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Influence of chemical composition of steels for production of grinding balls on their deformation characteristics

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Abstract. The conducted studies determined the patterns of influence of chemical composition and deformation parameters of ball steels with experimental chemical composition on their deformability. The development of experimental chemical compositions of ball steels was carried out based on the existing experience of domestic and foreign researchers, taking into account the possibility of further application of the obtained results for ball steels of standard grades. The studies were carried out using a specialized laboratory installation by the method of hot-rolling samples. An increase in the carbon content in the range of 0.72 – 0.85 %, manganese in the range from 0.72 to 0.85 %, chromium in the range of 0.38 – 1.71 % and nickel in the range from 0.08 to 0.87 % has a significant effect on increasing the deformation resistance of steels. At the same time, the quantitative effect of carbon content in the steels on their deformation resistance is much more pronounced in relation to manganese, chromium and nickel. It was determined that a decrease in the deformation temperature from 1200 to 900 °C, an increase in the deformation rate in the range from 1 to 10 s^{-1} and true deformation in the range 0.05 – 0.35 cause an increase in the deformation resistance of ball steels, regardless of their chemical composition. The influence of all these parameters on the deformation resistance of steels has a pronounced nonlinear character and the deformation temperature has the greatest relative influence on the deformation resistance. The data obtained are summarized in the form of a multiple regression equation, which establishes the quantitative relationship between the resistance of steel to deformation with its chemical composition and deformation parameters. Verification of the adequacy of the obtained equation in relation to the rolling conditions of ball steel billets of standard grades at the continuous medium-grade mill 450 of JSC EVRAZ United West Siberian Metallurgical Plant confirmed the possibility of using it to predict the energy-power parameters of rolling ball steels of various chemical composition.

Keywords: deformation resistance, grinding balls, long billet, hot torsion, chemical composition, temperature and velocity parameters of deformation

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Исследование влияния химического состава сталей для производства мелющих шаров на их деформационные характеристики

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Аннотация. Авторы определили закономерности влияния химического состава и параметров деформации шаровых сталей экспериментального химического состава на их деформируемость. Разработку экспериментальных химических составов шаровых сталей вели, опираясь на имеющийся опыт отечественных и зарубежных исследователей, с учетом возможности дальнейшего применения полученных результатов для шаровых сталей стандартных марок. Исследования проводились с использованием специализированной лабораторной установки методом горячего кручения образцов. Повышение содержания углерода в диапазоне 0,72 – 0,85 %, марганца в интервале от 0,72 до 0,85 %, хрома в диапазоне 0,38 – 1,71 % и никеля в интервале от 0,08 до 0,87 % оказывает значимое влияние на увеличение сопротивления деформации сталей. При этом количественное влияние содержания углерода в сталях на их сопротивление деформации является значительно более выраженным по отношению к марганцу, хрому и никелю. Определено, что снижение температуры деформации с 1200 до 900 °С, увеличение скорости деформации в интервале от 1 до 10 $с^{-1}$ и истинной деформации в диапазоне 0,05 – 0,35 обуславливают повышение сопротивления деформации шаровых сталей вне зависимости от их химического состава. Влияние всех перечисленных параметров на сопротивление сталей деформированию имеет выраженный нелинейный характер и наибольшее относительное влияние на сопротивление деформации оказывает температура деформации. Полученные данные обобщены в виде уравнения множественной регрессии, устанавливающего количественную взаимосвязь сопротивления стали деформированию с ее химическим составом и параметрами деформации. Проверка адекватности полученного уравнения применительно к условиям прокатки заготовок шаровых сталей стандартных марок на непрерывном среднесортном стане 450 АО «ЕВРАЗ Объединенный Западно-Сибирский металлургический комбинат» подтвердила возможность его использования для прогнозирования энергосиловых параметров прокатки шаровых сталей различного химического состава.

Ключевые слова: сопротивление деформации, мелющие шары, сортовые заготовки, горячее кручение, химический состав, температурно-скоростные параметры деформации

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Introduction

Currently, one of the main approaches to improving the hardness, wear resistance, and impact resistance of steel grinding balls involves refining their chemical composition [1 – 3]. This is due to the inability of standard ball steels to meet the required levels of these quality parameters [4 – 6].

A series of developments aim to improve the chemical composition of steels to enhance the operational properties of grinding balls. In studies [7; 8], pilot-industrial trials were conducted for the production of 35 mm diameter balls from the fifth hardness group using steel alloyed with manganese and chromium to concentrations of 0.90 – 1.05 and 0.40 %, respectively. The resulting grinding balls, after heat treatment, exhibited the following characteristics:

– surface hardness of 59 – 64 HRC;

– hardness at half of the radius of 55 – 60 HRC;

– coercive force (indicative of internal stresses) of 44 – 50 units.

A significant number of patents [9 – 11] propose varying the qualitative and quantitative composition of alloying elements in ball steels within a wide range. In Russian inventions, manganese and chromium are the primary alloying elements, with their content in steels reaching up to 0.90 and 0.60 %, respectively. In contrast, foreign patents distinguish themselves by including a broader range of alloying elements, such as silicon, nickel, molybdenum, and niobium, alongside manganese and chromium, with higher levels of manganese and chromium alloying (upper concentration limits of 2.0 and 1.5 %, respectively).

Currently, there is no consensus on the optimal chemical composition of steel for grinding ball production. However, there is a general trend toward increased alloying levels in these steels. Increasing the concentration of alloying elements in most cases enhances deformation resistance during rolling [12 – 14], leading to a corresponding increase in loads on rolling mill equipment [15; 16].

Given the significant inaccuracies that arise when extrapolating deformation resistance data for standard steel grades to steels with new chemical compositions [17 – 19], experimental studies are needed to evaluate these parameters for new grades of ball steels. In addition to cross-helical rolling mills, multi-stand large or medium-grade rolling mills used for producing initial round-section billets are also integral to the technological cycle of grinding ball production.

Research methodology

The study examined five steel samples, each representing a different variant of chemical composition, previously analyzed in [20] to investigate the microstructure formation processes in grinding balls after heat treatment. The key distinguishing features of these compositions were as follows (Table 1):

1) presence and degree of alloying with chromium and nickel;

2) carbon and manganese content in the steel.

The development of these chemical compositions for ball steels drew on the experience of both domestic and international researchers. The concentration ranges for carbon, manganese, chromium, and nickel in the experimental steels were chosen to facilitate the generalization of results. This allowed for the establishment of relationships between mechanical and deformation characteristics and the content of these elements, as well as their potential application to standard grade ball steels (Table 2).

The deformation resistance of the ball steels was studied using a specialized laboratory installation (Fig. 1) through the hot torsion method. The installation includes a movable and a fixed shaft located inside a resistance furnace. Cylindrical samples with additional heads at their ends are secured in grooves on the shafts. After being heated to the target temperature, the samples are subjected to torsion testing by rotating the movable shaft.

Table 1. **Chemical composition of experimental steel samples**

Таблица 1. **Химический состав образцов опытных сталей**

Element	Content, wt. %, steel (variant)				
	1	*2*	*3*	*4*	*5*
C	0.73 – 0.75	0.70 – 0.74	0.83 – 0.85	0.72 – 0.76	0.75 – 0.78
Si	0.31 – 0.38	0.32 – 0.36	0.34 – 0.37	0.36 – 0.39	0.30 – 0.32
Mn	0.75 – 0.84	0.75 – 0.78	0.80 – 0.85	0.76 – 0.78	0.72 – 0.75
Cr	0.38 – 0.42	1.43 – 1.49	0.81 – 0.83	1.63 – 1.71	1.06 – 1.10
Ni	0.08 – 0.11	0.73 – 0.75	0.19 – 0.21	0.85 – 0.87	0.46 – 0.48
Cu	0.09 – 0.12	0.10 – 0.12	0.11 – 0.13	0.09 – 0.11	0.11 – 0.13
Ti	0.004 – 0.006	0.004 – 0.005	0.007	0.014 – 0.016	0.007
V	0.03 – 0.04	0.04	0.07 – 0.08	0.04	0.04
S	0.010 – 0.014	0.010 – 0.013	0.015 – 0.018	0.009 – 0.011	0.009 – 0.010
P	0.009 – 0.012	0.009 – 0.013	0.009 – 0.012	0.005 – 0.008	0.008 – 0.010

The control unit of the installation, which records the torque and accumulated strain, enables the determination of deformation resistance using the following equation:

$$\sigma = \frac{12\sqrt{3}}{\pi d_0^3} M, \qquad (1)$$

where d_0 is the diameter of the sample before testing, and M is the torque.

The adequacy of this installation for determining the plastic and deformation characteristics of steels has been confirmed by previous studies on rail steels [21].

During the experimental research, the deformation temperature was varied between 900 and 1200 °C in increments of 50 °C, while the relative deformation ranged from 5 to 35 % in increments of 5 %. Deformation rates of 1, 5, and 10 s^{-1} were used. The selected range of deformation parameters corresponds to their variation during the production of section billets and grinding balls under industrial rolling mill conditions.

Results and discussion

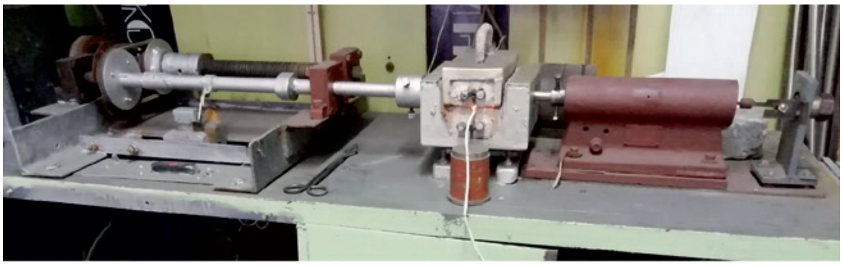
The analysis of the experimental research results revealed (Fig. 2) that, regardless of the combination of temperature-velocity parameters and deformation degree, Steel *4* is the most difficult to deform among the samples studied, while, Steel *1* demonstrates significantly lower deformation resistance. Meanwhile, the deformation resistance of Steels *2*, *3*, and *5* is approximately at the same level, occupying an intermediate position.

These results can be interpreted as follows: for Steels *1*, *2*, *4*, and *5*, the most significant factor influencing deformation resistance was the chromium and nickel

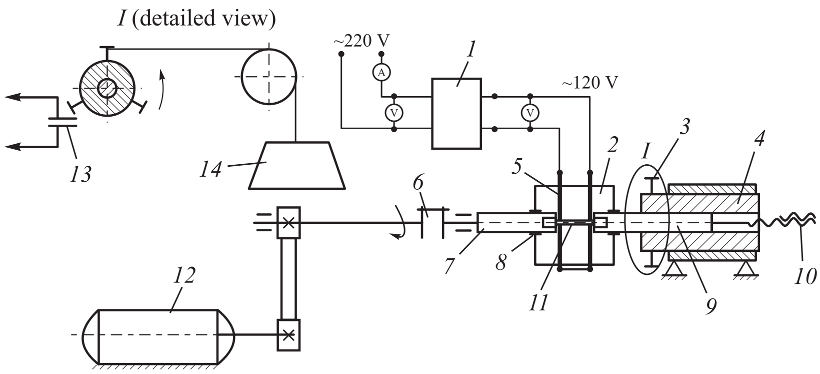
Table 2. **Chemical composition of standard grade ball steels**

Таблица 2. **Химический состав шаровых сталей стандартных марок**

Steel grade	Element content. wt. %								
	C	Si	Mn	Cr	Ni	Ti	Cu	S	P
Sh2.1	0.60 – 0.69	0.20 – 0.30	0.60 – 0.70	–	–	–	–	≤ 0.025	≤ 0.030
Sh2.2	0.70 – 0.80	0.20 – 0.30	0.60 – 0.70	–	–	–	–	≤ 0.015	≤ 0.020
Sh2.3	0.65 – 0.75	0.20 – 0.35	0.70 – 0.80	0.30 – 0.40	≤ 0.30	–	≤ 0.30	≤ 0.020	≤ 0.030
Sh2.4	0.65 – 0.75	0.20 – 0.35	0.70 – 0.80	0.35 – 0.45	≤ 0.30	–	≤ 0.30	≤ 0.020	≤ 0.030
Sh2.Л	0.65 – 0.75	0.20 – 0.35	0.70 – 0.80	0.50 – 0.60	≤ 0.30	–	≤ 0.30	≤ 0.015	≤ 0.020
Sh1	0.50 – 0.65	0.17 – 0.37	0.60 – 0.70	≤ 0.30	≤ 0.25	≤ 0.03	≤ 0.25	≤ 0.020	≤ 0.030
Sh2	0.60 – 0.75	0.17 – 0.37	0.65 – 0.80	≤ 0.30	≤ 0.25	≤ 0.03	≤ 0.25	≤ 0.020	≤ 0.030
Sh4.1	0.60 – 0.70	0.35 – 0.45	0.65 – 0.75	0.35 – 0.45	≤ 0.25	≤ 0.03	≤ 0.25	≤ 0.020	≤ 0.030
Sh4.2	0.55 – 0.65	0.35 – 0.45	0.65 – 0.75	0.50 – 0.60	0.30 – 0.40	0.02 – 0.05	≤ 0.25	≤ 0.020	≤ 0.030
Sh5	0.65 – 0.75	0.35 – 0.45	0.75 – 0.85	0.55 – 0.60	0.40 – 0.50	0.02 – 0.05	≤ 0.25	≤ 0.020	≤ 0.030



a



b

Fig. 1. General view (*a*) and diagram (*b*) of the installation for testing samples for hot torsion:
1 – transformer; *2* – resistance furnace; *3* – locking screw; *4* – fixed shaft housing; *5* – device for fixing the number of revolutions; *6* – silite heaters; *7* – movable shaft; *8* – seal; *9* – fixed shaft; *10* – screw nut; *11* – steel sample; *12* – electric motor; *13* – opening contact; *14* – load

Рис. 1. Общий вид (*a*) и схема (*b*) установки для испытаний образцов на горячее кручение:
1 – трансформатор; *2* – печь сопротивления; *3* – стопорный винт; *4* – корпус неподвижного вала; *5* – устройство для фиксации количества оборотов; *6* – силитовые нагреватели; *7* – подвижный вал; *8* – уплотнение; *9* – неподвижный вал; *10* – винт-гайка; *11* – стальной образец; *12* – электродвигатель; *13* – размыкающий контакт; *14* – груз

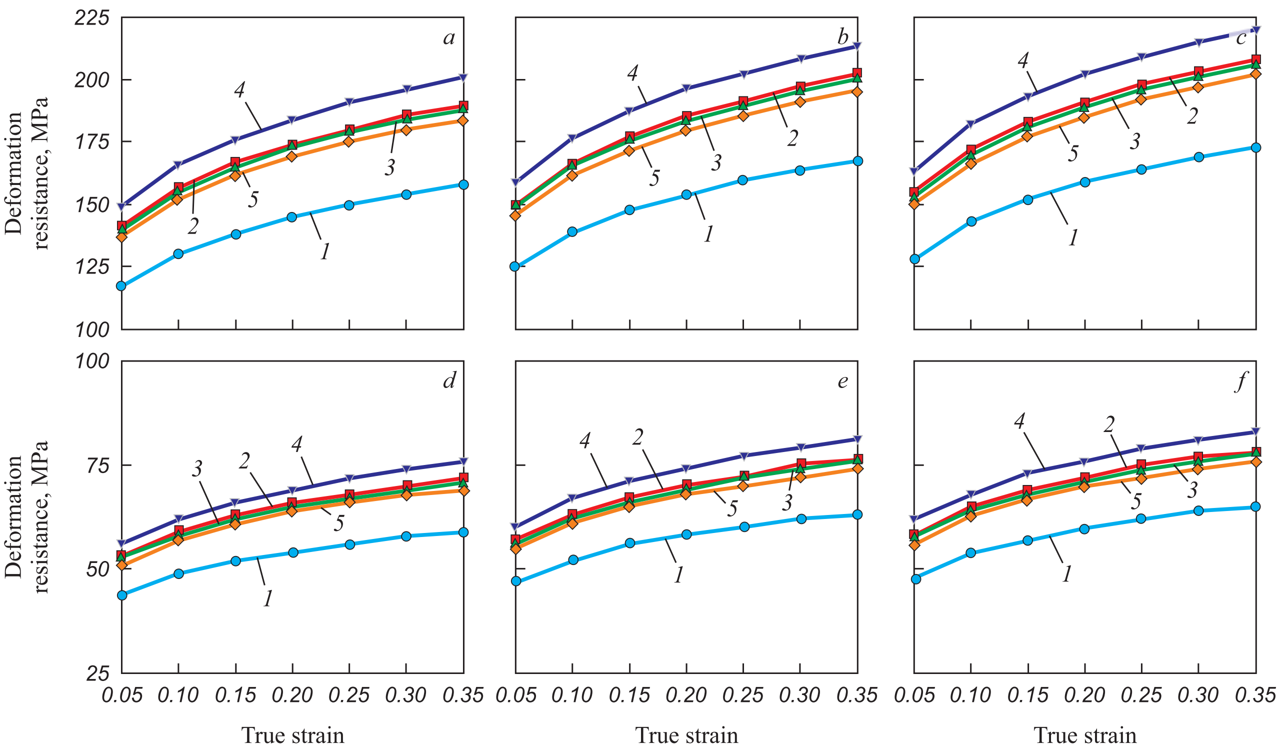


Fig. 2. Flow curves for ball steels at deformation temperatures of 900 (*a – c*) and 1200 °C (*d – f*) and deformation rates of 1 (*a*, *d*), 5 (*b*, *e*) and 10 s^{-1} (*c*, *f*)

Рис. 2. Кривые течения для шаровых сталей при температуре деформации 900 (*a – c*) и 1200 °C (*d – f*) и скорости деформации 1 (*a*, *d*), 5 (*b*, *e*) и 10 $с^{-1}$ (*c*, *f*) content. The deformation resistance of these steels is directly proportional to the concentration of these elements. This relationship is particularly evident given the minimal variations in the concentrations of other elements. Across the samples, the average deviations in carbon, silicon, and manganese content do not exceed 0.045, 0.065, and 0.060 %, respectively (Table 1). For Steel *3*, however, chromium and nickel content are not the determining factors for its deformability. Despite significantly lower concentrations of these elements in Steels *2* and 5 (Table 1), Steel *3* exhibits similar deformation resistance. This behavior in Steel *3* can likely be attributed to its higher carbon content, exceeding that of Steels *2* and *5* by 0.120 and 0.075 %, respectively, and its higher manganese content, exceeding those of Steels *2* and *5* by 0.06 and 0.09 %, respectively. Overall, the findings suggest that carbon content plays a quantitatively dominant role in influencing the deformation resistance of ball steels compared to other elements studied.

It was also determined that, for all the analyzed steel compositions, increasing the deformation degree and deformation rate, as well as decreasing the deformation temperature, reduces deformability (i.e., increases deformation resistance). Additionally, the influence of these parameters on deformation resistance exhibits a distinctly nonlinear pattern, aligning qualitatively with widely accepted principles. Among the deformation parameters, temperature has the greatest impact on deformation resistance. For example, lowering the deformation temperature from 1200 to 900 °C increases deformation resistance by an average of 2.7 times, with deformation rate and deformation degree held constant. In comparison, increasing the true deformation from 0.05 to 0.35 results in only 36 % average increase in deformation resistance under similar temperature-velocity parameters, while changes in deformation rate contribute to a maximum increase of approximately 9 %.

The comprehensive analysis and processing of the experimental results facilitated the development of a regression equation that quantitatively describes the relationship between the deformation resistance of steels used in grinding ball production, their chemical composition, and rolling parameters:

$$\sigma_s = (4032[\mathrm{C}] + 336[\mathrm{Mn}] + 546[\mathrm{Cr}] + 364[\mathrm{Ni}])3689e^{-3.255\left(\frac{t}{1000}\right)}\varepsilon^{0.153}u^{0.004}, \quad (2)$$

where σ_s is the deformation resistance of steel (MPa); [C], [Mn], [Cr] and [Ni] are the contents of carbon, manganese, chromium, and nickel in the steel (%); t is the rolling temperature (°C); ε is the true strain; and u is the deformation rate (s^{-1}).

The validity of the equation was confirmed by comparing the rolling force calculated based on the computed deformation resistances with the actual rolling forces measured during the production of 60 mm diameter grinding ball billets from Sh2.1 and Sh2.3 steel grades (Table 2) at the continuous medium-grade mill 450 of JSC EVRAZ United West Siberian Metallurgical Combine. The observed deviations did not exceed 10 % (Fig. 3), demonstrating the reliability of the equation and its suitability for designing and optimizing rolling modes for both grinding balls and initial billets.

Conclusions

Based on the experimental studies, the relationships between the chemical composition of ball steels, their deformation parameters, and deformation resistance were analyzed both qualitatively and quantitatively. The findings were consolidated into a multiple regression equa-

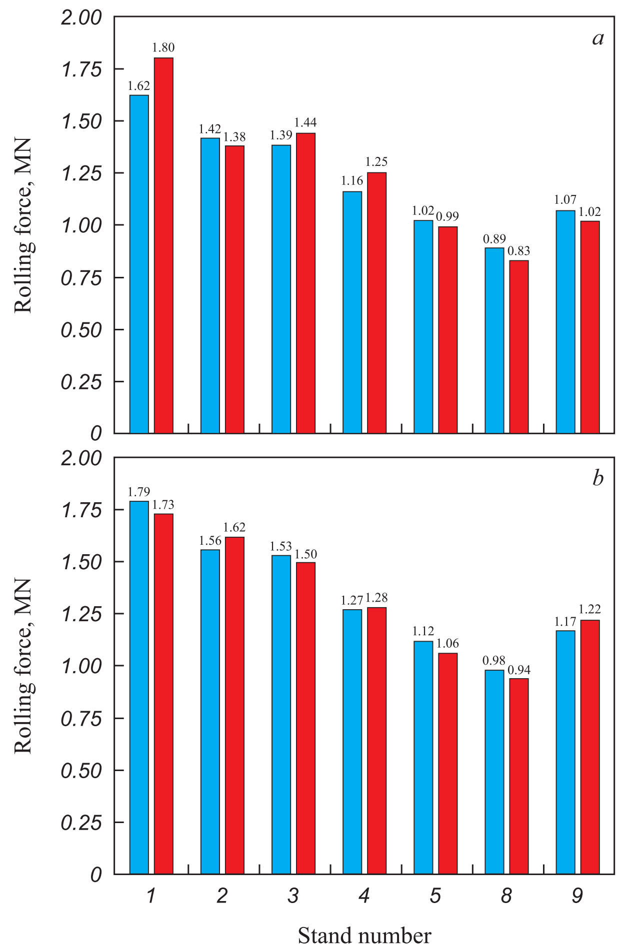


Fig. 3. Rolling force in the roughing stands of the medium-grade mill 450 of JSC EVRAZ United West Siberian Metallurgical Plant in the production of a ball furnace with a diameter of 60 mm made of steel grades Sh2.1 (*a*) and Sh2.3 (*b*): – calculation; – fact

Рис. 3. Усилие прокатки в черновых клетях среднесортного стана 450 АО «ЕВРАЗ Объединенный Западно-Сибирский металлургический комбинат» при производстве шаровой заготовки диаметром 60 мм из стали марок Ш2.1 (*a*) и Ш2.3 (*b*): – расчет; – факт tion, whose validity was confirmed under production conditions for ball steel billets at the continuous medium-grade mill 450 of JSC EVRAZ United West Siberian Metallurgical Plant.

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