, but also the quality of the crushed raw materials deteriorates due to the ingress of particles of chopped grinding balls into it.

The increase in the operational properties of balls is achieved by a combination of two methods: improvement of chemical composition of cast irons and steels used for the balls production and the use of special heat treatment modes. The article presents the analysis of existing trends in the development of ball production in these directions.

## 2. Results and discussion

The analysis of the structure of grinding balls production in Russia shows (figure 2) that the largest share is made of steel balls produced on specialized ball-rolling mills by screw rolling. High-performance ball-rolling mills are available at West Siberian (JSC “EVRAZ ZSMK”) and Nizhny Tagil (JSC “EVRAZ NTMK”) metallurgical plants, as well as at Guryevsky metallurgical plant – figure 2. Forging and stamping methods for the steel balls production are practically not used, due to their significantly lower (2-8 times) productivity and increased metal losses (10-15%).



**Figure 2.** The structure of the grinding balls production in Russia.

In Russia, the bulk of grinding balls is made of medium- and high-carbon unalloyed steels, while in order to achieve their high wear resistance, volumetric hardening of balls from rolling heating with subsequent self-tempering (“EVRAZ ZSMK”, “EVRAZ NTMK”) or low tempering (Guryev Metallurgical plant) should be performed. At the same time, heat treatment at the Guryevsk Metallurgical Plant is carried out in two stages in two quenching drums with intermediate exposure in the air, which allows the temperature gradient over the cross section of the ball and quenching stresses to be reduced.

The technologies used in the domestic metallurgical enterprises for the production of steel grinding balls make it possible to obtain a surface hardness 55–62 HRC with a hardened layer depth 10–15 mm [5]. It should be noted that the indicated surface hardness is achieved only on balls of small diameter

(40-60 mm), and the surface hardness of grinding balls with a diameter of 80-120 mm does not exceed 50-57 HRC even when using modern quenching devices. To obtain grinding balls of higher hardness groups, specialized steels with an increased content of carbon, manganese and chromium are used. In such steels, the carbon content is 0.60-0.75%; chromium – 0.30-0.75%; Manganese – 0.65-0.85%, in experimental steels – up to 1.05%. Also, a significant share in the total production volume is made up of balls produced from the rejection of rail steels alloyed with vanadium and nitrogen.

Domestic-made steel grinding balls, as a rule, have low wear resistance, which, in addition to low surface and bulk hardness, is also associated with the presence of macrostructure defects (shrinkage defects, flakes) [6, 7]. This fact is due to the fact that until recently this type of product was actually produced from production waste – rolled products of inappropriate quality from various steel grades. For domestic metallurgy, the possibility of using production waste for processing into grinding balls is largely conditioned by the absence in the standard for the production of this type of product (GOST 7524-2015) of strict requirements for the chemical composition (only the carbon content is regulated at a level not less than 0.40-0.60% depending on the hardness group of the balls and the carbon equivalent at a level not less than 0.50-0.85% also depending on the hardness group) – table 1.

**Table 1.** Requirements for the chemical composition of steel grinding balls in accordance with GOST 7524-2015.

Ball diameter, mm	Hardness group	Carbon content, %	Carbon equivalent
		not less than	
15-55	1. 2	0.40	0.50
	3	0.60	0.70
	4. 5	0.60	0.75
60-120	1. 2	0.50	0.70
	3. 4	0.60	0.75
	5	0.60	0.80

We can also note the complete absence of requirements regarding the macro- and microstructure of the balls produced and the minimum requirements for the quality of the surface of the balls (defects on the surface of the balls, that make the size of the balls beyond the maximum deviations, are not allowed). The main requirements of this standard relate to hardness (on the surface, depth  $\frac{1}{2}$  of the radius of the ball and volume), depending on which balls are assigned to one of five groups (table 2).

**Table 2.** Hardness requirements for steel grinding balls according to GOST 7524-2015.

Ball diameter, mm	Hardness, HRC (not less) by groups					
	1	2	3	4	5	
	surface		surface	at a depth of $\frac{1}{2}$ radius	surface	volumetric
15-45	45	49	55	55	45	57
50-70	43	48	53	53	43	53
80-100	39	42	52	52	40	48

In addition, in the current GOST the absence of requirements for impact resistance of balls, one of the main indicators characterizing the life and specific consumption of these products, should be noted. The standard stipulates only the ability to control shock resistance in agreement with the manufacturer and its methodology for balls of the fourth and fifth hardness groups (the highest hardness).

In recent years, due to increasing requirements for the quality of grinding balls and increasing competition in the market, a significant share of this type of product is supplied not according to GOST, but according to technical specifications (TU) or organization standards (STO), where steel grades with fixed the range of changes in basic chemical elements are provided.

It should be noted that the trend in the production of grinding balls from production wastes, for

example, trimmings of rail and beam mills, is to some extent characteristic of foreign manufacturers [8]. However, unlike Russia, in foreign countries, the bulk of steel grinding balls is made from chromium alloyed steels (about 1%). Grinding balls with a diameter of 15-150 mm made of such steels produced by leading Western companies (AGS, Gerdau Ameristeel, Vitkovice) have a hardness on the surface after hardening of 62-65 HRC, while the hardness in the central zone of the balls is at least 60 HRC. The leader in this technological niche is the South African company "Scow Metals". At its ten plants, about 600 thousand tonnes of balls are produced under the common brand "Moly-Sor".

The further prospect in increasing the wear resistance of steel grinding balls is the development and application of specialized spherical hypereutectoid steels. In balls made of such steels, it is possible to achieve two microstructural states that provide higher wear resistance compared to tempering martensite:

- the metal matrix of tempered martensite with evenly distributed granular inclusions of secondary cementite;
- the austenitic-martensitic carbide-free or low carbide structure in which austenite has an adjustable tendency to martensitic transformation during wear. This type of microstructure is preferable because it provides the balls with increased resistance to cracking during hardening and splits during operation due to the presence of viscous austenite.

Regarding the improvement of the heat treatment technology, a promising direction is the use of technology that provides for withholding of quenching cooling and subsequent heating in order to redistribute carbon from martensite to austenite with subsequent tempering [9].

According to the study [10], as a result of Q-n-P treatment, a heterogeneous microstructure is formed in the ball, consisting of sections of tempered martensite and austenite-martensite sections. The redistribution of carbon between martensite and austenite during tempering led to an increase in the fraction of residual austenite to 25–30% at a carbon concentration in Ares of 1.12%.

The resulting structure combines micro-sites with different strengths and ductility, which together provides an increased set of steel properties in connection with the implementation of the effect of the natural composite. Residual austenite lies between martensitic crystals in the form of film inclusions or interlayers. Studies [29] found that austenite in the form of films has a higher stability to deformation martensitic transformation than austenite in the form of blocks.

Although it should be noted that despite the positive results obtained, experience in the industrial use of Q-n-P technology for steel grinding balls is currently lacking.

Characterizing the production of grinding cast iron balls, it can be stated that the share of such balls in the total volume of production and consumption of Russia and the CIS countries is significantly inferior to steel balls (about 20%), although it has some upward trend. The main manufacturer of cast iron grinding balls in Russia and the CIS is the company "Krontif". Abroad, the proportion of grinding balls made of cast iron is much higher and amounts to approximately 35%, also having a tendency to increase. At the same time, gray cast irons are used in Russia and the CIS countries for the production of cast balls, and leading western companies use high-alloyed white cast irons (with a chromium content of 13-23%).

Due to the presence of a significant amount of carbides in the structure, pig-iron grinding balls have a higher operational stability compared to steel balls. In addition to less weight loss, the so-called "toothed" effect is realized in cast iron balls: the directional arrangement of carbide crystals perpendicular to the body surface and their alternation with softer interlayers of the matrix phase, which creates a specific surface roughness and improves the grinding effect by reducing slippage between the balls and grains ground material.

Modern brands of white wear-resistant cast irons are complex alloyed multicomponent alloys with a wide variety of structures and a wide range of physical and mechanical properties. The use of highly alloyed cast irons for casting balls with subsequent heat treatment provides a martensitic-carbide structure with high impact resistance over the entire cross-section of the grinding body. In the production of cast iron balls with a chromium content of 13-23%, a through hardness of 62-64 HRC is achieved. The world leader in this technological segment is the Belgian company "Magotteaux",

which produces about 320 thousand tonnes of such balls per year at 16 plants. For comparison, the surface hardness of ordinary cast iron balls can reach 50-52 HRC and at the same time they are characterized by low impact resistance.

Thus, the use of alloyed cast irons for the production of grinding balls is a promising direction.

### 3. Conclusion

The analysis established the distinctive features of the technology for the grinding balls production in Russia and foreign countries, causing lower quality characteristics of domestic grinding balls relative to foreign counterparts.

To improve the quality and competitiveness of grinding balls of domestic production, the following directions are promising:

- increase in the share with the prospect of a complete transition to the production of rolled balls from alloy steels and cast balls from alloy cast irons;
- improvement in the technology of balls heat treatment;
- development of new specialized steel grades for the production of balls.

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