

Розглядається проблема підвищення інтенсивності плавлення у виробництві сталей з використанням гарячобрикетованих окатишів (НВІ) в шихті, що складається в основному з відходів металу. Проведено аналіз особливості плавлення з використанням шихти складного складу. Для забезпечення кипіння металеві ванни рекомендується додавати в ванну вуглецьмістну сировину у вигляді відходів сталі більше 80 %. Було встановлено, що при використанні НВІ вихід придатного металу майже не знижується. Це пов'язано з високим вмістом металевих відходів, складових шихти.

Одночасно, аналізується роль процесу окислення кремнію і марганцю в рафінуванні рідкої сталі при плавленні в електродуговій печі легованих відходів, що використовуються як шихтовий матеріал. Наведено залежності рівноважних концентрацій кисню і кремнію при різних температурах в системі Fe–Si–O. Також, побудований графік залежності продуктів окислення марганцю в рідкому залізі від температури і концентрації марганцю в сплаві MnO–FeO. Визначені рівноважні концентрації кисню і кремнію з розкислюючою здатністю вуглецю, в області рідких силікатів і в області твердого SiO₂.

Якісне окислення кремнію і марганцю при виплавці сталі з металевих відходів та гарячобрикетованих окатишів (НВІ) сприяє найбільш повному рафінуванню рідкої сталі через фази метал – шлак або метал – газ.

Показано, що під час доведення електросталі вміст кремнію знижується до слідів. Таким чином, в разі використання в якості шихти металевих відходів та окатишів в сталеплавильному процесі реакція окислення кремнію не досягає рівноваги. Якщо проводиться кислий процес, то тоді окислення кремнію досягає рівноважного стану і при певних умовах плавлення шихти під дією тепла електричної дуги може відбуватися значне відновлення кремнію, яке відбувається при більш високій температурі (кремнієвідновлювальний процес). Рекомендовано основний процес плавлення шихти з металевих відходів та гарячобрикетованих окатишів в електродуговій печі. При цьому відновлений період плавки має на меті розкислення металу, видалення сірки, доведення хімічного складу сталі до заданого, регулювання температури процесу. Всі ці завдання вирішуються паралельно протягом усього відновного періоду. Після повного видалення окисного шлаку в ніч присаджували шлакоутворюючі суміші разом з розкислювачами, тобто наводили новий шлак (карбідний або білий).

З підвищенням температури у ванні печі зменшується константа рівноваги марганцю. Тому при відсутності присадок ферромарганцю у ванні в процесі доведення плавки з поведінки марганцю в ванні можна судити про температуру металу

Ключові слова: гарячобрикетований окатиш, електродугова ніч, інтенсивність плавлення, механічні властивості сталі, леговані відходи

IMPROVING STEEL MELTING INTENSITY IN THE PROCESS OF ELECTRO-SMELTING FROM WASTE AND PELLETS (HBI)

R. Karimov

Doctor of Chemical Sciences,
First Deputy General Director
for Production
Ltd «Baku Steel Company»
Mir-Jalal str., 15,
Baku, Azerbaijan, AZ1029
E-mail: raminki@bakusteel.com

1. Introduction

The technology of steel making for the production of construction structures is mainly based on the utilization of various types of metal waste. In addition to its affordability from the economic point of view, it also requires special control over, and attention to, a charge material [1–3]. At the same time, it should be taken into consideration that it is not always possible to obtain a high-quality metal waste. Therefore, improving the intensity of melting when using such charges is very important. This can be achieved in different ways:

- by adding metallized iron pellets to charge;
- by methods of physical influence [4–6].

It is known that one of the most important issues at electric steel making is the choice of a metal charge. Currently, many metallurgical enterprises use the charge that consists of metal waste from melting. Such a charge, in addition to a high iron content compared to iron pellets, has the insignificant amount of harmful additives, including phosphorus

and sulfur. However, in such charges, the amount of manganese and silicon, which are actively involved in the refining of liquid steel, is not always stable. In other words, their quantity can change dramatically even from charge to charge. It is therefore of particular interest to study the process of liquid steel oxidation and refining when using these elements in varying compositions of charges. These elements are included in a metal charge not in the form of ferromanganese and ferrosilicon but in the form of a solution in iron. Therefore, their participation in the processes of oxidation and refining is characterized by a change in the chemical composition of a primary steel [7–10].

Some researchers, for example in [11, 12], studied this problem during iron ore boiling when a significant oxidation of manganese is observed. Lately, many metallurgical plants [9, 13] have switched to smelting high manganese cast iron. The smelting and processing of such a cast iron are economically feasible. In this case, the quality of produced steel does not deteriorate, even if 0.20–0.25 % Mn is not maintained in the bath, as it was previously standardized by technological

instructions on steel making. These requirements were put forward in order to protect the metal from excessive oxidation, as well as to facilitate the process of desulphurization of a bath and its washing from a non-metallic phase.

However, the theory of metallurgy, as well as production practice, revealed the inaccuracy of previous concepts. For example, the level of oxidation of a liquid bath is regulated by carbon and the composition of slag. The desulphurization of a bath is defined by the basicity of the final slag, its low oxidability, and a melting end temperature.

Therefore, is it a relevant task to study the role of silicon and manganese oxidation in the refining processes of electric steel made from the charge that consists of metal waste and pellets only.

2. Literature review and problem statement

Paper [6] describes elements in the theory of a steel-making process. It is shown that all processes related to the production of liquid metal in steel-making furnaces are associated with the formation of slag. Slag mainly consists of oxides and a small amount of sulphides. Chemical analysis makes it possible to establish the composition of slag, but it could not provide information about its mineralogical structure, especially in the liquid state.

In determining the mineralogical structure of slag, of importance are the processes of silicon and manganese oxidation and reduction, which actively participate in the formation of a slag phase and steel refinement. All this suggests that it is appropriate to undertake a research into the effect of silicon and manganese oxidation processes on the quality of steel produced from metal waste and pellets.

There are several varieties of melting in arc steel-making furnaces: with a complete oxidation of additives, smelting of alloyed wastes without oxidation, melting on a liquid semi-product, etc. [7].

Under the influence of high temperature from electrical arc, charge melts first under the electrodes, with the liquid metal flowing down and accumulating in the central part of the bottom. Gradually, complete melting of the charge takes place. To accelerate melting, pieces of the smelted charge from the furnace slopes are shifted to the region of electric arcs. A characteristic feature of the first period of melting is the foundering of «wells» in the charge, around the electrodes. During smelting, there occurs the formation of slag, both due to the admixtures of lime and due to the oxidation of the constituent elements of the charge. Over the melting duration, silicon is completely oxidized, 50–60 % of manganese, carbon and iron are partially oxidized, as well as phosphorus [8].

For high-volume and mass production, it is rather important to accelerate the process of charge melting in the furnace [9, 10].

In some cases, to accelerate melting, engineers often use a turn of the furnace body at $\pm 40^\circ$, or heating charge outside a furnace (in the loading tub), or in the furnace by applying fuel burners. In addition, the melting of the greater part of the charge is followed by blowing with oxygen using lances and tubes. The oxidation of iron, manganese, and silicon is accompanied by the release of considerable amount of heat, which accelerates the melting of metal scrap residues. However, the application of techniques for turning a furnace and heating the charge outside a furnace is associated with additional costs that affect profitability of the electric steel-making process.

Refining occurs during the oxidative period of smelting, that is, there is a decrease in the metal's content of phosphorus, hydrogen, and nitrogen, as well as heating the metal to the desired temperature.

In electric steel making, of importance is the intensity of the process of melting. In this case, the proper choice of a rational ratio between pellets and metal wastes in charge is required [10]. On the one hand, it is impossible, at a small amount of pellets in the charge, to obtain steel of high quality, and on the other hand, at a large quantity of pellets in the charge, the process of melting is decelerated [11]. That is why many authors [10–12] attempted to load pellets into the furnace in batches using baskets. However, such an approach also resulted in a sharp deterioration of melting indicators. As a result, due to the low thermal conductivity of pellets, the metallized charge heated up slowly, part of pellets sintered, the melting time increased greatly, while the stability of furnace lining decreased [13].

To reduce the duration of melting process and to improve its indicators, it is important to properly select the rate of silicon and manganese oxidation. Therefore, to accelerate the melting processes of electric steel, it could prove promising to use in the charge from metal waste a certain amount of hot briquetted iron (HBI). In order to intensify the process of refining steel and bringing the temperature of the liquid steel to the required magnitude, it is possible to carry out at a higher qualitative level the oxidative period of smelting by introducing to the liquid metal the ferroalloys – ferrosilicon and ferromanganese [14]. Consequently, when smelting the charge made from metal waste and pellets in electric arc furnaces, it is necessary to have results from theoretical research into the oxidation process of silicon and manganese that are adequate for actual practice.

3. The aim and objectives of the study

The aim of this work is to identify patterns in the oxidation processes of silicon and manganese when melting steel in an electric arc furnace. This would make it possible to enhance the intensity of melting metallic charge made from metal waste and to improve the quality of refining a liquid steel.

To achieve the set aim, the following tasks have been solved:

- to design the charge from metal waste that contains a certain amount of hot briquetted iron (HBI), to increase the intensity of melting in an electric arc furnace;
- to refine a liquid steel by the intensive oxidation of silicon and manganese for the case when alloyed waste, ferroalloys, and HBI pellets are introduced to the furnace.

4. Materials and methods to study the refining process of electric steel

4.1. Materials for electric steel smelting

«Baku Steel Company» (Azerbaijan) uses the following metal wastes for smelting steel in electric arc furnaces:

- 1) heavy scrap produced directly at metallurgical enterprises;
- 2) scrap and chips from machine-building enterprises;
- 3) light scrap, which is an amortization source.

The wastes of metallurgical enterprises are considered to be a relatively high-quality scrap. The bulk density of this scrap is 1.5 t/m^3 ; it almost does not contain ferrous metals

and non-metallic additives, that is, it has an approximately known chemical composition. When the liquid steel is poured to metal moulds, the amount of waste from rolled steel is about 20–30 % of the total mass of the ingot. This high-quality scrap with a heavy weight is widely used in all processes of steel melting. Continuous casting of steel to a crystallizer, continuously cooled with water, decreases the quantity of waste from rolling (by up to 5–10 %). Thus, the proportion of high-quality scrap with heavy weight is sharply reduced. The shortage of high-quality scrap at smelting in electric arc furnaces, high requirements to the quality of produced steel, require the use of alternative metal charges. Such metallic materials include direct reduced iron (DRI) and hot briquetted iron (HBI). A distinctive feature of hot briquetted iron properties (HBI) from other types of raw materials, waste of scrap steel, is the least amount of sulfur, phosphorus, copper, nickel, chromium, and other additives. In the case where the amount of hot briquetted iron (HBI) does not exceed 25–30 % of the total mass of charge, and when it is added to the arc furnace, the melting process takes place in line with a standard procedure. Reducing the quantity of additives in a metallic raw material allows its use in two ways:

- to obtain a high-quality metal with the use of metallic raw materials in the charge;
- to obtain steel of standard quality, using relatively inexpensive and high-quality scrap.

4. 2. Methods to study the intensification of a smelting process

The bulk density of hot briquetted iron is high (1.2–1.5 t/m³), that is, it is close to the bulk density of specially prepared briquettes for furnaces with a capacity not exceeding 100 tons. Given the existence of a magnetized capability, hot briquetted iron is easily transported to a warehouse and loaded into the furnace. On the other hand, due to the low thermal conductivity of a metallic raw material, it is difficult to heat and melt it, which in turn complicates the technological process of steel melting. Considering all these processes, in order to automatically and uninterruptedly supply charge materials to an electric arc furnace, the following activities were undertaken. To load metal materials under the furnace arcs, including pellets (DRI) and (HBI), the equipment made by the Italian company Demora was installed and put into operation. Thus, the entire cycle of electric steel melting was improved in an electric arc furnace thereby providing for the fully-fledged process and intensive melting. At the same time, the electric arc furnace, in order to increase the intensity of melting, was complemented with the permanent electrical device STK-FKU, made in Germany, with a reactive power of 53 MVAR. The result was an increase in the melting intensity by 14 %, a decrease in time from 55–60 minutes to 45–39 minutes, lower cost of electrodes, current fluctuations. In this case, it was possible to improve performance by 14 %. The applied design of the transformer compensated for losses in active electric power, resulting in a lower cost of consumed active electricity. The average used power increased from 28 MW to 33 MW, the mean value for active power increased to 460 kW, which, in turn, made it possible to reduce the consumption of natural gas, oxygen, and other materials. The load sequence of charge materials in a comparative form is given in Table 1.

Table 1 shows that the use of steel and cast-iron scraps, together with hot briquetted iron (HBI), contributes to the yield of pure metal, averaging 90 %.

Table 1

The sequence of loading charge to the furnace using hot briquetted iron (HBI) in a metallic charge

No.	Melting No.	Tub 1	Tub 2	Tub 3	Cast iron scrap	Hot briquetted iron (HBI)	Total furnace load (tons)	Yield of usable metal (tons)
1	85,392	29.4	19.2	9.6	5.0	15.4	58.2	52.7
2	85,393	29.0	20.4	8.7	5.3	15.3	58.1	52.5
3	85,394	29.2	19.3	10.0	5.4	15.6	58.5	52.7
The sequence of loading charge to the furnace using a metallic charge								
1	85,628	22.0	16.8	11.4	8.2	–	58.4	56.1
2	85,629	23.2	17.0	10.5	9.5	–	60.2	54.6
3	85,630	22.6	16.8	11.2	9.0	–	59.6	52.4

However, when hot briquetted iron (HBI) is not used, when the charge is composed only of metal waste, the yield of pure metal at smelting increases to an average of 91.5 %. In addition, if pellets are used, there is a slight decrease in the amount of pure metal (Table 1).

Features of the technological process of melting are as follows:

- HBI shall be loaded after the formation of a liquid metal in a melting tub;
- continuous loading of HBI shall conform to the power supplied to the furnace;
- the periods of oxidation-decarburization and melting periods should be carried out simultaneously;
- due to the insignificant content of sulphur and phosphorus in the composition of charge, the technological melting process is simplified [15].

Following the initial melting of scrap in an electric arc furnace, HBI is continuously fed into a bath of molten metal. Typically, a specially prepared hole at the body of the furnace is used to load it in the electric arc zone by an automated system. The periods of loading and melting are combined with the stage of oxidation. This ensures continuous oxidation of carbon (bath boiling). The melting process begins with the loading of steel scrap into the furnace; it is 30–40 % of the charge weight. This amount is loaded with multiple tubs. The rate of HBI loading shall conform to the power supplied to the furnace. To this end, a bath temperature should be 30–40 °C above the metal's melting temperature. If the temperature is lower than these indicators, the duration of a melting phase is longer.

To ensure the boiling of the bath, the composition of a metallized raw material must include a certain amount of carbon. When the amount of carbon is insufficient, petroleum coke is injected to the bath for metal boiling. Because the amount of sulphur and phosphorus in HBI is low, the slag basicity may be lower than that when melting normal charge (1.5–2.0).

5. Results of research into steel refining

Chemical composition and mechanical properties of melting, and during rolling using HBI, are given in Table 2.

Table 2

Analysis of chemical composition and mechanical properties of the metal that was melted from hot briquetted iron

No.	Melting number	Chemical composition, %								Mechanical properties			Steel grade
		C	Mn	Si	P	S	Cr	Ni	Cu	Yield limit, R_p , N/mm ²	Strength limit, R_m , N/mm ²	Relative elongation δ , %	
1	85,392	0.20	0.67	0.22	0.017	0.014	0.08	0.06	0.09	545	630	22.1	A500
2	85,393	0.2	0.68	0.25	0.016	0.011	0.06	0.05	0.07	550	645	21.8	A500
3	85,394	0.2	0.65	0.21	0.015	0.012	0.08	0.07	0.09	535	640	22.0	A500
Analysis of chemical composition and mechanical properties of molten metal using metallic charge													
1	85,628	0.2	0.7	0.26	0.028	0.035	0.22	0.18	0.26	570	665	19.2	A500
2	85,629	0.20	0.72	0.27	0.020	0.031	0.23	0.20	0.28	580	672	19.0	A500
3	85,630	0.2	0.69	0.27	0.022	0.034	0.28	0.22	0.24	556	652	19.8	A500

Table 2 gives the results from analysis of chemical composition and mechanical properties of the metal, which was melted at «Baku Steel Company».

Preliminary results from experiments conducted by «Baku Steel Company» showed that when the charge materials are automatically loaded during melting, the weight of hot briquetted iron (HBI) is 40–60 % of the charge mass, which, without any changes to the technological melting process, makes it possible to obtain reinforcement products that meet European standards.

Table 2 demonstrates that using hot briquetted iron (HBI) along with metallic alloyed wastes at electric steel making leads to a slight reduction of the mechanical properties of steel. When the charge is used that consists of alloyed wastes only, the values for mechanical properties of steel are about 5–10 % higher.

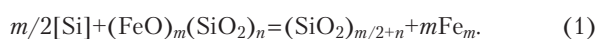
However, it should be noted that a slight decline in the output of a pure metal does not restrict the use of hot briquetted iron (HBI) as an alternative material. In the case when the supply of smelted alloyed steel waste is reduced or is not possible at all, the use of different types of metallized pellets (DRI) and (HBI) becomes appropriate. In such cases, it is necessary to work out modes for a new technological process of melting, which necessitates new research. Therefore, in this case, refining of a liquid metal in the furnace and ladle is of particular importance. Given this, one can argue that the application of oxidation processes of silicon and manganese at charge melting is particularly important in order to enhance the intensity of charge melting in an electric arc furnace.

5. 2. Oxidation of silicon

When dissolved in the remelted metal, silicon can oxidize with oxygen dissolved in the bath of metal, in line with reaction No. 8 (Table 3).

The equilibrium constant of reaction No. 8 is largely dependent on temperature, that is, at low temperatures the susceptibility of silicon to oxygen is very high and decreases significantly at its increase.

The oxidized alloy in the system Fe–Si–O can exist in a liquid form only at $(\text{SiO}_2) \leq 50\%$ in a temperature range from 1.200 to 1.650 °C ($\alpha_{\text{SiO}_2} \leq 1$). Only the solid phase of SiO_2 (at 1.710 °C) may exist under relatively higher concentrations of SiO_2 . Schematically, this can be represented by equation:



According to the rules of phases, three phases (a metal, solid SiO_2 , and a liquid metal oxide) cannot coexist under equilibrium conditions. The boundary concentrations of silicon and oxygen were studied in detail [13]; they separate the areas of liquid silicate alloys and solid (SiO_2). Based on data by the author, in analogy to diagrams constructed in [1, 13, 16], the curve MN was built that separates the curves of equilibrium concentrations of $[\text{Si}]$ and $[\text{O}]$ and the presence of liquid silicates of iron and the solid silicon oxides at their borders at temperatures of 1.540, 1.590, 1.650, and 1.700 °C (Fig. 1). The diagram shows the equilibrium concentration of carbon and oxygen (line AB), as well as oxygen concentration (BGDE) in the corresponding amount of carbon.

As can be seen from the diagram in Fig. 1, at lower temperatures that provide for the onset of melting, even low concentrations of silicon (0.1–0.3 %) ensure small oxygen concentrations under conditions of equilibrium. Therefore, only at high concentrations of carbon (1.5–3 %) there is indeed the melting of pure alloy Fe–C–O.

It is clear that, especially at the beginning of the melting process, carbon cannot be a competitor to silicon. The oxidation of silicon under these circumstances proceeds in line with a two-stage pathway:



Thus, non-metallic silicate compounds may form inside a metal during this melting period. The oxidation of silicon under conditions of oxygen blowing into a metal can occur at the metal and gas interphase (Table 3, reaction No. 9). This is a single-stage (or direct) oxidation of silicon. It is known [16–18] that silicon, when forming the grouping of type Fe–Si with iron, is a weak surface-active component, though more active than carbon.

Based on the analysis performed, one can assume that the conditions for the oxidation of silicon at the metal-gas interphase are more favorable and, with a lack of oxygen (that is, when the amount of oxygen inside a gas volume, enclosed by a liquid metal, is not enough to oxidize all atoms of iron and its impurities, present at the surface that encloses gas, the conditions for silicon oxidation are more favorable than for carbon oxidation [19–21].

Table 3

Thermodynamic characteristics for the oxidation reactions of components in a metal bath at electric steel melting [17, 6]

Reaction No.	Reaction	Standard change in isobar potential, kJ/mol	Thermal function of equilibrium constant
1	$1/2\{O_2\}=[O]$	$\Delta G_1^\circ = -116.94 - 0.0024T$	$\lg K_1 = \lg([O]/\rho_{O_2}^{1/2}) = (6100/T) + 0.12$
2	$Fe_l + 1/2\{O_2\} = (FeO)$	$\Delta G_2^\circ = -237.95 + 0.05T$	$\lg K_2 = \lg(\alpha_{FeO}/\rho_{O_2}^{1/2}) = (12420/T) - 2.61$
3	$Fe_l + [O] = (FeO)$	$\Delta G_3^\circ = -121.00 + 0.052T$	$\lg K_3 = \lg(\alpha_{FeO}/[O]) = (6320/T) + 2.734$
4	$[C] + [O] = \{CO\}$	$\Delta G_4^\circ = -36.63 - 0.031T$	$\lg K_4 = \lg(\rho_{CO}/[C][O]f_{CO}) = (1860/T) + 1.643$
5	$[C] + 1/2\{O_2\} = \{CO\}$	$\Delta G_5^\circ = -152.57 - 0.034T$	$\lg K_5 = \lg(\rho_{CO}/[C]f_{CO}^{1/2}) = (7965/T) + 1.77$
6	$[C] + \{O_2\} = \{CO_2\}$	$\Delta G_6^\circ = -431.26 + 0.051T$	$\lg K_6 = \lg(\rho_{CO_2}/[C]f_{CO_2}) = (22510/T) - 2.64$
7	$\{CO\} + 1/2\{O_2\} = \{CO_2\}$	$\Delta G_7^\circ = -278.69 + 0.084T$	$\lg K_7 = \lg(\rho_{CO_2}/\rho_{CO}\rho_{O_2}^{1/2}) = (14550/T) - 4.40$
8	$[Si] + 2[O] = (SiO_2)$	$\Delta G_8^\circ = -593.84 + 0.233T$	$\lg K_8 = \lg(\alpha_{SiO_2}/[Si][O]^2) = (31000/T) - 12.15$
9	$[Si] + \{O_2\} = (SiO_2)$	$\Delta G_9^\circ = -827.73 + 0.228T$	$\lg K_9 = \lg(\alpha_{SiO_2}/[Si]\rho_{O_2}) = (43200/T) - 11.90$
10	$[Si] + 2(FeO) = (SiO_2) + 2[Fe]$	$\Delta G_{10}^\circ = -351.71 + 0.127T$	$\lg K_{10} = \lg(\alpha_{SiO_2}/[Si]\alpha_{FeO}^2) = (18360/T) - 6.68$
11	$[Mn] + [O] = (MnO)$	$\Delta G_{11}^\circ = -244.53 + 0.109T$	$\lg K_{11} = \lg(\alpha_{MnO}/[Mn][O]) = (12760/T) - 5.68$
12	$[Mn] + 1/2\{O_2\} = (MnO)$	$\Delta G_{12}^\circ = -361.56 + 0.107T$	$\lg K_{12} = \lg(\alpha_{MnO}/[Mn]\rho_{O_2}^{1/2}) = (18860/T) - 5.56$
13	$[Mn] + (FeO) = (MnO) + Fe_l$	$\Delta G_{13}^\circ = -123.35 + 0.056T$	$\lg K_{13} = \lg(\alpha_{MnO}/[Mn]\alpha_{FeO}) = (6440/T) - 2.95$
14	$2[P] + 2.5\{O_2\} = (P_2O_5)$	$\Delta G_{14}^\circ = -154.68 + 0.438T$	$\lg K_{14} = \lg(\alpha_{P_2O_5}/[P]^2\rho_{O_2}^{2.5}) = (80750/T) - 22.88$
15	$2[P] + 5[O] + 4(CaO) = (Ca_4P_2O_9)$	$\Delta G_{15}^\circ = -1372.83 + 0.55T$	$\lg K_{15} = \lg(\alpha_{Ca_4P_2O_9}/[P]^2[O]^5\alpha_{CaO}^4) = (71667/T) - 28.73$
16	$[S] + 2[O] = \{SO_2\}$	$\Delta G_{16}^\circ = -5.63 + 0.054T$	$\lg K_{16} = \lg(\rho_{SO_2}/[S][O]^2) = -(294/T) - 2.80$

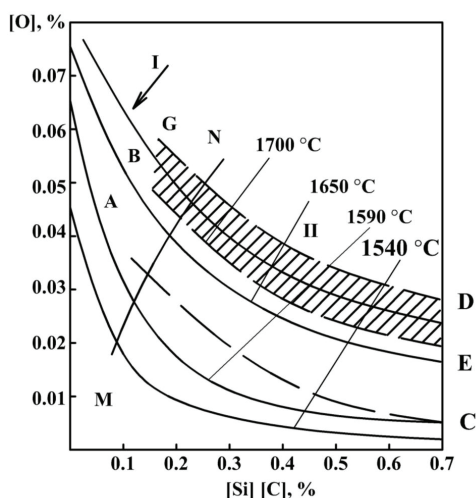


Fig. 1. Dependence of the equilibrium concentrations of oxygen and silicon at different temperatures at different values for α_{SiO_2} when compared with the oxidation capability of carbon: I – region of liquid silicates $\alpha_{SiO_2} < 1$; II – region of solid SiO_2 , $\alpha_{SiO_2} = 1$; AC – curve of equilibrium concentrations – $[C]$ and $[O]$, $[C] \cdot [O] = 0.0027$; BGDE – region of the observed concentrations of carbon in alloy Fe–C–O at melting

Finally, the oxidation of silica may occur in the slags of iron oxides at the boundary between metal and slag (Table 3, reaction No. 10).

Elementary calculations show that in basic slags ($\alpha_{FeO} > 0.10$; $\alpha_{SiO_2} < 1$) silica can fully transfer into the composition of slag at any possible temperatures for melting steel, and at very high temperatures (1.650–1.700 °C) a slight reduction of silicon with iron is possible.

Thus, silicon, as an additive, easily oxidizes to traces in the metallic phase independent both of the participation of components and the high propensity for oxygen under normal melting conditions at the borders metal-gas and metal-slag (Table 3).

This is confirmed by the temperature function of equilibrium constants of reactions as the relatively large values for negative coefficients indicate high rates of reactions.

5. 3. Oxidation of manganese

As shown in Tables 3, 4, manganese has a significantly lower affinity for oxygen than silicon. The oxidation of manganese within a molten metal is simplistically characterized by reaction No. 11 (Table 3).

However, studies [4, 8, 22] show that at the normal concentrations of manganese the oxidation products never demonstrate the pure oxide MnO; they were always represented by alloys (FeO)+(MnO), and the process can be properly described by the following equations:



or



In accordance with the rule of phases, at a constant temperature a mono-variant system is compatible with the manganese oxidation reaction. This means that each specific manganese concentration defines both the amount of oxygen and the compositions of oxidation products (MnO)/(FeO).

Fig. 2 shows the dependence (MnO)/(FeO) on manganese concentration. Before steel deoxidation, at normal concentrations of manganese, the ratio (MnO)/(FeO) varies from 0.5 to 2.5. In a clean system, it was discovered inside a metal that α MnO varies from 0.5 to 0.75 at the elevated concentration of manganese. The isotherms of deoxidization of manganese with a metal in equation No.11 (Table 3) (or equilibrium concentrations of manganese with oxygen dissolved in a metal at different temperatures), constructed by author in analogy to [1, 4, 23], are shown in Fig. 3.

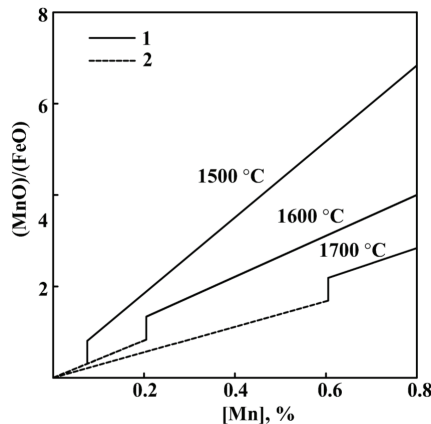


Fig. 2. Dependence of the composition of oxidation products of soluble manganese in a liquid iron on temperature and concentration of manganese in the alloy MnO–FeO: 1 – solid alloys; 2 – liquid alloys

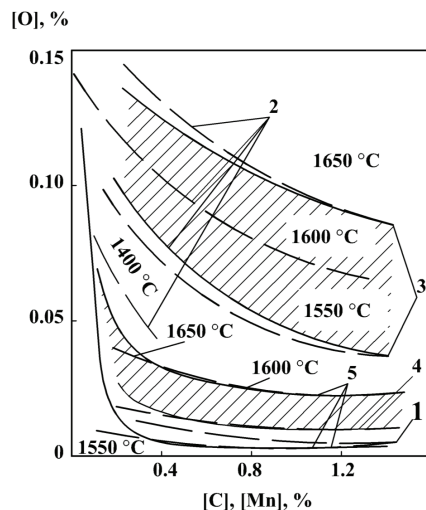


Fig. 3. Equilibrium oxygen concentrations: 1 – with carbon; 2 – with manganese in the pure system Fe–Mn–O; 3 – with basic slags of an electric furnace; 4 – observed with basic slags for open-hearth furnaces; 5 – equilibrium concentration of [O] and [Mn] in the presence of basic slag

Fig. 3 shows that at the amount of carbon of 0.1 % [C] in the bath manganese cannot oxidize in a liquid metal. Only when the amount is <0.1 [C] and at $T \leq 1400$ °C, the equilibrium concentration of oxygen with manganese in a metal is

approximately equal to the concentration of oxygen. In this case, it is in equilibrium with carbon in a metal [20–23]. Manganese has the capability to oxidize in metals and can «control» its oxidation. The deoxidation of a metal with ferromanganese is an exception; in this case, when melting the pieces of a deoxidizer, there forms several percent of its local concentration with the local oxidation of manganese (Table 4).

Table 4

Change in the isobar-isothermal potential during formation of certain oxides of metals

Reaction No.	Reaction	$\Delta H(A)$, kC/mol	$-\Delta S(B)$, C/(mol·K)
1	$Fe_l + 1/2O_{2(g)} = FeO_l$	-237.497	+49.93
2	$Mn_l + 1/2O_{2(g)} = MnO_s$	-406.139	+89.6
3	$Ni_l + 1/2O_{2(g)} = NiO_s$	-254.360	+105.09
4	$Mg_g + 1/2O_{2(g)} = MgO_s$	-739.005	+197.2
5	$Ca_g + 1/2O_{2(g)} = CaO_s$	-803.904	+205.58
6	$2Al_l + 3/2O_{2(g)} = Al_2O_{3(s)}$	-1,674.800	+320.72
7	$Si_l + O_{2(g)} = SiO_{2(s)}$	-897.274	+196.8
8	$Zr_s + O_{2(g)} = ZrO_{2(s)}$	-1,071.872	+184.2
9	$Ti_s + O_{2(g)} = TiO_{2(s)}$	-911.912	+175.4
10	$Mo_s + O_{2(g)} = MoO_{2(s)}$	-573.619	+164.4
11	$W_s + O_{2(g)} = WO_{2(s)}$	-582.62	+174.6
12	$2Cr_s + 3/2O_{2(g)} = Cr_2O_{3(s)}$	-1,109.74	+252.8
13	$2V_s + 3/2O_{2(g)} = V_2O_{3(s)}$	-1,202.925	+227.35

In other cases, the oxidation of manganese occurs at the borders of the following phases: metal-slag or metal-gas.

The first of these reactions correspond to equation No. 13 (Table 3) provided α MnO is equal to 0.05–0.1, depending on [Mn] and temperature (group of isotherms 5 in Fig. 3 or equation No. 13 in Table 1).

A MnO activity coefficient varies depending on the composition of slag; in high-base slags, it is 1.2–1.25, at $(CaO)/(SiO_2) \geq 2$; for pure alloys FeO–MnO γ_{MnO} is equal to 1; for acidic slags, it is 0.2–0.25.

Thus, by setting a temperature of the bath, one can define a constant for the equilibrium of manganese, and, based on the magnitude for this parameter, it is possible to determine the content of manganese in a metal if the content of manganese oxide and iron oxide in slag is known.

6. Discussion of research results aimed to enhance the intensity of electric steel melting

The use of hot briquetted iron in the charge from metal waste does not complicate the automated loading of charge materials. In this case, the mass of HBI being loaded into an electric arc furnace is 40–60 % of the total charge mass. Application of HBI during melting ensures that the steel, as well as structures that are based on it, are of acceptable quality that meets European standards. In addition, of interest is an increase in the amount of HBI in the charge made from metal waste. This approach allows steel smelting from the charge consisting of alloyed waste and HBI. The charge for such melting can be made as follows. Upon melting, the carbon content in a metal should equal 0.05–0.1 % below the specified steel grade, because at alloying and oxidation

the carbon content slightly increases. In this case, the charge is prepared only from the waste of alloyed steels, obtained both directly from a given metal factory and from machine-building enterprises. When making the charge it is necessary to use the maximum amount of waste of a given steel grade or related grades, as well as HBI. Such a rational use of the charge components provides for a greater saving of alloying elements, electricity, and improves the performance of electric furnaces.

The melting based on remelting methods has no oxidation period. At proper calculation of the charge, the melting is immediately followed by a reduction period, a metal is deoxidized, added with certain alloying additives, and released. Such a melting, that is melting by the methods of remelting alloyed wastes, is significantly shorter than a standard melting.

To intensify the process of steel smelting in an electric arc furnace, in addition to using alloyed wastes and HBI in the charge, very important are the processes of oxidation of such elements as silicon and manganese. High-quality oxidative process of these elements contributes to the improved refining of steel and to bringing the temperature of a liquid steel to the required magnitude as a result of the course of exothermic reactions.

The dependence of equilibrium concentrations of oxygen and silicon at different temperatures at varying values of X_{SiO_2} in comparison with the deoxidation capability of carbon shows that at high concentrations of carbon (1.5–3 %) one observes the melting of pure alloy Fe–C–O. At the beginning of the process of melting, silicon oxidation under these conditions may occur in line with a two-stage pathway, that is initially there is the reduction of iron oxide, the oxidation of silicon, followed by the formation of silicate compounds. The further oxidation of silica occurs in slags at the expense of iron oxides at the border metal-slag.

Hence, silicon, as an additive in the amount of 0.35 %, easily oxidizes to traces in the metallic phase and does not depend on the participation of charge components and their high affinity to oxygen under melting conditions at the borders metal-gas and metal-slag. This creates a favorable condition for using the maximum amount of HBI in charge and for intensifying the process of charge melting.

The dependence of composition of the oxidation products of soluble manganese in liquid iron on temperature and concentration of manganese in the alloy MnO–FeO shows that at normal concentrations of manganese the ratio (MnO)/(FeO) varies from 0.5 to 2.5. At the carbon content in the bath >0.1 % [C], manganese does not oxidize in a liquid metal. Manganese oxidation requires that the amount of carbon in the melt

should be not less than 0.1 %. The deoxidation of a metal with ferromanganese is characterized by a different mechanism of manganese oxidation. In other cases, the oxidation of manganese occurs at the interphases metal-slag or metal-gas.

Thus, one can argue that the use in the charge, made from metal waste, the remelted material, combined with HBI, as well as control over the processes of oxidation of silicon and manganese, could intensify the process of steelmaking in an electric arc furnace and obtain steel and reinforcement products that meet the requirements of European standards.

However, a given approach provides steel refining, in terms of sulphur and phosphorus in the range of 0.014–0.035 and 0.028–0.017, respectively, which matches the average level of refining indicators. To provide for a deeper refining of steel, one should further explore the refining technology of steel by blowing powders in the furnace and ladle.

7. Conclusions

1. It has been established that the use of hot briquetted iron (HBI) in the electric arc steel making processes increases the intensity of melting. This manifests itself by the fact that employing such a technological solution made it possible to shorten the duration of melting by 15–20 %. It has been established that the application of hot briquetted iron (HBI) ensures the output of usable metal in the amount exceeding 90 % of the total mass of charge loaded into a furnace, depending on the sequence of loading the components of metallic charge. However, the charge, which includes hot briquetted iron, yields the usable steel in the amount that is by 1.5 % less than that in the case when the charge that consists only of metal waste is applied. This is due to the presence of non-metallic and other compounds on these pellets.

2. It was found that the intensity of the emergence of a new phase in a homogeneous liquid metal (oxidation products of slag-forming components) is significantly higher than during oxidation of carbon and CO evolution. The silicon and manganese oxidation processes were estimated and analyzed; the data on the thermodynamics of their reactions at the border metal-slag was specified. The result of this approach is the achieved refining of reinforcing steel. The amount of sulphur and phosphorus in it was, respectively, 0.14–0.035 and 0.017–0.028. A thermodynamic analysis of oxidation reactions of silicon and manganese at steel electric melting has revealed that the oxidation of these elements occurs both at the borders metal-slag and metal-gas and inside the metallic phase, regardless of the presence of other components.

References

1. Yavoyskiy V. I. *Teoriya protsessov proizvodstva stali*. Moscow: Metallurgiya, 1993. 450 p.
2. Efroyimovich Yu. E. *Optimal'nye elektricheskie rezhimy dugovykh staleplavil'nyh pechey*. Moscow: Metallurgiya, 1996. 158 p.
3. Myuller F. *Elektrostaleplavil'noe proizvodstvo v nachale XXI veka // Stal'*. 2004. Issue 11. P. 31–34.
4. Gorodets V. G., Gavrilova M. N. *Proizvodstvo stali v dugovoy pechi*. Moscow: Metallurgiya, 1986. 208 p.
5. *Proizvodstvo stal'nykh otlivok: ucheb.* / Kozlov L. Ya., Kolokol'tsev V. M., Vdovin K. N. et. al.; L. Ya. Kozlov (Ed.). Moscow: «MISIS», 2003. 352 p.
6. Kudrin V. A. *Teoriya i tekhnologiya proizvodstva stali: ucheb.* Moscow: «Mir», OOO «Izdatel'stvo AST», 2003. 528 p.
7. Gusovskiy V. L., Orkin L. G., Tymchak V. M. *Metodicheskie pechi*. Moscow: Metallurgiya, 2010. 430 p.
8. *Protssesy i mashiny elektrometallurgicheskogo proizvodstva: monografiya* / Rahmanov S. R., Topalov V. L., Gasik M. I., Mamedov A. T., Azimov A. A. Baku-Dnepr: «Sistemnye tekhnologii» – Izdatel'stvo «Sabah», 2017. 568 p.
9. Dupp E., Pardaens S., Freibnuth A. *Fachberichte Hüttenpraxis // Metallweiterrverarbeitung*. 2013. Vol. 21, Issue 10. P. 776–779.
10. Knep K., Rommerswinkel H. W. *Arch. Eisenhüttenwesen*. 2015. Issue 8. P. 493–498.

11. Olette M., Gateller C. Clean steel // Proc. Engl. 2nd Int. Conf. Balatonfüred, 2011. P. 122–137.
12. Sidorenko M. F., Magidson I. A., Smirnov N. A. Scan inject // 3rd International Conference of Retining on iron and steel by powder injection. Lulea, 2013. P. 7/1–7/36.
13. Trubin K. G., Oyks G. N. Metallurgiya stali. Moscow: Metallurgiya, 1997. 515 p.
14. Efimov V. A. Razlivka i kristallizatsiya stali. Moscow: Metallurgiya, 2006. 550 p.
15. Povolskiy D. Ya. Raskislennyye stali. Moscow: Metallurgiya, 1992. 207 p.
16. Kudrin V. A. Metallurgiya stali. Moscow: Metallurgiya, 1991. 488 p.
17. Bigeev A. M. Metallurgiya stali. Moscow: Metallurgiya, 2007. 440 p.
18. Bewar J. Fachber. Hüttenprax // Metallweiterarbeiten. 2011. Issue 1. P. 55–58.
19. Yashimura M., Yochikawa S. Mitsubishi sted // Mtg. Techn. Rev. 2010. Vol. 14, Issue 1-2. P. 1–12.
20. Abratis H., Langhammer H. J. Radex Kdsh. 2011. Issue 1-2. P. 436–442.
21. Itskovich G. M. Raskislenie stali i modifitsirovanie nemetallicheskih vklyucheniy. Moscow: Metallurgiya, 2011. 306 p.
22. Oyks G. N., Iofore H. M. Proizvodstvo stali. 4-e izd. Moscow: Metallurgiya, 2009. 525 p.
23. Trubin K. G., Oyks G. N. Metallurgiya stali. Moscow: Metallurgiya, 2004. 535 p.

Досліджено спосіб протягування товстостінних труб. Запропонований спосіб полягає в деформуванні пустотілої заготовки без оправки. Розроблено методіку проведення теоретичних досліджень МСЕ. Методика призначена для визначення теплового, деформованого стану та формозміни заготовки при куванні труб без використання оправки. Змінними параметрами були внутрішній діаметр пустотілої заготовки, який варіювався в інтервалі 0.30; 0.55; 0.80. На основі скінчено-елементного моделювання були встановлені: розподіл температур і інтенсивності логарифмічних деформацій в об'ємі труби після протягування без використання оправки. Визначався діаметр отвору труби, який утворюється при протягуванні даним способом. Встановлювалися залежності інтенсивності подовження та потовщення стінки труби. Був розроблений спеціальний показник для оцінювання подовження труби. Було визначено, що при збільшенні внутрішнього діаметру подовження труби збільшується та знижується інтенсивність зменшення отвору. Загальною залежністю змодельованих схем протягування є те, що величина подовження пустотілої заготовки несуттєво змінюється для різних ступенів обтискань при сталих відносних розмірах труби. Це дозволило встановити рекомендацію подачу для збільшення подовження пустотілої поковки та зменшення ступеня закриття отвору. Раціональна подача повинна складати (0.05...0.15)D. Результати скінчено-елементного моделювання перевірялися експериментальними дослідженнями на свинцевих зразках. Була запропонована методіка експериментального моделювання. Встановлено, що при внутрішньому діаметрі заготовки (0.5...0.6)D, спостерігається максимум потовщення стінки. Встановлено, що результати з формозмінення заготовки, які отримані у теоретичному дослідженні МСЕ, на 9...14 % більше за експериментальні. Достовірність результатів теоретичного моделювання підтверджується даними експерименту зі зменшення внутрішнього діаметру труби. Різниця теоретичних результатів й експериментальних складає 9...12 %. Встановлені закономірності дають можливість визначати остаточний діаметр отвору труби. За результатами моделювання встановлено, що протягування трубних заготовок без оправки цілком можливе. Цей спосіб розширює можливості техпроцесів виготовлення трубних заготовок

Ключові слова: товстостінна труба, протягування без оправки, кування, заковування отвору, подовження заготовки, МСЕ, тепловий стан, деформований стан

UDC 621.735.3

DOI: 10.15587/1729-4061.2019.167077

MODELING THE TECHNOLOGICAL PROCESS OF PIPE FORGING WITHOUT A MANDREL

O. Markov

Doctor of Technical Sciences,
Professor, Head of Department*
E-mail: oleg.markov.ond@gmail.com

O. Gerasimenko

PhD, Associate Professor*

A. Khvashchynskiy

Postgraduate student*

R. Zhytnikov

Postgraduate student*

R. Puzyr

Doctor of Technical Sciences,

Associate Professor

Department of Mechanical Engineering

Kremenchuk Mykhaylo Ostrohradskiy

National University College

Chumatskiy Shliakh str., 7,

Kremenchuk, Ukraine, 39621

*Department of Computerized Design

and Modeling of Processes and Machines

Donbass State Engineering Academy

Akademichna str., 72,

Kramatorsk, Ukraine, 84313

1. Introduction

A priority task for the development of power engineering is to reduce the cost of parts and to improve their mechanical

properties [1–3]. Such parts include thick-walled pipes. These forgings must be produced by forging on a mandrel. However, the thick-walled pipes are manufactured from solid shafts by using the operation of drilling a hole [4]. The result is the