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AN IMPACT OF THE LADLE LINING ON THE REFINING OF REINFORCED STEEL WHEN BLOWING WITH POWDERS

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При рафінуванні сталі продуванням порошками матеріал футерування ковша грає серйозну роль. Представлені графіки залежності ступеня десульфурації від витрати порошку силікокальція під час продування в ковшах, футерованих різними матеріалами. Відзначається, що кількість FeO в шлаку чинить серйозний вплив на середню ступінь десульфурації. При великій кількості FeO в шлаку, сильно підвищується ступінь ресульфурації. Представлений план розміщення обладнання для рафінування рідкої сталі в ковші. Одночасно для продування порошку представлена схема пристрою піч-ківш, оснащена обладнанням для продування рідкої сталі порошками. В цьому обладнанні можна використовувати порошкове футерування і здійснити продування сталі порошками на основі силікокальція. На ступінь десульфурації серйозний вплив здійснює також вихідна кількість сірки в металевій шихті для виплавки сталі. Наявність кришки в ливарних ковшах покращує умови продування металу, зменшується окислення і втрата металу.

Відзначено, що процес рафінування рідкої сталі в ковші є складним процесом і залежить від багатьох факторів. Кількість сірки в первинній шихті металу, футерування ковша, склад порошку продуваного матеріалу і технологічні параметри продування мають важливе значення. Повна десульфурація сталі шляхом продування порошками, в першу чергу, залежить від початкової кількості сірки в металі. Виявлено, що існує лінійна залежність кінцевого вмісту сірки від її вихідного змісту в сталі під час продування металу в ковші з сумішшю 70 % MgO, 20 % CaO і 10 % CaF_2. На десульфурацію сталі продуванням порошками, особливо продуванням сплавів магнію і кальцію, футерування ковша може мати значний вплив

Ключові слова: футерування ковша, продування порошками, десульфурація, ресульфурація, доломітове футерування, ківш-піч

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1. Introduction

Intensive introduction of various methods of secondary steelmaking provides a guaranteed production of liquid steel with a minimum content of undesirable impurities. The implementation of these methods requires the use of the necessary equipment (vacuum chamber, powder injection devices, introducing special wire, metal purging and its mixing, steel heating during its processing, etc) and high-quality refractories.

Nowadays, the most effective way to reduce losses on the way from the steelmaking device to the production of applicable rolled products is transition from casting into molds to the use of continuous casting machines. In this respect, a reduction in metal overspending due to insufficiently high quality, as well as a reduction in metal consumption owing to ordinary alloyed steel (with minimum alloying losses) is ensured by the widespread introduction of ladle refining method. When using these methods, the concentration of harmful impurities in the metal, composition and temperature fluctuations, as well as the consumption of deoxidizers and alloying additives decrease.

Among the methods of secondary treatment of steel, the injection of powdered reagents in electric steelmaking can be considered as the most effective.

The process of liquid steel refining in a ladle is complex and depends on many factors: the amount of sulfur in the primary metal charge, ladle lining, the powder composition of the purged material and the technological parameters of the purge are of great importance.

At present, there is still no clear answer to the question of which reagents are preferable to introduce into the metal at individual links of the technological chain and how.

However, the desulfurization of steel by powder purging, especially by purging magnesium and calcium alloys, can be significantly affected by ladle lining.

2. Literature review and problem statement

Steel refining both in the furnace and in the ladle is important in the production of electrical steel from remelting waste. In this case, better refining is achieved using the method of introducing various reagents into the depth of the metal [3].

Presently, one of the most common methods of secondary treatment of steel is blowing with powders. Calcium-containing materials are most frequently used as powdered materials for treating metal in a ladle [4]. This is due to the following: calcium has a high chemical affinity for oxygen; therefore, its introduction into the metal provides a high degree of metal deoxidization. Calcium also has a high chemical affinity for sulfur; therefore, its introduction into the metal provides a high degree of steel desulfurization and low sulfur content after processing [5].

The most common deoxidizer of steel is aluminum. It forms refractory inclusions of alumina worsening metal purity, mechanical properties of products made of it and complicates casting due to the overgrowth of nozzles [6]. Calcium oxide (CaO) formed when calcium is introduced into steel, interacting with Al_2O_3 particles ensures the occurrence of less refractory nonmetallic inclusions [7]. Those that remain in the metal are very small and spherical in shape. During pressure treatment, they are not deformed and they are not stretched in chains of acute-angle clusters. This is common for alumina inclusions, which to a small extent worsen the properties of the metal [8].

In this context, it should be noted that the use of magnesium, which has a higher oxygen-affinity than calcium in powder mixtures and furnace lining could give better results [9].

Aluminum-deoxidized steel after the introduction of magnesium can practically have no plastic silicates. Magnesium in comparison with calcium can also more effectively reduce the harmful effects of sulfur remaining in steel, since the mechanical properties of magnesium sulfide (MgS) are significantly higher than those of calcium sulfide (CaS), especially manganese sulfide (MnS). Consequently, sulfites can also acquire a more rounded shape with a much shorter length (along the direction of plastic deformation) [10].

This allows to conclude that the use of a dolomite-lined ladle ($MgCO_3 \cdot CaCO_3$) can also lead to the above effects during secondary steelmaking.

Research on the use of magnesium as the main component of a powder mixture for liquid steel injection and lining material in the literature are very scarce, therefore carrying out researches in this direction would be interesting.

3. The aim and objectives of the study

The aim of the research is to study the influence of the ladle lining material on the refining of steel when purging it with magnesium-containing powders. To achieve this aim, the following tasks have been assigned:

– study of the effect of the lining material on the degree of desulfurization at different silicocalcium consumption;

– study of the degree of desulfurization of steel on argon blowing time at different oxide Fe content in the slag;

– development of the equipment placement plan for hot metal refining in the dolomite lined ladle;

– improvement of the installation scheme of the ladle-refining furnace equipped with powder injection equipment;

– study of the effect of the initial amount of sulfur in the metal on the degree of steel desulfurization.

4. Discussion of experimental data

4. 1. The influence of the ladle lining

Fig. 1 illustrates the results of steel desulfurization by blowing with silicocalcium powders in the ladle furnace lined with different refractory materials. This figure is based on our experimental data by analogy with [9]. All experiments were carried out in a 50 tons ladle lined with various bricks. Steel from remelting wastes is melted in an electric arc furnace with a capacity of 60 tons. The data given in Fig. 1 is the average results of 10 heats.

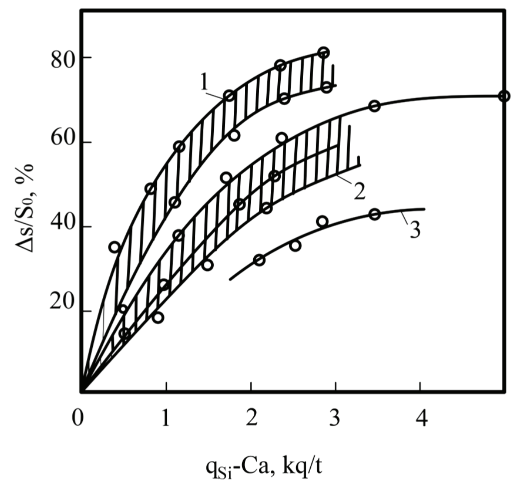

Fig. 1. Dependence of desulfurization degree on the silicocalcium consumption in the dolomite lined ladles (1), schamotte (2), silicium oxide (3) (1,000 kg surface furnace slag): 1 — dolomite lining; 2 — fireclay lining; 3 — silica lining

It is worth mentioning that the highest degree (~80 %) and the lowest silicocalcium consumption (~1 kg/t) for refining 1 ton of steel correspond to dolomite-lined ladle. To achieve this degree of desulfurization in acid-lined ladles, very high consumption of silicocalcium (3.5–4.5 kg/t) is required, which is primarily not always technically possible. This significantly reduces the amount of silicon in the steel and increases heat loss. According to [9], in a 125 tons dolomite-lined ladle with the consumption of calcium, silicocalcium and calcium carbide at the rate of 1 kg/t with powder blowing, the degree of steel desulfurization is 80 % and the final amount of sulfur is 0.003 %. It was noted that these results were obtained in a ladle without a roof. Lower sulfur concentrations can be obtained in basic ladle furnaces with a roof, which helps reduce heat loss, prevent spatter and allow dust to be trapped. With an increase of the ladle capacity, the consumption of the desulfurizing agent is decreased. For instance, in the ladle with a capacity of 250 tons silicocalsium consumption is 30 % lower than in a ladle with a capacity of 125 tons. The optimal consumption of silicocalcium, the precise regulation of its blow for desulfurization are achieved as a result of formation of highly basic slag on the metal surface before blowing. If the furnace slag enters the ladle, the level of desulfurization is reduced by 20–25 %. In dolomite lining ladles, the degree of calcium absorption is much higher (25 %). Therefore, steel refining with TN method [10] is carried out in dolomite lined casting ladles with a durable removable roof where steel can be stored for a long period without significant heat loss.

The ladle lining significantly affects the composition and basicity of slag [3]. When using a ladle, lined with schamotte and 75 % Al_2O_3, the reason for the lower basicity of the slag is the destruction of the lining. In this case, the considerable amount of the introduced magnesium and calcium is spent on the interaction with ladle lining. The same situation occurs during the steel refining process in a ladle lined with alumina, but in this case the recovery rate of silicon decreases slightly. Thus, the use of an unstable acidic heat-resistant coating for ladle lining worsens desulfurization conditions by injection of calcium and magnesium alloys. The results of our experiments carried out in a ladle with high alumina lining (75 % Al_2O_3) are characterized by a significant difference in the data on electric steel blowing. This is due to unstable experimental conditions: significant fluctuations in the composition and amount of furnace slag entering the ladle, the amount of aluminum in the metal and temperature. In this case, the experimental values of the oxygen activity are close to equilibrium (0.0004–0.0008 %), considering that the oxygen activity in the liquid metal is controlled by the interaction of the heat-resistant lining of the ladle. The highest value of the ratio $(S)/a_s$ was obtained by injecting the mixture of CaO-CaF_2 into the dolomite lined ladle.

According to the authors [11], it is necessary to use ladles with a lining that does not contain siliceous compounds. Such ladles successfully perform steel desulfurization in a 60 tons ladle when silicocalcium blowing and they also provide imparting globular shape to non-metallic inclusions. In case of using the ladle made of refractory bricks consisting of silica, it was impossible to reduce the amount of sulfur in the steel (0.003–0.004 %) to the required level. In this regard, the specific ladles lined with magnesite bricks were used for desulfurization. After placing 3.5 kg/t lime hydrate on the surface of the slag in the ladle, the latter one was transferred to a steel desulfurization stand. The roof of the ladle was closed down to prevent liquid metal splashes and heat loss. To increase the powder extraction rate, silicocalsium powder was blown with a 15 mm heat-resistant lined coil and an 8 mm diameter metal pipe (25 kg/min at a rate of 12 kg/t). The immersion depth in the lower part of the ladle was 50 cm and in pneumatic conveyors, its flow rate was 15 dm^3/s at an argon pressure of 1 MPa.

Dolomite lining ladles were also used. Before steel processing, lime and a mixture of slag and fluorspar were fed into the ladle. Powder blowing was carried out using a ladle with a roof. An inert atmosphere of argon or nitrogen was created on the surface of the liquid before the injection process. Injection of 1 kg/t of silicocalcium powder for 8 minutes allowed obtaining the amount of sulfur ≤0.005 % and all non-metallic inclusions (even large ones) in globular forms. With an increase in silicocalcium consumption up to 2 kg/t and blowing time up to 13 minutes, the sulfur content is ≤0.003 % and it becomes possible to obtain high-quality steel. In this case, the strength and viscosity characteristics of steel intended for the production of rebar significantly improved [12].

In [13] it was indicated that in order to successfully carry out desulfurization of steel by blowing powder mixtures, as well as giving nonmetallic inclusions of globular shape, it is necessary to use ladles with silica-free lining. Metal blowing with CaO–CaF_2–Al_2O_3 powder mixtures in 60 tons ladles with high alumina lining allows achieving a desulfurization degree of 60–80 % at initial sulfur contents of 0.010–0.035 % and final 0.004–0.007 %. In this case, at 1550–1700 °C, we injected 30 kg/t of the mixture for 3–4 minutes. Desulfurization degree in schamotte lining ladle furnaces was observed to increase up to 70–90 %. The initial and final concentration of sulfur was measured to be 0.015÷0.030 % and 0.002÷0.008 %, respectively. When using fireclay lining in a ladle with a capacity of 60 tons along with injection powders in the shortest time (3–3.5 minutes), the degree of desulfurization, which is relatively low when blowing, was also achieved in the case of using powders of lime and fluorspar. A high degree of desulfurization (90 %) in ladles with fireclay lining was achieved using 85 % lime, 15 % fluorspar with the addition of silicocalcium (0.3 kg/t), aluminum (0.2 kg/t) in an amount of 10 kg/t in a short time (2–3 min) injection of it into the metal. However, the effect of fireclay lining on the amount of sulfur in the metal appears during its subsequent exposure to the ladle and casting. The amount of sulfur in the finished steel usually increases to 0.001–0.003 %. The degree of desulfurization depends on a number of factors, and above all, on the chemical composition of the slag formed in the ladle, especially on the amount of FeO.

4. 2. Effect of argon blowing time

If after blowing with powder mixture, pure argon was blown into steel, an increase in the high degree of resulfurization and an increase in the amount of FeO in the slag are observed due to the blowing time of the metal with argon (Fig. 2). It is necessary to take into account the phenomenon that for the complete removal of gases and non-metallic inclusions, the processing of steel with argon should be further carried out in a schamotte ladle lining [14–17]. An important factor is the integrity level of desulfurization that is achieved by the steel refining with powder mixtures. As a result of processing, to achieve very low sulfur concentrations (≤0.003 %), subsequent significant resulfurization is possible (Fig. 2).

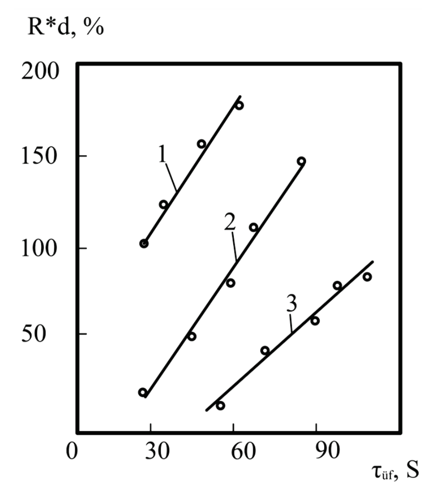

Fig. 2. Dependence of the steel resulfurization degree on argon blowing time in different concentrations of FeO in the slag: [5]: 3.08 (1), 2.08 (2), 0.51 % (3): 1 – 3.08 % FeO; 2 – 2.08 % FeO; 3 – 0.51 % FeO

The degree of resulfurization is determined by a number of factors and primarily depends on the chemical composition of the forming slag in the ladle, especially on the content of FeO in it (Table 1).

Table 1

The relationship of desulfurization degree and average content of FeO in slag (wt. %)

Average concentration of FeO in slag	3.80	2.15	1.88	0.58
Average degree of desulfurization	1.15	65	38	18

The use of a ladle with a base lining allows obtaining a desulfurization degree >85 % when blowing well-deoxidized steel with argon, MgO–CaO–CaF_2 powders together with slag for 8 minutes. However, in [18] it was observed that high desulfurization degree (~80 %) could be obtained in the large capacity ladles with schamotte lining. This experience is important for workshops with limited carrying capacity, which cannot always be used. We have established that mixing slag and metal with argon and blowing a mixture of powders of 50 % MgO, 25 % CaO, 15 % CaF_2, and 10 % Al_2O_3 in a fireclay lined ladle with a capacity of 60 tons lead to a desulfurization process. The ladle is closed with a heat-resistant roof with holes, which are for fixing the tuyer. In order to reduce the partial pressure of oxygen, argon is supplied under the roof. Then, for intensive mixing of the metal with slag, argon (1.4–2.0 m^3/min) is supplied using a lined tuyer. The tuyer has two ends located on a horizontal plane, which ensures good penetration of gas or powder into the liquid metal and good atomization during prolonged contact with it.

The authors [19] noted that the shape and dimensions of the ladle significantly affect the feed rate of powders and gas, as well as heat loss. We found that with increasing depth of blowing, high pressures are required. The main disadvantage of blowing metal with powders in the open ladle is the need for extreme heating of liquid metal in the smelting unit for the compensation of metal temperature during the refining. The best results are obtained in case of using the ladles with a roof. In this case, the most radical solution is replacing conventional steel-making ladles with auxiliary metallurgical units, in which the metal is refined from harmful impurities and the required composition and temperature are reached. In all cases, applying the roofs for ladles improves the blowing condition, reduces metal loss by splattering and if necessary allows keeping inert atmosphere on the metal surface.

The bucket must be preheated. Installing the roofs on casting ladles requires further replacing the stoppers with slide gates, which eliminates long delays in the steel refining process when blowing with powders. In some cases, the refining and casting ladles in the slag zone were lined with dolomite or alumina bricks and equipped with a porous plug for bottom argon blowing.

At Krupp Stahl AG factories [7] all casting ladles in secondary steelmaking are equipped with porous fire-resistant devices in the center of the ladle for bottom argon blowing of metal. Ladle lining is made of schamotte or magnesite and dolomite, whereas in the slag belt is made of dolomite. The durability of the ladles with intermediate ladle bottom repair is 40 heats. Heating the ladles up to 1,200 °C is limited only by the durability of the lining. In order to reduce the effect of splashes on the edges and roof of the ladle, the shape of the ladle has been modified (converter-type ladle).

We have found that injection of powders is accompanied by metal cooling in the ladle which depends on the blowing time, the flow rates of the powders and the transported gas, the type and capacity of the ladle, the used tuyer and its immersion depth. When the powder is injected to a depth of 2–3 m, the ferrostatic pressure at the tuyer section increases and in order to remove the storing of the metal in the tuyer channel, it is necessary to increase the gas flow rate, which leads to additional heat loss (up to 60 % of all losses during blowing with powders). According to various researchers, the cooling rate of the metal in the ladle ranges from 1.8–3.72 °C/min. As a rule, when processing steel for medium-sized ladle furnaces, the blowing time does not exceed 15–20 %.

At the Tokyu Works plant (Japan), the Mitsubishi Steel has developed equipment for the integrated refining of steel, including the blowing by powders [7]. The plant mainly produces 36,000 tons of low alloy steels in a month, of which ~2,300 tons are processed in the ladle.

4. 3. Layout of equipment for steel refining in the ladle

Fig. 3 shows the layout of the equipment for the metal refining in an electric arc furnace with a ladle capacity of 50 tons.

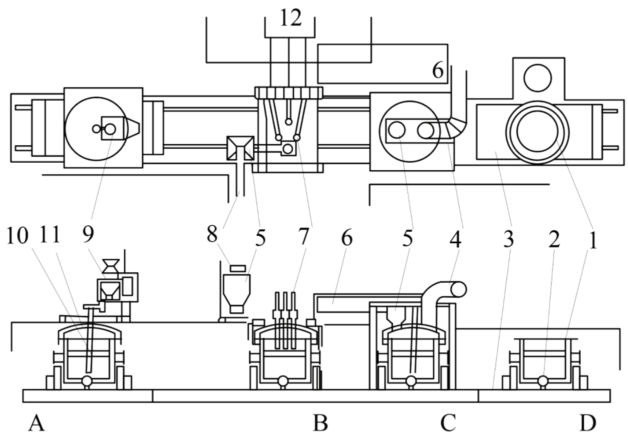

Fig. 3. Layout of equipment for steel refining in a ladle furnace: A — slag remover; B — vacuum degassing (VD); C — metal refining in the ladle furnace (LF); D — metal refining by powder (1J); 1 — ladle furnace; 2 — porous plug; 3 — electro-waggon; 4 — vacuum-pipe; 5 — bunker for storage of the alloying materials; 6 — operator room; 7 — graphite electrodes; 8 — belt conveyer; 9 — powder additive; 10 — tuyer; 11 — ladle roof; 12 — electric transformer

This placement plan for liquid metal refining equipment in the ladle includes four processes:

1) removing of slag;
2) vacuum degassing (VD);
3) metal refining in a ladle furnace (LF);
4) metal refining with powder materials (1J).

For complete removal of slag that comes from an electric arc furnace, the ladle is equipped with turning arrangement that ensures the tilt of the ladle by ≤35 °C and with an electric drive. To determine the mass of the metal in the ladle, automatic scales are used. When processing metal in a vacuum (VD), the ladle is closed by a roof with stainless-steel bellows, which eliminates air leakage. Usually, evacuation is carried out at a pressure of <135 Pa for 10–15 minutes and it takes 3 minutes to obtain the required pressure. The roof, in vacuum for the introduction of alloyed additions and fluxes is equipped with a bunker. Metal is heated with three carbon electrodes (∅=304.8 mm) for the refining in the ladle furnace (LF) and is mixed by argon blowing through the porous plug installed in the center of the ladle bottom. Heating of the metal is carried out by an electric arc furnace with the formation of foamy surface slag. The heating rate of the metal was 3–4 °C/min. Unburnt high-alumina bricks are used as the refractory materials for lining the walls and the bottom, and resin-impregnated MgO–CaO bricks are used for lining the ladle in the slag zone. The ladle is equipped with a slide gate. Fluxes and alloyed materials are weighed on the automatic scales, and then transferred to bunkers using a belt conveyor, which are installed on the ladle roof. In this case, the chemical composition and temperature of the liquid metal are regulated in a narrow range. Metal processing with powdered materials (1 J) is performed in this ladle. In order to implement this operation, the equipment consists of a roof, a tuyer which is necessary for injecting powders and a feeder into the metal, which is mounted on a sliding rod having a stroke of 4 m. Powdered materials are stored in four bunkers with a capacity of 500 kg and fed to the feeder by a screw conveyor after automatic weighing and mixing.

The powder was blown into the metal using a tuyer having a replaceable tip immersed in liquid metal to a depth of 1.4 m with a total bath depth of 1.5 m. Powders are blown horizontally from two holes with a diameter of 12 mm in a stream of high-purity argon at a pressure of 0.3–0.4 MPa and a flow rate of 0.2–0.4 m^3/min. The processing time is usually 5–15 minutes. The heat loss of the metal during processing with powders depends on the type and amount of the blown powders, as well as on the consumption of argon. In this case, the average cooling rate of metal is 2 °C/min. During powder injecting, the sulfur content decreases on average from 0.02 % to ≤0.003 %. After powder injection, the amount of oxygen in the metal is 0.0022–0.0026 %, and the amount of FeO in the slag is 0.5–0.8 %. The use of synthetic surface slag with a basicity of 8.2 and metal blowing with lime powder at a rate of 4 kg/t allows reducing the sulfur content in steel from 0.023 to 0.0002 % for 10 minutes. Thus, according to the ladle-refining scheme (Fig. 3), the liquid steel drained from the electric arc furnace entering the ladle mounted on the electric carriage can be transported for metal refining in one of the above four ways. In this case, steel refining using powder treatments is carried out according to the scheme VD-LF-1J in combination with additional vacuum degassing to produce steel with a very low content of gases.

4. 4. Installing a ladle furnace for blowing liquid steel

Apparently, the most promising is the installation of a ladle-furnace, in which the operations of mixing metal with argon (if necessary electromagnetic mixing), its heating and blowing with powdered materials are combined (Fig. 4) [8].

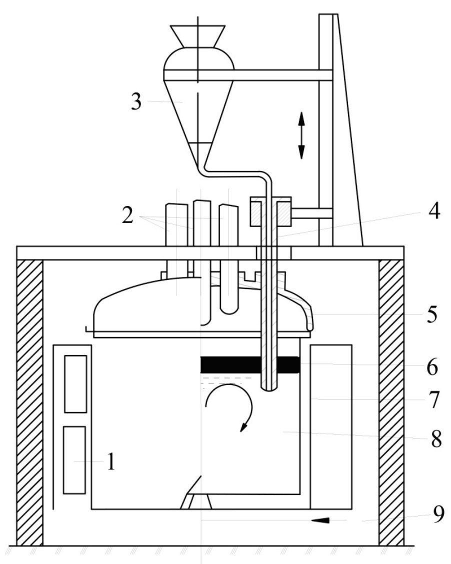

Fig. 4. The scheme of ladle furnace with blowing of powders: 1 — inductor for mixing; 2 — electrodes; 3 — bunker; 4 — tuyer for the powder; 5 — roof of the ladle; 6 — alkaline slag; 7 — ladle; 8 — steel; 9 — argon supplier

In the ladle furnace, the heating system helps to transfer the heating stage of steel from the furnace to the ladle, which is necessary by blowing with powders for steel desulfurization and thereby increases the productivity of expensive melting equipment. In this case, the possibility of obtaining sufficiently high-quality steel due to heat loss during powder blowing is compensated by the loss of the required overheating of the metal. The ability to control the shape and morphology of the inclusions when blowing the liquid metal with powders ensures successful casting of aluminum-deoxidized steel. If we consider the temperature of steel and the development of a high degree of alloyed materials, then the advantages of such a combined metallurgical technology are undoubted.

According to the date given in [3] after vacuum treatment of 50 tons of metal with a sulfur content of 0.005 %, it is poured into the ladle furnace equipped with three carbon electrodes for heating the metal, as well as by stirring with argon through a central porous plug, and processed under the base slag. In the initial state, the metal temperature is 1540 °C, the oxygen activity is 0.003 % and the aluminum content is 0.012 %. After the first 10 minutes, the temperature rises to 1,560 °C, the oxygen activity increases up to 0.0004 % and the amount of oxygen in the ladle atmosphere decreases to 7 %. After 5 minutes of treatment, the oxygen activity for a given aluminum content reaches an equilibrium value and then remains unchanged with increasing temperature to 1610 °C, that is, it remains below the equilibrium state for a given temperature. At a temperature of 1,610 °C, we carried out blowing metal with silicocalcium powder; as a result, the oxygen activity in the initial state decreased to 0.0003 %. At the end of the treatment, the sulfur concentration was 0.002 %. A comparison of the operation of the equipment with or without powder blowing shows that in case of powder blowing to achieve the same level of properties of the obtained steel, the processing time should be significant.

4. 5. The effect of the initial amount of sulfur in the metal on the degree of desulfurization

The completeness of desulfurization of steel by powders injection first depends on the initial amount of sulphur in metal. We have found out (Fig. 5), ceteris paribus, there is a linear dependence of the final sulfur content on its initial content in steel when the metal is injected in the ladle with a mixture of 70 % MgO, 20 % CaO and 10 % CaF_2. The desulfurization degree of the steel strongly depends on the degree of deoxidation of the metal. It is known that a high degree of desulfurization is achieved only when refining well-deoxidized steel. The degree of deoxidation of steel depends on the ratio between the rate of oxygen input from the slag and the lining and the rate of deoxidation. In [3] it was shown that steel deoxidation and slag recovery processes occur simultaneously with intensive mixing of the metal with the slag in the ladle. In this case, the oxygen activity in the liquid metal is determined mainly by the content of FeO and MnO in the slag.

We ascertained that depending on the final content of sulphur $[S]_k$, the maximum oxygen activity in the steel has the following values (Table 2).

According to the data [1], the rate of oxygen supply from the ladle lining into the steel when blowing with CaC_2 powder is %/min: 0.007 (schamotte), 0.0035 (Al_2O_3) and 0 (dolomite). The rate of oxygen supply from the lining also depends on the intensity of mixing, the deoxidation degree of the metal, the ratio of surface area to volume, etc. The supply of oxygen from the lining increases the activity of oxygen in the metal, reduces the distribution coefficient of sulfur between the metal and slag and, therefore, reduces the desulfurization degree.

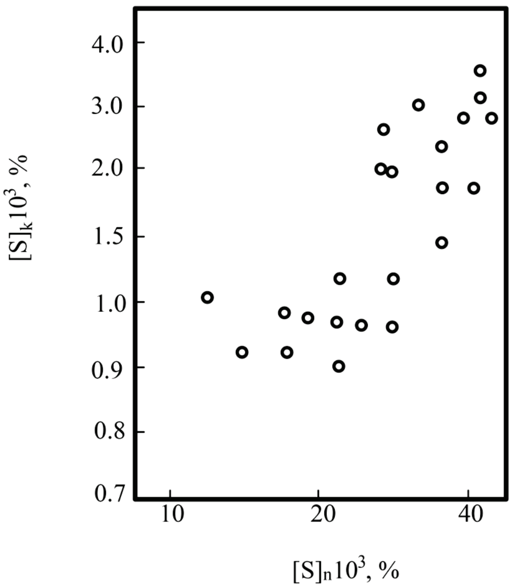

Fig. 5. Dependence of the sulphur concentration in the metal at the end of the blowing with powders on its initial concentration

Table 2

The relationship of oxygen activity and the final sulfur content

$[S]_k$, %	0.0028	0.0048	0.009
$a[O]\cdot10^4$	1.08	1.88	3.6

Fig. 6 presents results of desulfurization we have obtained in a ladle with high-alumina lining (60 % Al_2O_3) by blowing with silicocalcium (1–2 kg/t) of steel, deoxidized with aluminum content in metal ≤0.0038 % and 0.010–0.020 %.

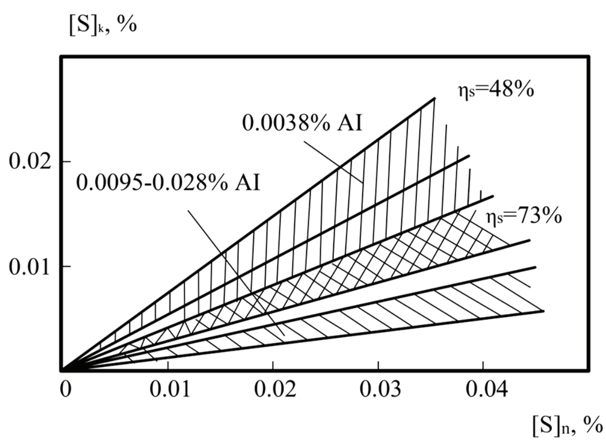

Fig. 6. Dependence of desulfurization degree of steel on its aluminum content when blowing with silicocalcium (1–2 kg/t) powder in high-alumina lining ladle (60 % Al_2O_3): $\eta_s=([S]_n-[S]_k)/[S]_n\cdot100$ %, here $[S]_n$ and $[S]_k$ – the initial and final content of sulphur in a metal

The aluminum content in steel increases from 40–70 % (≤0.0038 % Al) up to 60–85 % (0.01–0.03 % Al). The reproducibility of desulfurization results and obtaining low sulfur contents in the metal after blowing are ensured provided that the aluminum and oxygen content in steel is ≥0.02 and ≤0.002 %, respectively.

5. Discussion of experimental results

Research has shown that refining electrical steel in the ladle is very important. For this purpose, some methods are used, among the most important of which is blowing the liquid steel with powders of various components.

Calcium-containing materials are predominately used as powder components. The use of calcium-containing components, however, leads to a decrease in the service life of the ladle lining. Therefore, we have conducted studies of the effect of the ladle lining on the electrical steel refining process.

In the case of using a lining consisting of silica, it is impossible to reduce the amount of sulfur in the steel to the desired level. The ladle coating has high acid capacity and therefore it quickly degrades. Fireclay lining also does not give the expected result in reducing the amount of sulfur in electrical steel. Moreover, such lining leads to its destruction due to the low basicity of slag.

Thus, higher results were obtained in desulfurization of electrical steel when blowing liquid steel with silicon-calcium in the case of using a dolomite lined ladle. Dolomite lining contains a large amount of magnesium oxide.

Nonetheless, the use of dolomite lining gives non-metallic inclusions globular shape, which is especially important for the production of steel with high mechanical properties.

In the presence of a high content of iron oxide (FeO) in the slag, the degree of desulfurization of steel is greatly increased. It is inadmissible, since it leads to an increase in the sulfur content with all the ensuing consequences [20].

Therefore, when using dolomite brick in the ladle lining, it is possible to reduce sulfur in the final steel, to obtain non-metallic inclusions of a globular shape in the steel structure. This form of non-metallic materials does not lead to a reduction of the mechanical properties of electrical steel.

It has been established that when blowing liquid steel in a ladle with powders in an argon jet, a high degree of resulfurization is observed due to an increase in the blowing time and in the amount of FeO in the slag. Only the use of a ladle with schamotte lining when blowing with argon and low FeO content (~0.58 %) increases the degree of steel desulfurization.

The developed layout plan of ladle-vacuum degasser equipment for refining liquid steel in the ladle is more compact. It includes four processes and a ladle is provided with a turning arrangement for complete slag removal. The process involves the vacuum degassing of a liquid which can significantly increase the degree of steel refining.

Experiments have shown that in order to improve the productivity of smelting reinforcing steel, it is necessary to use the ladle-furnace scheme proposed in [8]. The ladle-furnace installation is provided with a heating system blowing powders to desulfurize the steel, which prevents its overheating in the furnace, that is, this process is transferred to the ladle.

The experimental results confirmed that the less the amount of sulfur in the steel source from the waste, the higher the degree of desulfurization of the liquid steel in the ladle when blowing with powders. It requires a great deal of attention when selecting the metal component of the charge (i. e. steel waste from remelting). In other words, used steel waste would be better desulfurized.

6. Conclusions

1. The effect of the ladle lining on the degree of desulfurization when blowing the liquid steel with the powder mixture has been studied. It has been revealed that the material of the ladle lining significantly affects the composition and basicity of the slag formed. The presence of low basicity slags leads to a rapid destruction of the ladle lining. For instance, the presence of a large amount of magnesium and calcium in the slag interacts with the ladle lining and eventually destroys it.

2. Depending on the amount of FeO in the slag, the degree of desulfurization with argon blowing has precisely been determined. It has been established that with increasing FeO content in the slag, a process of resulfurization (reverse desulfurization process) is observed. With various FeO contents in the slag and blowing the liquid metal in the ladle with argon, an increase in the blowing time leads to an increase in the degree of resulfurization. However, the presence of ladle roofs improves the condition of metal blowing, reduces metal loss and the degree of oxidation.

3. For secondary refining of reinforcing electrical steel in the ladle, the equipment layout design has been proposed. For blowing liquid metal by powdered reagents, a ladle-furnace device has been presented. When blowing the liquid metal by powders, the effect of its chemical composition on the degree of steel desulfurization has been studied. With the complete desulfurization in the metal, a significant effect of the initial amount of sulfur has been revealed.

4. The study of the effect of the initial and final amount of sulfur in the metal showed that high initial amount of sulfur in the high-alumina ladle lining has a negative impact on desulfurization process.

5. The developed furnace ladle fitted with equipment for blowing liquid steel with powders allows the use of a dolomite lined ladle and blowing with silicocalcium-based powders. All these measures in their entirety lead to the effective refining of reinforcing electrical steel in a dolomite lined ladle. The steel refined in this equipment has significantly high mechanical properties, compared with steel refined in a conventional ladle lined with schamotte or siliceous bricks.

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