Metallurgical technologies / Металлургические технологии

UDC 621.771.65
DOI 10.17073/0368-0797-2023-6-645-652

Original article
Оригинальная статья

Formation of microstructure in rail steel grinding balls depending on quenching medium parameters

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Abstract. Studies of the formation of microstructure of grinding balls from the rejects of rail steel were carried out during their quenching in various polymer media. At the first stage, based on studies of the cooling capacity of solutions of polymers PCM and Thermovit with varying concentrations and temperatures, the authors constructed the cooling curves of grinding balls made of K76F rail steel. It was found that at concentration of these polymers in an aqueous solution of 2 and 4 %, cooling rate of grinding balls made of K76F steel is almost identical at solution temperatures of 20 and 30 °C and significantly decreases when the temperature of the polymer solution increases to 40 °C. At the same time, the most noticeable decrease in the cooling rate is characteristic of PCM polymer with its concentration at the level of 2 %. At the second stage, the authors carried out metallographic studies of the microstructure of grinding balls made of K76F rail steel, which were quenched in laboratory conditions using polymers PCM and Thermovit with concentrations of 2 – 4 % and temperature of 20 – 40 °C. As a result, it was determined that the use of the PCM solution for quenching balls provides a significantly higher quality of microstructure and hardness of heat-treated balls compared to the use of the Thermovit polymer. At the same time, varying the concentration and temperature of the PCM polymer quenching medium allows one to obtain grinding balls with different performance characteristics that determine the potential areas of their application. Thus, quenching of balls in a solution of the specified polymer with concentration of 2 % and temperature of 20 – 30 °C ensures the production of balls with high hardness (corresponding to the IV hardness group according to the state standard GOST 7524 – 2015), and the use of a solution of the same polymer with concentration of 4 % and temperature of 20 – 30 °C for quenching creates the possibility of producing balls with lower hardness, but potentially high impact resistance.

Keywords: microstructure, grinding balls, rail steel, polymers, heat treatment, quenching medium, impact resistance

Acknowledgements: The research was supported by the Russian Science Foundation, grant No. 22-29-20170, and by the Kemerovo Region – Kuzbass.

For citation: Umanskii A.A., Baidin V.V., Simachev A.S., Dumova L.V., Safonov S.O. Formation of microstructure in rail steel grinding balls depending on quenching medium parameters. *Izvestiya. Ferrous Metallurgy*. 2023;66(6):645–652. https://doi.org/10.17073/0368-0797-2023-6-645-652

Исследования процессов формирования микроструктуры мелющих шаров из рельсовой стали в зависимости от параметров закалочной среды

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Аннотация. Проведены исследования формирования микроструктуры мелющих шаров из отбраковки рельсовой стали при их закалке в различных полимерных средах. На первом этапе, на основании исследований охлаждающей способности растворов полимеров «ПКМ» и «Термовит» при варьировании их концентраций и температуры построены кривые охлаждения мелющих шаров из рельсовой стали марки К76Ф. При концентрации указанных полимеров в водном растворе 2 и 4 % скорость охлаждения мелющих шаров из стали К76Ф практически идентична при температурах раствора 20 и 30 °С и значимо снижается в случае увеличении температуры раствора полимера до 40 °С. При этом наиболее заметное снижение скорости охлаждения характерно для полимера «ПКМ» при его концентрации на уровне 2 %. На втором этапе проведены металлографические исследования микроструктуры мелющих шаров из рельсовой стали К76Ф, закалка которых проводилась в лабораторных условиях с использованием полимеров «ПКМ» и «Термовит» с концентраций 2 – 4 % и температурой 20 – 40 °C. Использование раствора «ПКМ» для закалки шаров обеспечивает значительно более высокие качество микроструктуры и твердость термообработанных шаров по сравнению с применением полимера «Термовит». Варьирование концентрации и температуры полимерной закалочной среды «ПКМ» позволяет получать мелющие шары с различными эксплуатационными характеристиками, определяющими потенциальные области их применения. Закалка шаров в растворе указанного полимера с концентрацией 2 % и температурой 20 – 30 °C обеспечивает получение шаров с высокой твердостью (соответствующей IV группе твердости по ГОСТ 7524 – 2015), а использование для закалки раствора этого же полимера с концентрацией 4 % и температурой 20 – 30 °C создает возможность производства шаров с более низкой твердостью, но потенциально высокой ударной стойкостью.

Ключевые слова: микроструктура, мелющие шары, рельсовая сталь, полимеры, термообработка, закалочная среда, ударная стойкость

Благодарности: Исследование выполнено за счет гранта Российского научного фонда № 22-29-20170, гранта Кемеровской области – Кузбасса.

Для цитирования: Уманский А.А., Байдин В.В., Симачев А.С., Думова Л.В., Сафонов С.О. Исследования процессов формирования микроструктуры мелющих шаров из рельсовой стали в зависимости от параметров закалочной среды. *Известия вузов. Черная металлургия*. 2023;66(6):645–652. https://doi.org/10.17073/0368-0797-2023-6-645-652

Introduction

In recent years, there has been a noticeable trend towards the intensive development of domestic ball rolling production. Several modern ball rolling mills have been commissioned [1; 2], and significant efforts are underway at various operational mills to enhance the technological processes for grinding ball production [3 – 6]. This phenomenon is attributed to the growing demand for grinding balls with superior performance characteristics, specifically hardness, wear resistance, and resistance to shock loads. This demand arises from the desire to extend the service life of grinding balls used in the metallurgical, mining, and cement industries. Prolonging the service life significantly reduces the cost of the final product and enhances its quality [7 – 9]. Cost reduction is achieved through a decrease in the specific consumption of balls, while quality improvement results from minimizing the entry of broken ball particles into the crushed materials [10].

An analysis of materials from both domestic and foreign researchers indicates that the enhancement of hardness and impact resistance in balls is primarily achieved through the optimization of the chemical composition of steels employed in ball production [11 – 13]. Additionally, improvements in heat treatment modes play a crucial role in achieving these properties [14 – 16]. It is noteworthy that, aside from the mentioned characteristics, the impact resistance of grinding balls is significantly affected by the quality of their macrostructure [17; 18].

The steels used for the production of grinding balls can be categorized into two main groups based on their chemical composition [19; 20]:

– specialized ball steel;

– steels initially designed for the production of other types of rolled products (either carbon or alloyed).

It's worth noting that within the second group of steels, a substantial portion consists of rejected rail steel blanks [21 – 23].

The technologies for the heat treatment of grinding balls can be categorized into three main organizational options:

1) hardening followed by self-tempering of the balls in the air;

2) hardening followed by low tempering;

3) "interrupted hardening" (hardening in several stages), followed by low tempering.

The second and third options for the heat treatment of balls are deemed more preferable, as they facilitate the alleviation of quenching stresses [24; 25]. However, implementing the third option is more challenging.

Irrespective of the chosen heat treatment option for grinding balls, the development of their high-quality quenching microstructure is largely influenced by the cooling capacity of the quenching medium employed. Polymers emerge as the most promising type of quenching medium, as their cooling ability can be effectively regulated across a wide range by adjusting water dilution at different concentrations.

In summary, it can be affirmed that investigations into the processes governing the formation of the quenching microstructure in grinding balls made of rail steel using polymer quenching media are currently of significant scientific and practical interest.

Materials and methods

The research focused on grinding balls that had not undergone heat treatment, selected from the mill line after rolling but before hardening, sourced from the current production of JSC Guryev Metallurgical Plant and made from rejected rail steel grade K76F.

The research was carried out in two stages:

1 – examination of the cooling effectiveness of PCM and Thermovit polymer quenching media on the Kompaton facility, with variations in polymer concentration and temperature;

2 – investigation of the microstructure of grinding balls after quenching using PCM and Thermovit polymer quenching media, with variations in their concentration and temperature.

The temperature of the cooling medium varied in the range of 20 – 40 °C with increments of 10 °C, and the concentration of each studied polymer was set at 2 and 4 %.

The Kompaton facility used in the research is equipped with a digital thermometer featuring a temperature sensor.

The temperature was recorded at specified intervals in automatic mode, and the TC Soft program was employed for data processing, enabling the construction of cooling curves.

To assess the cooling effectiveness of polymer quenching media, grinding balls were heated in a laboratory furnace to the quenching temperature and subsequently cooled in a tank filled with the respective quenching medium. The hardening temperature was maintained 30 °C higher than the Ac_3 point, taking into account the actual chemical composition factoring in the actual chemical composition of the samples, as determined by *X*-ray spectral analysis using the Shimadzu XRF-1800 spectrometer. The actual heating temperature of the samples for quenching fell within the range of 790 – 802 °C, with a low tempering temperature ranging between 195 – 215 °C.

Microstructure and hardness studies of the balls were conducted on samples that underwent heat treatment. For each ball, one portion underwent quenching, while the other underwent quenching followed by low tempering. The microstructure analysis utilized an OLYMPUS GX-51 optical metallographic microscope, and hardness was determined using a TK-2M hardness tester.

Results and discussion

The analysis of the obtained cooling curves for grinding balls made of K76F rail steel suggests that, with both PCM and Thermovit polymer quenching media, the cooling rate remains practically identical at solution temperatures of 20 and 30 °C, regardless of their concentrations (2 or 4 %). However, a noticeable decrease in the cooling rate is observed when the polymer solution temperature is increased to 40 °C (Figs. 1 and 2). Notably, the most pronounced decrease in the cooling rate is observed with the PCM polymer at a concentration of 2 %.

Examination of the microstructure of grinding balls after a complete heat treatment cycle (quenching + low tempering) reveals that the most optimal microstructure, comprising martensite + carbides with some residual austenite, is achieved under specific quenching medium parameters:

1) at a PCM concentration of 2 % and a solution temperature of 20 and 30 °C (Fig. 3, *a*, *b*);

2) at a PCM concentration of 4 % and a polymer temperature of 40 °C (Fig. 3, *c*);

3) at a Thermovit polymer concentration of 4 % and a temperature of 20 °C (Fig. 3, *d*).

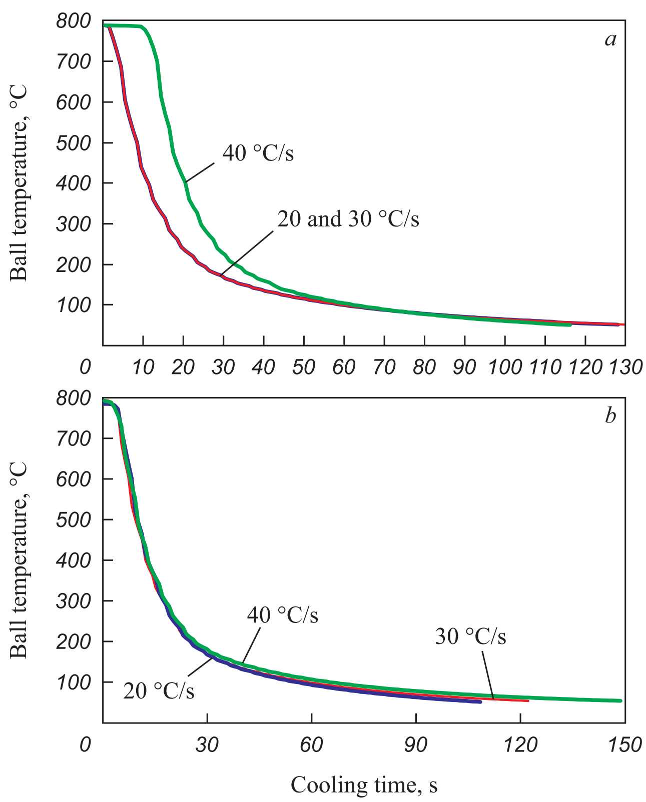

Fig. 1. Cooling curves of K76F rail steel during quenching in an aqueous solution of polymers PCM (*a*) and Thermovit (*b*) with concentration of 2 % depending on the quenching medium temperature

Рис. 1. Кривые охлаждения рельсовой стали К76Ф при закалке в водном растворе полимеров «ПКМ» (*a*) и «Термовит» (*b*) с концентрацией 2 % в зависимости от температуры закалочной среды

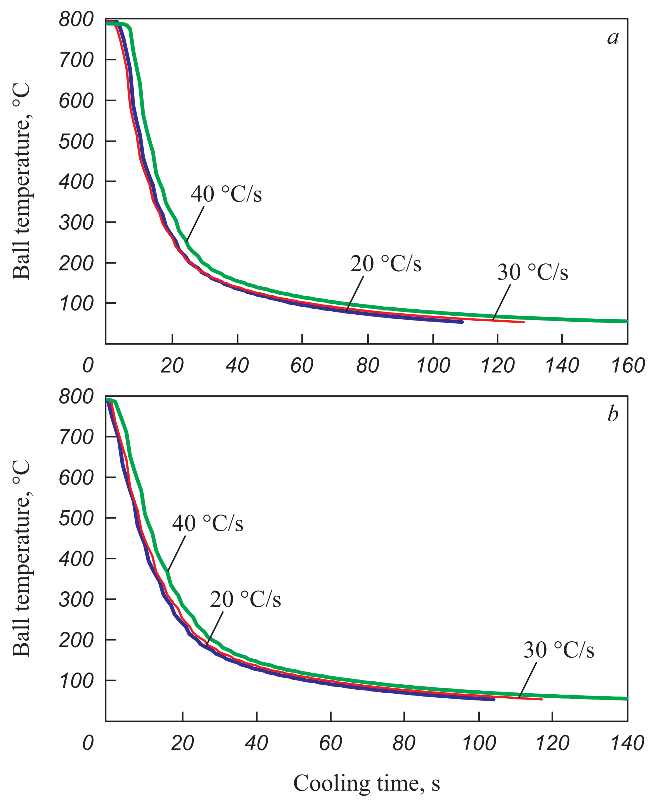

Fig. 2. Cooling curves of K76F rail steel during quenching in an aqueous solution of polymers PCM (*a*) and Thermovit (*b*) with concentration of 4 % depending on the quenching medium temperature

Рис. 2. Кривые охлаждения рельсовой стали К76Ф при закалке в водном растворе полимеров «ПКМ» (*a*) и «Термовит» (*b*) с концентрацией 4 % в зависимости от температуры закалочной среды

Simultaneously, the highest hardness, aligning with hardness group IV as per the state standard GOST 7524–2015 (refer to the Table), is exhibited by balls hardened using the first set of hardening medium parameters (PCM concentration 2 %, solution temperature 20 and 30 °C). Grinding balls hardened by employing the parameters of the quenching medium according to the second and third options only meet the criteria for hardness group II, as per GOST 7524–2015 (PCM concentration 4 %, temperature 40 °C; Thermovit concentration 4 %, temperature 20 °C).

When a 4 % PCM polymer solution is utilized for hardening balls at temperatures of 20 and 30 °C, a microstructure in the form of troostomartensite + carbides + residual austenite is formed (Fig. 4). Although the hardness of such balls falls within hardness group II according

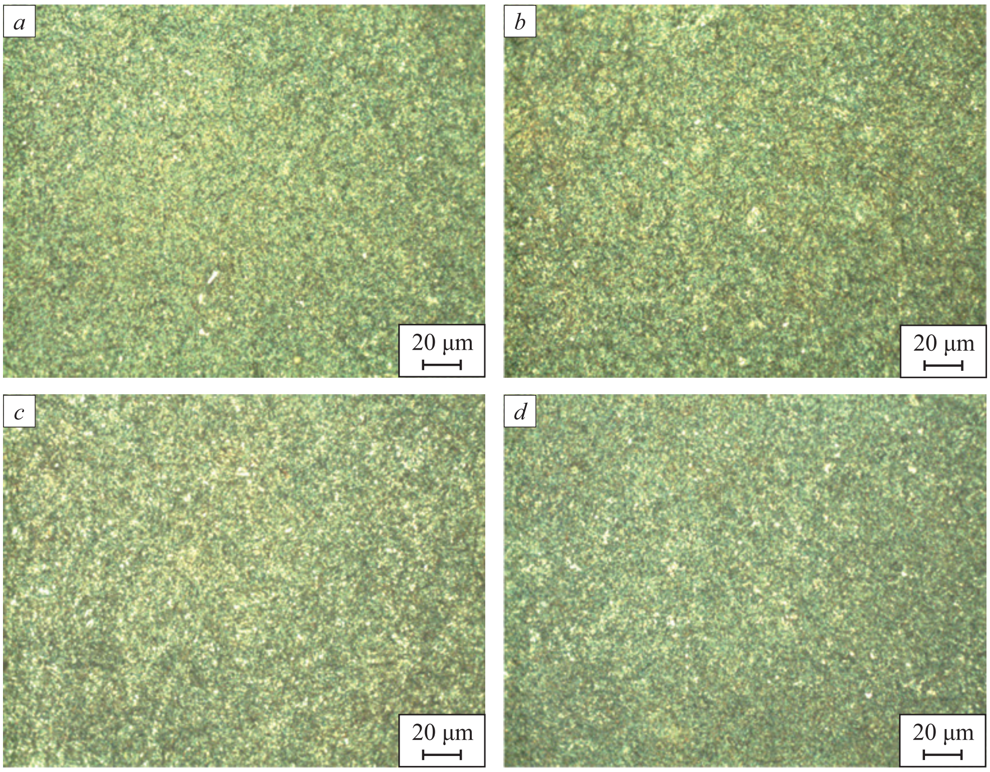

Fig. 3. Microstructure of grinding balls made of K76F rail steel after quenching with subsequent low tempering:
a, *b* – PCM polymer concentration of 2 % at 20 and 30 °C; *c* – PCM polymer concentration of 4 % at 40 °C;
d – Thermovit polymer concentration of 2 % at 20 °C

Рис. 3. Микроструктура мелющих шаров из рельсовой стали К76Ф после закалки с последующим низким отпуском:
a, *b* – концентрация полимера «ПКМ» 2 %, температура 20 и 30 °C; *c* – концентрация полимера «ПКМ» 4 %, температура 40 °C;
d – концентрация полимера «Термовит» 2 %, температура 20 °C

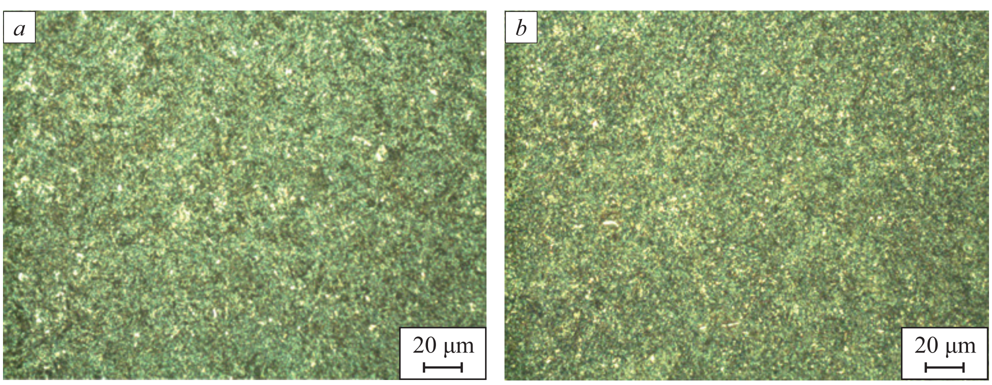

Fig. 4. Microstructure of grinding balls made of K76F rail steel after quenching in a solution of PCM polymer with concentration of 4 % at 20 (*a*) and 30 °C (*b*)

Рис. 4. Микроструктура мелющих шаров из рельсовой стали К76Ф после закалки в растворе полимера «ПКМ» с концентрацией 4 %, температура 20 °C (*a*) и 30 °C (*b*)

Comparative analysis of hardness of the balls after heat treatment using various quenching media

Сравнительный анализ твердости шаров после термообработки при использовании различных закалочных сред

Temperature of quenching medium, °C	Ball hardness after heat treatment using various quenching media and their concentrations, HRC			
	PCM		Thermovit	
	2 %	4 %	2 %	4 %
Surface				
20	54 – 56	48 – 51	48 – 50	43 – 45
30	53 – 55	47 – 49	44 – 46	38 – 45
40	50 – 52	48 – 50	44 – 45	46 – 48
Requirements of GOST 7524–2015 for balls 60 mm in diameter by groups				
Group I	at least 43 HRC			
Group II	at least 48 HRC			
Groups III, IV	at least 53 HRC			
At the depth of 1/2 ball radius				
20	52 – 54	48 – 51	48 – 50	39 – 41
30	51 – 53	47 – 49	44 – 46	38 – 45
40	50 – 51	48 – 50	44 – 45	38 – 42
Requirements of GOST 7524–2015 for balls 60 mm in diameter by groups				
Groups I, II, III	–			
Group IV	at least 43 HRC			

to GOST 7524–2015 (refer to the Table), they exhibit potentially higher impact strength owing to the properties of the troostomartensite phase.

However, quenching balls according to other combinations of quenching medium parameters results in a defective microstructure. In addition to martensite, there is the presence of quenching troostite in various forms: acicular, spheroidal, and in the form of a network (Fig. 5). The existence of troostite in the structure indicates a lower cooling rate, signifying inadequate cooling capacity of the quenching medium. Regardless of the type of troostite, its negative impact on the hardness of the grinding balls is evident (refer to the table). Notably, the more pronounced negative influence is naturally exerted by the spheroidal troostite and the form of a grid.

In general, it is noteworthy that the quality of the microstructure in balls hardened with PCM solution is significantly superior compared to those hardened with Thermovit polymer solution. For instance, balls hardened in a PCM solution with a 2 % concentration at a temperature of 40 °C exhibit only acicular troostite in the structure (Fig. 5, *a*); balls hardened with Thermovit polymer at a similar concentration and temperature display spheroidal troostite and troostite in the form of a grid (Fig. 5, *c*). Moreover, the hardness of balls hardened using PCM polymer with the specified concentration and temperature, both on the surface and in the core, is, on average, 6 – 7 HRC higher than the hardness of balls hardened in Thermovit polymer medium (refer to the Table).

In conclusion, it can be inferred that altering the parameters of the polymer quenching medium enables the variation of performance characteristics in grinding balls made of rail steel, thus determining potential applications. For example:

- quenching balls in a PCM polymer solution with a 2 % concentration at a temperature of 20 – 30 °C ensures the production of balls with high hardness (hardness group IV as per GOST 7524–2015).
- employing the same polymer solution for quenching with a 4 % concentration and a temperature of 20 – 30 °C creates the possibility of producing balls with lower hardness but potentially high impact resistance.

However, caution is advised as certain combinations of PCM and Thermovit polymer concentrations and temperatures may lead to a high risk of obtaining a defective microstructure.

Conclusions

Based on laboratory experimental studies, cooling curves were constructed for hardening of the balls made of K76F rail steel in solutions of PCM and Thermovit polymers, each with a concentration of 2 and 4 % and temperature ranging from of 20 to 40 °C. The experimental research in the laboratory has elucidated the patterns

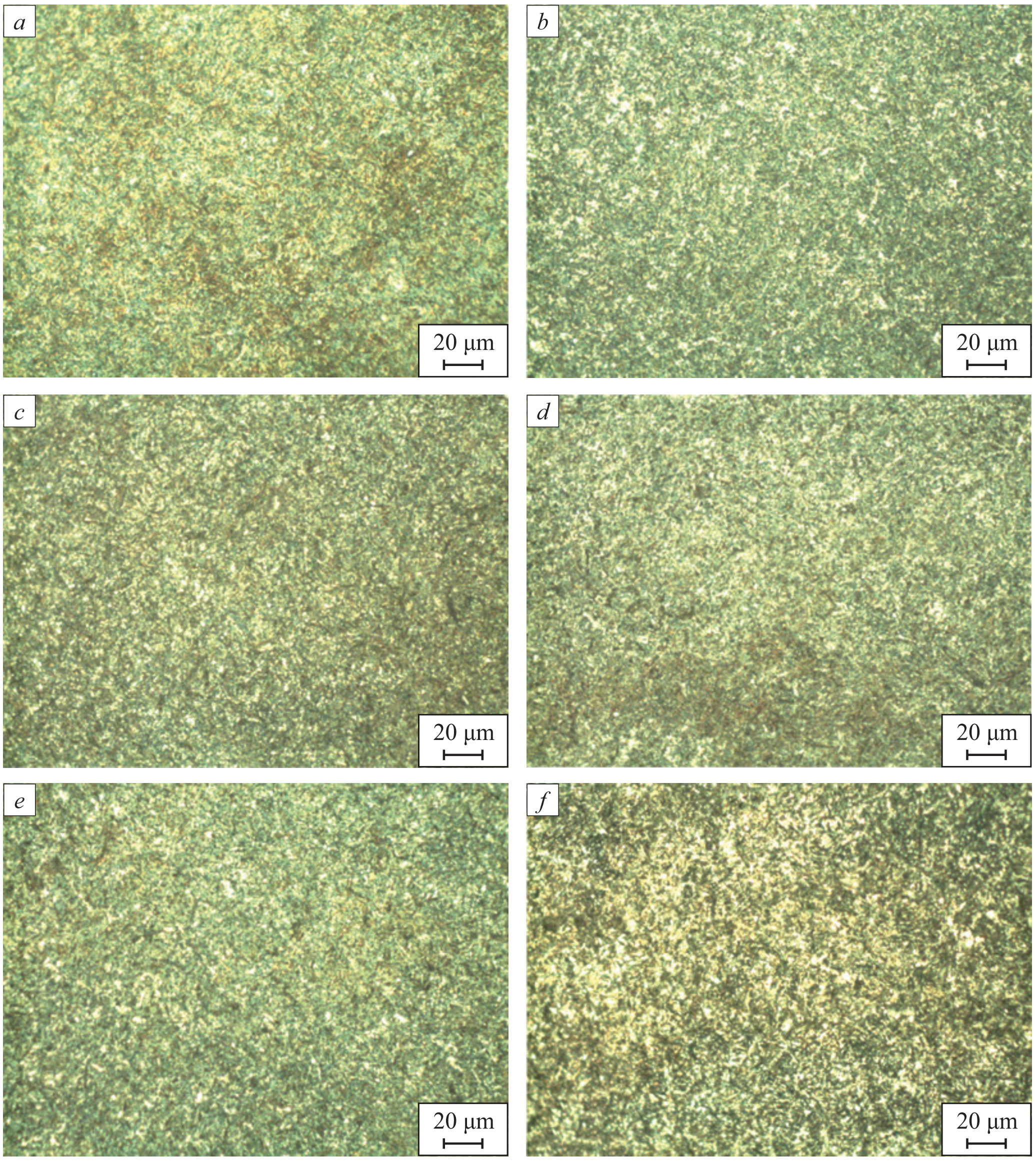

Fig. 5. Defective microstructure of grinding balls made of K76F rail steel after quenching and low tempering:
a – PCM polymer concentration of 2 % at 40 °C;
b, *c* – Thermovit polymer concentration of 2 % at 30 and 40 °C;
d, *e*, *f* – Thermovit polymer concentration of 4 % at 20, 30 and 40 °C

Рис. 5. Дефектная микроструктура мелющих шаров из рельсовой стали К76Ф после закалки и низкого отпуска:
a – концентрация полимера «ПКМ» 2 %, температура 40 °C;
b, *c* – концентрация полимера «Термовит» 2 %, температура 30 и 40 °C;
d, *e*, *f* – концентрация полимера «Термовит» 4 %, температура 20, 30 и 40 °C

governing the formation of the microstructure in grinding balls from the specified steel when utilizing PCM and Thermovit polymer quenching media with varying heat treatment parameters.

Notably, the use of PCM solution for ball hardening ensures a significantly higher quality of the microstructure and hardness of the balls compared to utilization of Thermovit polymer. As a result, recommendations have been developed for optimal combinations of concentration and temperature of PCM polymer. These recommendations aim to ensure the production of balls with increased hardness as well as the production of balls with lower hardness but with a heightened level of impact resistance.

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A. A. Umanskii – development of a research plan, analysis of mechanisms of formation of the microstructure and mechanical properties of grinding balls, formulation of conclusions.
V. V. Baidin – generalization of the results of experimental studies on cooling capacity of polymer quenching media and microstructure of grinding balls.
A. S. Simachev – metallographic studies of microstructure and hardness analysis of grinding balls before and after heat treatment.
L. V. Dumova – conducting an analytical review on the article topic, design of the article.
S. O. Safonov – conducting studies of cooling capacity of polymer quenching media with varying concentrations and temperatures.

А. А. Уманский – разработка плана исследований, анализ механизмов формирования микроструктуры и механических свойств мелющих шаров, формулирование основных выводов.
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Received 28.08.2023
Revised 11.09.2023
Accepted 29.09.2023

Поступила в редакцию 28.08.2023
После доработки 11.09.2023
Принята к публикации 29.09.2023