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ASSESSMENT OF THE EFFICIENCY OF USING BAKAL SIDERITES IN BLAST FURNACE SMELTING

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Abstract. Metallurgical plants in the Urals are experiencing a shortage of iron ore. This has been compensated by the use of materials imported from Central Russia, the Kola Peninsula and Kazakhstan. Replacing them with local resources would increase the competitiveness of the metal produced in the Urals, which makes the question of assessing the possibility of replacing imported resources with local ones very relevant. Siderite ores from the Bakal deposit could be such resources. They are not in demand among metallurgists because of their low iron and high magnesium content. Calculations of blast furnace smelting made with the help of a balance logical-statistical model showed that additions of calcined and metallized concentrates improve performance. However, with increasing amount of siderites in the charge, the content of magnesium oxide in the slag increases. This in turn affects the viscosity and makes it difficult or impossible to smelt using more than 20 % siderites. The use of boron oxide for slag liquefaction is proposed. Thermodynamic modeling has been used to evaluate the effect of adding 1 – 3 % B_2O_3 to the charge on chemical composition of the slag and the distribution of boron between the metallic and oxide phases. It is shown that in the process of smelting, Boron is reduced from the slag phase, resulting in its partial transition into metal. This causes a decrease in the B_2O_3 content in the final slag. A comparative analysis of the calculated and experimental data shows a similar content of boron in metal, which has been determined both theoretically and experimentally. This should be taken into account when calculating the charge. According to the data obtained, the main reducing agent of boron is silicon, while experimental data show that it is carbon.

Keywords: iron ore, Bakal siderites, ore processing, roasting, metallization, viscosity, slag, boron oxide

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Оригинальная статья

ОЦЕНКА ЭФФЕКТИВНОСТИ ИСПОЛЬЗОВАНИЯ БАКАЛЬСКИХ СИДЕРИТОВ В ДОМЕННОЙ ПЛАВКЕ

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Аннотация. Металлургические предприятия Урала испытывают дефицит железорудного сырья, который компенсируется использованием материалов, завозимых из Центральной России, Кольского полуострова и Казахстана. Замена их на местное сырье увеличит конкурентоспособность производимого на Урале металла, поэтому вопрос оценки возможности замены привозного сырья на местное является весьма актуальным. Таким сырьем могут быть сидеритовые руды Бакальского месторождения. Они не пользуются спросом у металлургов из-за низкого содержания железа и высокого магния. Расчеты доменной плавки, произведенные с помощью балансовой логико-статистической модели, показали, что добавки обожженного и металлизованного концентратов улучшают показатели. Однако с ростом сидеритов в шихте увеличивается содержание оксида магния в шлаке, что влияет на его вязкость и делает затруднительным или невозможным плавку с использованием более 20 % сидеритов. Для разжижения шлака предложено использовать оксид бора. С помощью термодинамического моделирования проведена оценка влияния добавок в шихту 1 – 3 % B_2O_3 на химический состав шлака и распределение бора между металлической и оксидной фазой. Показано, что в процессе плавки происходит восстановление бора из шлаковой фазы и его частичный переход в металл. Это вызывает уменьшение содержания B_2O_3 в конечном шлаке. Сравнительный анализ полученных расчетных и экспериментальных данных показывает близкое содержание бора в металле, определенное теоретически и экспериментально. Это необходимо учитывать при расчете шихты. По расчетным данным основным восстановителем бора является кремний, а экспериментальные данные показывают, что им является углерод.

Ключевые слова: железорудное сырье, бакальские сидериты, обогащение руды, обжиг, металлизация, вязкость, шлак, оксид бора

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The Urals account for 14 % of the Russia's total iron iron ore reserves. This is 13.87 bln t (of which categories $A + B + C_1$ make 8.51 bln t), and their annual production is 22 % of the total Russian production [1]. At the same time, metallurgical enterprises in the Urals are experiencing a shortage of iron ore [2 – 6]. Ore from own production accounts for 50 – 60 %. The rest is imported from Central Russia (Mikhailovsky and Lebedinsky mining and processing complexes), the Kola Peninsula (Kostomuksha mining and processing complex) and Kazakhstan (Sokolov-Sarbai mining and processing complex). The reason is that out of 50 deposits in the Urals, which feature on the state balance sheet, only 23 are in operation. For a variety of reasons, many deposits in the Urals are not being developed at all, or are not being developed intensively enough. In particular, the Bakal deposit of carbonate (siderite) iron ores is located in the Chelyabinsk Region. Its category $A + B + C_1 + C_2$ reserves amount to about 1 bln t [7 – 9]. Mining and geological conditions allow annual extraction up to 20 – 25 mln t of ore. The actual production is many times less. This is associated with weak interest among metallurgists for this resource due to its low quality. The content of iron in crude ore does not exceed 36 % [10]. Roasting and magnetic processing allows it to be increased up to 50 % [11], and metallization increases it up to 70 % [12, 13]. However, a large amount of waste rock remains everywhere due to the absence of an efficient technology for its removal [14].

The constant increase in railroad tariffs has led to an increase in the cost of metal produced in the Urals. This in turn reduces its competitiveness and underlines the need to assess the possibility of replacing imported resources with local ones.

To this end, we have analyzed the efficiency of using siderite ores from the Bakal deposit in blast furnace smelting by comparing the performance of blast furnace No. 9 at the Magnitogorsk Iron and Steel Works (MMK) (Table 1) with the results of analytical calculations. Calculations predicted changes in smelting parameters given the partial replacement in the ore component of a charge consisting of a mixture of the MMK sinter and pellets from the Sokolov-Sarbai Mining and Processing Complex (SSGOK), taken at a 2/1 ratio, with materials made of siderites by different technologies for their preparation for blast furnace smelting (Table 2). Crude siderite ore (CS), concentrate produced by roasting and magnetic processing (RC) and concentrates reduced to different degrees of metallization (MC) were used.

The calculations were based on the mathematical balance logical-statistical model [15] using the thermal and material balances of blast furnace smelting, heat and mass transfer regularities. These take into account the kinetic factors of iron oxides reduction, cast iron and slag temperature, as well as statistical data on the effect of various factors on the furnace performance.

The results of calculations are shown in Fig. 1. They show that blast furnace smelting indicators change linearly when the amount of siderite in the charge is increased.

The addition of crude siderite decreases furnace productivity and increases coke consumption. The reason is that when the average iron content in the charge is reduced, more ore is used to produce 1 t of cast Iron. In addition, the reduction of crude siderites is preceded by their decarbonization [16], shifting the process to the direct reduction zone, thus requiring an increase in total heat consumption.

The use of crude siderite to replace imported resources is ineffective. When using annealed siderite, the smelting parameters deteriorate insignificantly. The change does not exceed 5.5 %. Substitution with metallized concentrate improves the smelting performance, and the higher the metallization, the higher the parameters. This suggests possible efficiency of substitution at a lower cost of siderite concentrates, when compared to imported materials.

However, it should be noted that one of the main conditions for high efficiency of blast furnace smelting is the selection of optimal slag conditions. In this regard, certain requirements are imposed on blast furnace slags. At a temperature of the furnace (1500 °C) they must have:

– viscosity <0.3 – 0.35 Pa·s and <5 Pa·s at the outlet;

– high fusibility;

– low chilling temperature [17]. Waste rock of siderites, regardless of the methods of their preparation, consists of magnesium oxide by more than a half. This passes completely into slag in the process of smelting. According to the calculations, its content in the slag is about 30 % when 45 % siderites are added to the charge. A study of the properties of high-magnesium blast-furnace slags showed

Table 1

Basic indicators of blast-furnace smelting (A_0)

Таблица 1. **Базовые показатели доменной плавки (А0)**

Working volume of furnace, m^3		2014	Cast iron	
Throughput capacity, t/day		4390	composition, %	
Total ore consumption, kg/t cast iron		1660	Si	0.70
MMK sinter, kg/t cast iron		1110	Ti	0
SSGOK pellets, kg/t cast iron		550	S	0.02
Average content of Fe, %		58.80	Mn	0.60
Total flux consumption, kg/t cast iron		8	Ni	0
Total coke consumption, kg/t cast iron		450	P	0.05
Dust output, kg/t cast iron		32	Fe	94.00
Metal losses, kg/t cast iron		20	C	4.50
Consumption of gaseous fuel, m^3/t cast iron		97	temperature, °C	1470
Air blasting			Slag	
quantity	m^3/t cast iron	1070	output, kg/t cast iron	306
	m^3/min	3262	composition, %	
temperature, °C		1064	SiO_2	35.10
moisture content, g/m^3		8	CaO	40.20
oxygen	m^3/t cast iron	26.4	MgO	8.70
	m^3/min	13 830	Al_2O_3	13.90
Blast furnace gas			TiO_2	0.30
output, m^3/t cast iron		1650	FeO	0.60
pressure, atm		1,44	MnO	0.10
content in blast-furnace gas, %	CO	24.2	R_2O	0.74
	CO_2	20.1	S	1.00
	H_2	7.8	CaO/SiO_2	1.14
temperature, °C		187	Heat balance, MJ/t cast iron	
calorific capacity, kJ		3903	input	10 250
degree of usage	CO	0.45	consumption	10 250
	H_2	0.43	Material balance, kg/t cast iron	
theoretical temperature of burning, °C		2018	input	3585
			consumption	3585

that slag with the MgO content of ~10 – 15 % and basicity (CaO/SiO_2) of 0.8 – 1.0 is optimal for blast furnace smelting on Bakal siderites. In terms of desulfurization capacity high-magnesia slags are not inferior to conventional low-magnesia slags.

In this case, an increase of the MgO concentration up to 15 – 20 % at the same basicity does not cause great difficulties in the smelting process. Such slags crystallize at temperatures below 1350 °C and are fluid [18, 19]. A further increase in the magnesium oxide content in slags makes them short and refractory. Slag containing 30 % MgO will be in a solid state at 1400 °C [13]. It can thus be concluded that smelting with a charge containing more than 20 % MgO is difficult or impossible. However, the addition of boron oxide to blast furnace slag [20, 21] reduces its viscosity over the whole temperature range and makes it longer. Since we studied slags containing less than 20 % MgO, it can only be assumed that this tendency will persist forslags with a higher magnesium oxide content. In order to confirm this assumption, the corresponding experimental studies were carried out.

Assuming the possibility of blast furnace smelting at the magnesium oxide content increase in the slag up to 30 % by addition of 20 – 45 % of the roasting and magnetic processing concentrate, the balance logistic-statistical model was used to evaluate the effect of addition of 1 – 3 % B_2O_3 on the process.

Table 2

Chemical composition of ore components

Таблица 2. **Химический состав рудных компонентов**

Component	MMK sinter	SSGOK pellets	CS	RC	MC 20 %	MC 40 %	MC 60 %	MC 80 %
			Symbols on diagrams					
			1	*2*	*3*	*4*	*5*	*6*
$Fe_{tot.}$	56.64	63.10	34.54	49.75	55.15	56.94	58.86	60.91
$Fe_{met.}$	0	0	0	0	11.03	22.78	35.32	48.73
FeO	10.91	3.75	40.47	1.54	56.72	43.93	30.27	15.66
CaO	9.53	1.24	1.95	2.81	3.11	3.20	3.32	3.44
MgO	2.00	0.40	8.01	11.54	12.79	13.21	13.65	14.12
SiO_2	5.72	5.31	7.20	10.37	11.50	11.87	12.27	12.70
Al_2O_3	1.60	2.10	0.99	1.43	1.58	1.63	1.69	1.75
MnO	0.70	0.10	1.83	2.64	2.92	3.02	3.12	3.23
P_2O_5	0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.04
SO_3	0.08	0.12	0	0.30	0.31	0.32	0.33	0.35
$CaCO_3$	0	0	1.53	0	0	0	0	0
$MgCO_3$	0	0	32.18	0	0	0	0	0
$MnCO_3$	0	0	0.89	0	0	0	0	0
FeS_2	0	0	0.60	0	0	0	0	0

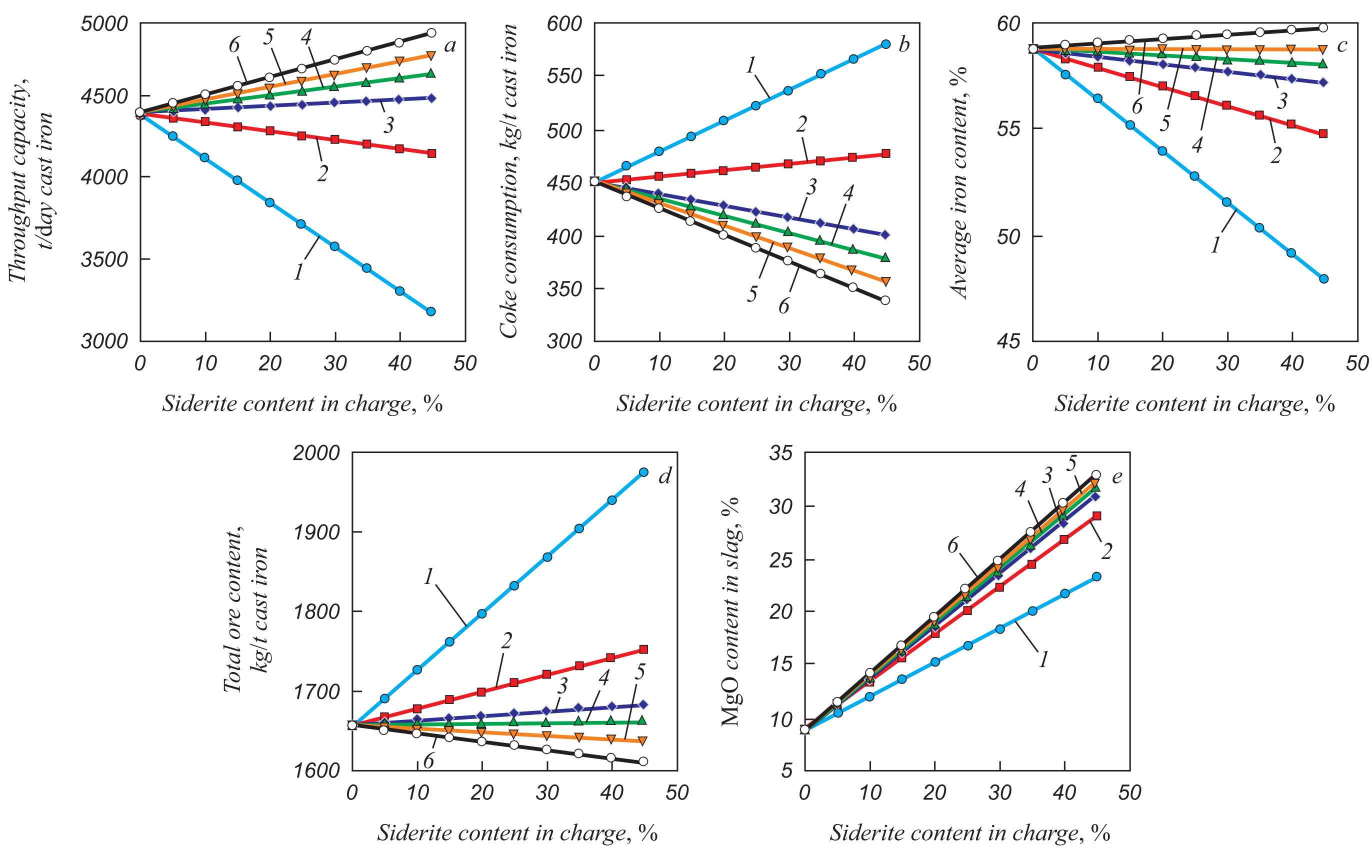

Fig. 1. Dependence of indicators of blastfurnace smelting on the proportion of siderite in the charge, %
(material used: *1* (■), *2* (●), *3* (◆), *4* (▲), *5* (▼), *6* (○) – see Table 2)

Рис. 1. Зависимость показателей доменной плавки от доли сидерита в шихте, %
(используемый материал: *1* (■), *2* (●), *3* (◆), *4* (▲), *5* (▼), *6* (○) – см. табл. 2)

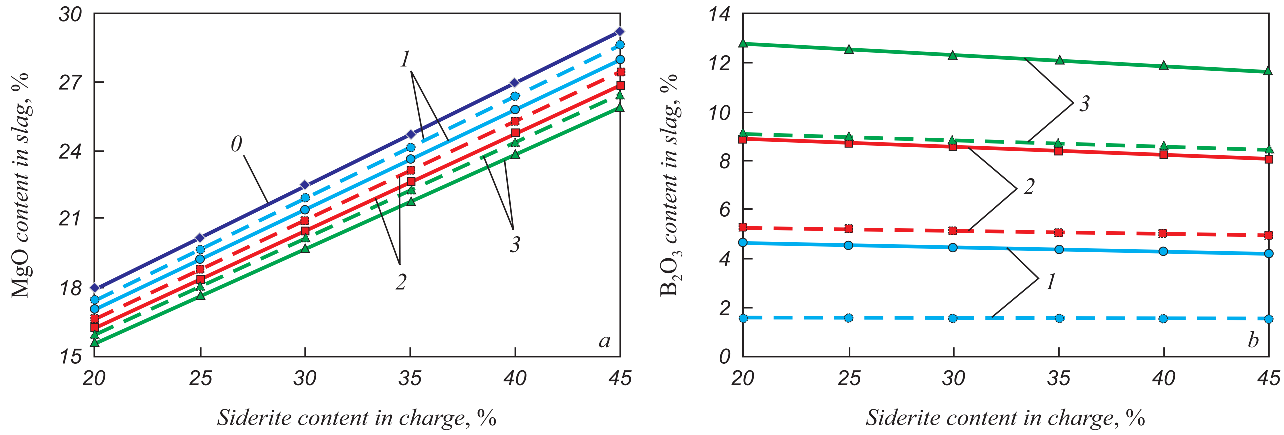

Fig. 2. Change in the content of magnesium oxide and boron oxide in the slag depending on the proportion of siderite in the charge, % (numbers – the content of B_2O_3 in the initial charge)

Рис. 2. Изменение содержания оксида магния и оксида бора в шлаке в зависимости от доли сидерита в шихте, % (цифры – содержание B_2O_3 в исходной шихте)

Calculations show that smelting parameters change insignificantly within 3 %. The productivity and the average iron content decrease, and the consumption of coke and the total consumption of the ore increase.

The addition of B_2O_3 leads to a decrease in the content of all oxide components in the slag, including MgO, and the occurrence of B_2O_3 (solid lines in Fig. 2).

The logical-statistical model does not allow Boron distribution between the metal and slag to be estimated. For this purpose, we used thermodynamic modeling using the IVTANTERMO software [22].

The following system was chosen as a working medium:

– 1 kg of metal containing 94.75 % Fe, 0.75 % Si, and 4.5 % C;

– slag, the mass of which varied depending on the share of siderite and boron oxide in the source ore part from 360 to 450 g, containing 31 – 36 % SiO_2, 19 – 27 % CaO, 8.5 – 11.5 % Al_2O_3, 4.4 – 12.8 % B_2O_3 (according to the logical-statistical model calculations);

– medium – argon, pressure – 10^5 Pa, temperature – 1470 °C.

For simplification, it is assumed that metallic and oxide melts are ideal solutions. Calculations showed that regardless of the proportion of siderites in the charge, when 1, 2 and 3 % B_2O_3 is added to it, 0.36, 0.45 and 0.49 % of boron is transferred to the metal, respectively.The content of B_2O_3 in the slag decreases, and the content of other components, including MgO, increases (dashed lines in Fig. 2).

Paper [23] showed that when 20 % of SSGOK pellets containing 0.26 % B_2O_3 were added to the ore part of the MMK blast furnace charge, the amount of boron in thecast iron produced was 0.007 %, and the B_2O_3 content in the slag was 0.12 %.

Since this data differs significantly from that obtained from the calculation as a result of thermodynamic modeling, we experimentally evaluated the distribution of boron between the metal and the slag. For this purpose, synthetic slag with the following composition was obtainedby remelting a mixture of oxides in the resistance furnace with a graphite heater (Tammanfurnace) at 1500 – 1550 °C, %: 35.6 SiO_2; 21.1 CaO; 25.2 MgO; 9.1 Al_2O_3; 8.3 B_2O_3. A metal alloy containing 4.2 % C and 1.4 % Si was obtained by fusion of iron with silicon and carbon in a resistance furnace with a graphite heater in controlled atmosphere (Ar) at 1550 °C (TVV-type furnace). The next stage was to remeltthe metallic product obtained (cast iron) with an oxide product (slag) at a rate of 40 g of slag per 100 g of cast iron. The composition of the charge was: cast iron – 167.2 g; slag – 66.8 g. Remelting of cast iron and slag was carried out in a resistance furnace with a graphite heater in controlled atmosphere (Ar) at 1550 °C (TVV-type furnace). As a result, iron-based alloy containing %: 2.8 C; 2.2 Si; and 0.84 B and slag with the following composition, %: 40.2 SiO_2; 21.2 CaO; 25.3 MgO; 9.1 Al_2O_3 and 4.1 B_2O_3 were obtained. For comparison, a thermodynamic calculation of equilibrium of the working medium with the same composition and under the same conditions was carried out. As a result, metal containing, %: 4.2 C; 0.2 Si; and 0.6 B and slag with the following composition, %: 41.9 SiO_2; 21.0 CaO; 25.1 MgO; 9.1 Al_2O_3 and 8.3 B_2O_3 were obtained.

A comparative analysis of the calculatedand experimental data shows that the content of boron in the metal is close to that determined theoretically and experimentally. Also boron reduction causes a decrease in its content in the final slag, and this should be taken into account when calculating the charge. According to the calculations, the main reducing agent of boron is silicon, while experimental data shows that it is carbon.

Conclusion

The analytical calculations to predict blast furnace smelting parameters using the mathematical balance logical-statistical model showed that using siderites for substitution of a part of imported blast-furnace resources results in the formation of slag with considerable magnesium oxide content. This adversely affects its physicochemical properties, namely, viscosity and crystallization temperature. In the case of using thinning fluxes and production of fluid slag, the replacement of a portion of imported resources in the charge with roasting and magnetic or metallized concentrate made from siderite ore of the Bakal deposit allows production costs to be reduced. The use of materials containing boron oxide as a flux is expected to produce slag with the necessary properties. It was demonstrated both theoretically and experimentally that cast iron with a boron content of about 1 % will be produced as a result.

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