ABSTRACT

to dissertation for the Doctor of Philosophy degree PhD
on the specialty 6D070900 «Metallurgy»

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Development of technology for smelting complex calcium-containing ferroalloys from dump metallurgical slags and high-ash coals

Relevance and novelty of the topic

The relevance of the work is determined by the objectively urgent need to meet the needs of the domestic steel industry and iron foundries with high-quality metal products from Kazakhstani raw materials, as well as to involve in the metallurgical redistribution, substandard, secondary technogenic resources - high-ash coals of Central Kazakhstan and waste metallurgical slags, unsuitable for the energy purposes of the national economy. The content of basic oxides in metallurgical slags, as well as the price of materials, allows us to consider them as a cheap source of the relevant elements in the composition of complex ferroalloys, instead of expensive high-grade materials for obtaining complex calcium-containing ferroalloys. The obtained alloy is an import substitute for silicocalcium purchased in China and the Russian Federation.

Research works on calcium-containing ferroalloys the smelting were carried out earlier using blast furnace slag, iron ore, quartzite, coal and coke in the composition of the charge. The complexity of regulating the process for four to five charge components did not allow reaching a stable technological regime. Therefore, the work was suspended. At the present time, the accumulated practical experience and the theoretical studies carried out allowed us to approach the solution of the problem of smelting calcium-containing ferroalloys from new positions. At the same time, there are no world analogues for the production of alloys with such a complex chemical composition by the one-stage carbothermal slag-free method.

The novelty of the results of research work is confirmed by the patent dated 21.05.2021, Registration No. 35075 «Charge for obtaining complex ferroalloys with calcium in an ore thermal furnace»

Relationship of this work to other research work

The dissertation work was implemented as part of the of targeted program funding (TPF) aimed to implementing the Strategy «Kazakhstan-2050», the message of the Head of State «The third modernization of Kazakhstan: global competitiveness» dated January 31, 2017, under the project «Development of technology for smelting calcium-containing ferroalloys from dumps metallurgical slags and high-ash coals» (TPF 2015-2017, No. GR0115RK01633, responsible executor), and on the topic «Development of technology for smelting complex ferroalloys with alkaline earth metals» (TPF 2018-2020, within the framework of STP BR05236708, No. GR 0118RK00699, responsible executor) and «Pilot-industrial tests of new types of ligatures with calcium, boron and chromium for alloying and modification of steel and technologies for their production.

Development and implementation of innovative technologies for the development of the mining and metallurgical industry of the Republic of Kazakhstan for 2018-2020» (responsible executor).

The purpose of the work is to develop a rational resource-saving technology for smelting a complex calcium-containing ferroalloy using high-ash coal and dump metallurgical slag.

The object of the research is the technology of smelting a complex calcium-containing ferroalloy by the carbothermal slag-free method.

Research objectives

In accordance with the goal in the dissertation, the following objectives were solved:

- carrying out a metallurgical assessment of high-ash coal for suitability for calcium-containing ferroalloy smelting;
- carrying out thermodynamic diagrammatic analysis of the phase composition of the calcium-containing ferroalloy;
- carrying out a complete thermodynamic analysis of the carbothermal reduction of silicon, aluminum and calcium using software packages to determine and refine the temperature range of metal formation and the features of reduction processes;
- experimental verification of obtaining a complex alloy with calcium in conditions close to industrial ones;
- study of the physical and chemical properties of a new complex ferroalloy with calcium.

Scientific novelty

In this work, for the first time:

- a diagram of the four-component metallic system Ca-Si-Al-Fe was built using the method of thermodynamic diagrammatic analysis. The most optimal phase regions have been established, they promote high extraction of calcium into the alloy;
- a full thermodynamic modeling of the process of calcium-containing ferroalloy smelting was carried out. The optimal ratio of the solid reductant to the ore part of the charge has been determined. Metal-forming phases were found, they are $Ca_2Al_2Si_7$, Mn_5Si_3, $CaSi_2$ and CaSi;
- the technology of calcium-containing ferroalloy smelting by carbothermal and slag-free method from dump metallurgical slags and high-ash coal in a 200 kVA ore-thermal furnace has been developed and tested. It has been established that the smelting process must be carried out with an excess of solid carbon by 15-25 % of the stoichiometry.
- the basic properties of a new complex alloy with calcium have been determined by methods of physical and chemical analysis. The phase composition of the alloy is represented by $CaAl_2Si_{1.5}$ and free Si. According to differential thermal analysis, it was found that the primary destruction of the crystal structure of the alloy occurs at a temperature 910 °C. The density of the new type of calcium-containing ferroalloy is 3,5-4,5 g/cm^3.

The practical value of the work

Based on the data obtained, it was established that it is possible to use dump slags (with a high content of calcium oxide) and high-ash coals as a charge material for calcium-containing ferroalloys smelting. The involvement of such materials in metallurgical processing contributes to solving the problem of their utilization and expanding the raw material base of the ferroalloy industry with obtaining a competitive complex alloy with calcium.

Tests for the smelting of calcium-containing ferroalloy were carried out in an ore-thermal furnace with a 200 kVA transformer power. A pilot batch of calcium-containing ferroalloy has been produced. A part of the pilot batch was sent to the QazQarbon LLP foundry as a replacement for the standard grade silicocalcium used in gray iron smelting. QazQarbon LLP has shown commercial interest and readiness to purchase the alloy on a regular basis. Krylysmet LLP of ArcelorMittal Temirtau JSC (AMT JSC) carried out a series of industrial tests on the use of calcium-containing ferroalloy for modification of 110G13L steel. Tests have shown that alloying steel 110G13L with a calcium-containing ferroalloy improves the composition of non-metallic inclusions, making the steel fusible and low contamination. The tests were carried out in an arc steelmaking furnace DS-6NT with 6 tons capacity.

AlbaStroyDor LLP expressed a great interest in support letter for the development of technology and organization of smelting of new types of calcium-containing ferroalloys from dump metallurgical slags, which, under an outsourcing agreement with AMT JSC, is the management company of the slag processing site of the blast furnace shop of AMT JSC.

For a calcium-containing ferroalloy a technical condition and technological reglament have been developed. The main results obtained in the dissertation work are introduced into the educational process of the KarTU for undergraduate specialty 6B07204 – «Metallurgy» in the disciplines «General metallurgy» and «Perspective metallurgical processes».

Research methods

During the dissertation work, the following methods were used: differential thermal analysis, X-ray phase analysis, determination of electrical resistivity, thermodynamic modeling on the ASTRA-4 software package, thermodynamic-diagram analysis, determination of the mechanical strength of coal briquettes, smelting in an ore-thermal furnace, microstructural analysis.

Provisions to be defended:

- diagram of the phase structure of the Ca-Si-Al-Fe metal system;
- results of complete thermodynamic modeling of the process of calcium-containing ferroalloy smelting;
- results of preparation of briquetted mono-charge from coal sludge and fines of high-ash coal with blast-furnace slag;
- results of smelting calcium-containing ferroalloy from dump metallurgical slags and high-ash coal in a 200 kVA ore-thermal furnace;
- results of studying the physical and chemical properties of a new complex ferroalloy with calcium.

Place of research work

The work was carried out at the «Nanotechnology and Metallurgy» Department of Karaganda Technical University and in the «Pyrometallurgical Processes» laboratory and the experimental site of the Chemical and Metallurgical Institute named after Zh. Abishev.

Personal contribution of a doctoral student to writing a dissertation.

The author took part in defining the purpose of the work and setting the research objectives and in writing articles and abstracts. The author personally obtained the main part of the scientific and practical results of this work, which determines both the scientific novelty and the practical value of the work as a whole. In addition, the entire range of applied work on the development and development of new technological processes for smelting complex calcium-containing ferroalloys from dump metallurgical slags and high-ash coals was carried out within the framework of grant and program-targeted funding projects, where the author was the responsible executor.

Approbation of the work

The main scientific results of the dissertation work are presented in 14 publications published in the Republic of Kazakhstan and abroad, including:

- Four articles have been published in the publications recommended by CCSES MES RK (3 articles are in «Industry of Kazakhstan», 1 article is in «University Proceedings»);
- 1 article in the journal «Ferrous metallurgy. Bulletin of Scientific, Technical and Economic Information» was published;
- 3 articles in journals included in the Scopus database («Steel in translation», «CIS Iron and Steel Review» and «Metalurgija») were published;
- 1 patent of the Republic of Kazakhstan for the invention was received «Charge for obtaining complex ferroalloys with calcium in a thermal ore furnace».

The main results were reported at 5 international conferences:

- 2 theses of reports at the congress «Fundamental research and applied development of the processes of processing and utilization of technogenic formations. TECHNOGEN - 2017 and TECHNOGEN 2019» (Yekaterinburg, RF) were published;
- 1 thesis at the international scientific-practical conference «Physical and chemical foundations of metallurgical processes» (Moscow, RF) was published;
- 1 thesis at the international scientific and practical conference «New technologies for metallurgical processing of mineral raw materials» (Karaganda, RK) was published;
- 1 thesis at the international scientific and practical conference «Scientific and personnel support for the innovative development of the mining and metallurgical complex» was published (Almaty, RK).

The structure and scope of the dissertation

The dissertation consists of an introduction, the main part of 4 chapters, a conclusion, 8 appendices. The volume of the thesis is 125 pages of text, the work contains 40 figures, 24 tables, a list of used sources, including 100 titles.

MAIN CONTENT OF WORK

The introduction provides a brief substantiation of the relevance of the applied, scientific and technical problem related to the development of a new technology for smelting a calcium-containing ferroalloy, the novelty of scientific and technical developments, the goal and tasks of the work are formulated, practical value is given, data on the structure of the thesis are indicated.

The first chapter provides an overview of the literature data on the smelting of complex ferroalloys from high-ash coals of Central Kazakhstan. Metallurgical evaluation of high-ash coal for smelting calcium-containing ferroalloy has been carried out. The results of laboratory research and analysis of literature data served as the basis for determining the direction of research and setting tasks for the implementation of the goal of the dissertation.

To clarify the phase patterns in the Ca-Si-Al-Fe metal system, which simulates the composition of the final alloy with the participation of calcium metal, **in the second chapter**, theoretical studies were carried out to plot the phase structure diagrams of this system by the method of thermodynamic diagram analysis (TDA). It was established that the topographically four-component system Ca-Si-Al-Fe is a tetrahedron, on the vertices of which are located pure chemical elements: calcium, silicon, aluminum and iron. There are double junctions on the edges of the tetrahedron, and triple junctions on the edges.

In the investigated 4-component Ca-Si-Al-Fe system there were 15 tetrahedrons: 1 Al-Si-$Al_2Ca_2Si_7$-Fe_2Al_5, 2 $Al_2Ca_2Si_7$-Al-Al_2Ca-Fe_2Al_5, 3 Si-$Al_2Ca_2Si_7$-Al_2Fe_2Si-Fe_2Al_5, 4 $Al_2Ca_2Si_7$-Al_2Fe_2Si-Fe_2Al_5-Al_2Ca, 5 Al_2Ca-Fe_2Al_5-Fe-Al_2Fe_2Si, 6 Al_2Ca-Al_2Fe_2Si-Fe-Ca, 7 Ca-CaSi-Al_2Fe_2Si-Fe, 8 Ca-CaSi-Al_2Fe_2Si-Al_2Ca, 9 $Al_2Ca_2Si_7$-Al_2Fe_2Si-Al_2Ca-CaSi, 10 CaSi-FeSi-Al_2Fe_2Si-Fe, 11 CaSi-$CaSi_2$-FeSi-Al_2Fe_2Si, 12 CaSi-$CaSi_2$-Al_2Fe_2Si-$Al_2Ca_2Si_7$, 13 $Al_2Ca_2Si_7$-$CaSi_2$-Al_2Fe_2Si-FeSi, 14 Si-$Al_2Ca_2Si_7$-$CaSi_2$-FeSi, 15 Si-$Al_2Ca_2Si_7$-Al_2Fe_2Si-FeSi.

The sum of the relative volumes of elementary tetrahedrons is equal to one (1,000000), which confirms the correctness of the performed tetrahedron. Transformation coefficients, calculated by the Heath method, intended to determine the phase composition of the primary components, and the volumes of elementary tetrahedrons of the Ca-Si-Al-Fe system. The data presented and the results of the calculations performed confirm the reliability of the tetrahedration of the phase structure diagram of the Ca-Si-Al-Fe metal system. This will subsequently make it possible to determine the phase composition of metal products in the calcium-containing alloys smelting in the processes of calcium recovery from dump metallurgical slag and high-ash coal.

Thus, for a four-component Ca-Si-Al-Fe metal system, the following stable compounds were determined: FeSi, Fe_2Al_5, CaSi, $CaSi_2$, Al_2Ca, Al_2Fe_2Si и $Al_2Ca_2Si_7$ and the ΔG_{298} values were determined for each of the compounds. Based on the calculation data ΔG_{298} for each coexisting phase, triangulation was performed in three-component systems. Next, tetrahedration was carried out for the Ca-Si-Al-Fe metal system, where 15 elementary tetrahedrons were established, which

characterizes the calcium-containing ferroalloy. For each tetrahedron, a balance equation was calculated, where it is possible to establish the quantitative distribution of the initial elements in phases.

In this connection, to obtain a calcium-containing ferroalloy, it is necessary to select the composition of the initial charge materials with a high content of calcium, silicon and aluminum oxides and a minimum content of iron oxide, which will provide the possibility of smelting a ferroalloy in these phase regions.

In the third chapter, the results of thermodynamic modeling of the process of smelting a calcium-containing ferroalloy and experimental research on the smelting of a calcium-containing ferroalloy in laboratory conditions are showed.

It is necessary to study the basic reactions in the systems Si-Al-Ca-Fe-O-C and Si-Al-Ca-Mn-O-C for establishing the mechanism of joint carbothermal reduction of silicon, aluminum, calcium, manganese and iron. Computer modeling of the process of smelting a calcium-containing ferroalloy was carried out by using «ASTRA-4» software package to establish the optimal mode and feasibility of smelting.

A complete thermodynamic analysis was carried out for three real charge compositions (with a lack of 10% solid reducing agent, with a normal course of the regime and with an excess of 15% solid reducing agent) for smelting a complex alloy from blast-furnace slag, in order to determine the optimal mode of the carbothermal process.

According to thermodynamic analysis, the temperature of the beginning of the joint carbothermal reduction of silicon, calcium and aluminum is 200-220 °C lower than the separately occurring reactions. In the temperature range 1700-2300 °C, the formation of a metallic condensed phase begins. Metal formation in the form of $Ca_2Al_2Si_7$ and Mn_5Si_3 begins at a temperature of 1700 °C. Above 2000 °C, the main amount of silicon, calcium and aluminum is in gaseous form. This requires the adoption of technical measures to condense and capture them, is always carried out and in all technologies of ferroalloy production. In general, the process takes place at high temperatures and has a complex character of reduction reactions.

Based on the theoretical data and data on the physicochemical properties of the charge materials studied above, a series of laboratory experiments on a Tamman furnace is required to establish the temperature regime and obtain a prototype alloy.

Thus, according to the results of a complete thermodynamic analysis on the ASTRA-4 software package and a series of laboratory experiments on the Tamman furnace, it was found that:

- reduction processes and metal formation begins at a temperature of 1700 °C. Calcium-containing ferroalloy is presented in the form of intermetallic compounds $Ca_2Al_2Si_7$ and Mn_5Si_3. With an increase in temperature, the phases $Ca_2Al_2Si_7$ and Mn_5Si_3 decompose into independent phases, like free silicon Si, calcium Ca and calcium disilicide $CaSi_2$, intermetallics completely disappear. In the gas phase, the content of calcium and silicon increases, which leads to losses;

- the most optimal condition for smelting a calcium-containing alloy from waste slags and high-ash coals is a charge mixture with an excess of a reducing agent with a slag to high-ash coal ratio of 34/66, respectively (O/C_{solid} = 1,04-1,16). This

is due to the fact that after the reduction processes there is practically no oxide phase (slag), however, there is a silicon carbide phase, but in real conditions a small amount of carbon will burn out on the top, which levels the process for solid carbon to the optimal mode;

- there is a very large loss of mass, therefore, the reaction zone of the furnace must always be closed under a layer of charge to reduce the loss of metal in the form of gaseous oxides. Intense gas evolution leads to the loss of silicon, calcium and aluminum in the form of suboxides, since complete reduction occurs through the formation of intermediate products such as SiO_g, CO_g, CaC_2;

- the operating temperature of the Tamman furnace is in the range of 1700-1750 °C. During the experiments, it turned out that this temperature is not enough, therefore, it is necessary to provide a high concentration of heat for the reduction processes of complex oxides of silicon, calcium and aluminum, since the main reduction reactions of the complex alloy with calcium proceed at temperatures of ~ 2000 °C;

The obtained results of laboratory experiments on the smelting of a complex alloy with calcium require optimization of technological parameters and development of technology in large-scale laboratory conditions that simulate industrial ones.

The fourth chapter presents the results of large-scale laboratory tests on the smelting of a calcium-containing ferroalloy and the study of the physicochemical properties of the new alloy. Based on the obtained results of thermodynamic modeling of the process and diagrammatic analysis, a series of enlarged laboratory tests were carried out for smelting a calcium-containing ferroalloy in a 200 kVA ore-thermal furnace. The tests were carried out at the experimental production site of the Chemical and Metallurgical Institute named after Zh. Abishev. The main task of the tests is to develop an easily controlled and stable slag-free mode of smelting a calcium-containing ferroalloy.

Two variants of the charge mixture were prepared for testing. In the first version of the charge mixture, lump blast furnace slag of AMT JSC and slag of refined ferromanganese were used. For the second variant of the charge mixture, a batch of briquettes was prepared, consisting of fine coal-sludge fines (fraction 0-5 mm) and granular blast furnace slag, in various ratios. The charge was calculated for 100 kg of coal. Solid carbon was calculated for the complete recovery of all ash oxides, the excess carbon was neutralized by slag.

In a 200 kVA ore-thermal furnace, the fundamental possibility of calcium-containing ferroalloy obtaining from dump metallurgical slags and high-ash coals has been established by experimentation. In terms of chemical composition, the resulting alloy has a high calcium content of 6-18 %. The composition of the charge mixture completely excludes the use of expensive coke and iron ore. The process is completely slag-free and is carried out with an excess of solid carbon, with a ratio of oxides to solid carbon (O_{batch}/C_{solid} 1,04-1,16). More than 0,55 tons of alloy have been produced. Alloy using blast-furnace slag, with an average chemical composition, %: Ca - 11,74; Si - 46,41; Al - 18,01; Fe - 16,18; C - 0,93. Alloy using ferromanganese slag, with an average chemical composition, %: Ca - 6,81;

Si - 36,50; Al - 29,53; Mn - 14,51; Fe - 12,61; C - 0,9. Alloy using briquetted mono-charge, with an average chemical composition, %: Ca - 13,11; Si - 47,51; Al - 14,97; Fe - 23,54; C - 0,79.

The dependence of the content of silicon, iron and manganese (Si/Fe and Si/(Fe + Mn)) to the content of calcium in the alloy has been established. The equation of dependencies is revealed, for an alloy using a blast-furnace slag $y = 0,4305 x – 1,4099$, for an alloy using manganese slag $y = 0,156 x – 0,3451$, for an alloy using a briquetted charge $y = 0,2964 x – 1,6605$ where y - Si/Fe, Si/(Fe + Mn) and x - Ca.

The main characteristics of the new calcium-containing ferroalloy have been studied by the physical and chemical analysis methods. X-ray diffraction patterns of the prototypes indicate that the phase composition of the alloy is presented in the form of $CaAl_2Si_{1.5}$ and free silicon Si. The density of new types of calcium-containing ferroalloys is 3,5-4,5 g/cm^3. The microstructure and phase composition of the new complex alloy with calcium was studied in a complex manner using OLYMPUS BX51 optical microscopes and JEOL-JSM7001F scanning electron microscopes. Metallographic analysis showed that the calcium-containing ferroalloy is represented by three main structural components, which are distinguished by different shades: white - in the form of narrow-long needles of a dendritic structure, gray - occupies the main area of rounded shape, dark gray - a matrix.

CONCLUSION

Brief conclusions based on the results of dissertation research

1 Evaluation of the efficiency of using high-ash coals of Kazakhstan for complex silicon-aluminum ferroalloys smelting, in particular for calcium-containing ferroalloy smelting, has been carried out.

2 Physical and chemical properties of high-ash coal used for calcium-containing ferroalloy smelting have been investigated. It was found that the electrical resistivity of coal from the Saryadyr deposit, when heated from 25 to 1500 °C, is relatively high, which satisfies the process of smelting a calcium-containing ferroalloy in an ore-thermal furnace with a deep immersion of the electrode.

3 Using the method of thermodynamic diagram analysis a phase analysis of the four-component metallic system Ca-Si-Al-Fe was carried out, where the following stable compounds were determined FeSi, Fe_2Al_5, CaSi, $CaSi_2$, Al_2Ca, Al_2Fe_2Si и $Al_2Ca_2Si_7$. The tetrahedration of the Ca-Si-Al-Fe metal system was carried out, where 15 elementary tetrahedrons were established, characterizing the calcium-containing ferroalloy. An optimal phase region was established for smelting a calcium-containing ferroalloy with high calcium recovery.

4 A complete thermodynamic analysis was carried out using the ASTRA-4 software package. Also, a series of laboratory experiments was carried out to smelt a calcium-containing ferroalloy in a Tamman furnace, during which the optimal consumption of solid carbon was established (O/C_{solid} = 1,04-1,16) and the nature of the recovery processes.

5 The mode of briquetting of coal sludge and granular slag has been worked

out. The optimal ratio of the reducing agent to the ore part of the charge was established - 80/20. As a result, a pilot batch of briquettes has been developed, the mechanical strength of which meets the requirements for materials for an ore-thermal furnace.

6 In a 200 kVA ore-thermal furnace, the fundamental possibility of obtaining a calcium-containing ferroalloy from dump metallurgical slags and high-ash coals has been established by experimentation. In general, a pilot batch of alloy with a volume of more than 0.55 tons has been produced. Alloy using blast-furnace slag, with the following average chemical composition, %: Ca - 11,74; Si - 46,41; Al - 18,01; Fe - 16,18; C -0,93. Alloy using ferromanganese slag, with an average chemical composition,%: Ca - 6,81; Si - 36,50; Al - 29,53; Mn - 14,51;Fe - 12,61; C - 0,9. Alloy using briquetted mono-charge, with an average chemical composition,%: Ca – 13,11; Si - 47,51; Al - 14,97; Fe - 23,54; C - 0.79.

7 The main characteristics of the new calcium-containing ferroalloy have been studied by the methods of physical and chemical analysis. X-ray diffraction patterns of the samples indicate that the phase composition of the alloy is presented by $CaAl_2Si_{1,5}$ and free silicon Si. The density of new types of calcium-containing ferroalloys is 3,5-4,5 g/cm^3.

8 LLP «Krylysmet» at JSC «AMT» carried out a series of industrial tests on the use of calcium-containing ferroalloy to modify steel 110G13L in an arc steelmaking furnace DS-6NT. A part of the pilot batch was sent to QazQarbon LLP for addition to gray cast iron. AlbaStroyDor LLP showed interest in the technology of smelting calcium-containing ferroalloy using blast-furnace slag

9 The main results obtained in the dissertation work are introduced into the educational process of the KarTU for the undergraduate specialty 6D070900 «Metallurgy» in the disciplines «General metallurgy» and «Perspective metallurgical processes». A technical condition and technological regulations have been developed, where the grade composition of the calcium-containing ferroalloy and the delivery conditions are determined.

10 Based on the results of the experiment, a patent for an invention was obtained. No. 35075 «Charge for obtaining complex ferroalloys with calcium in an ore-thermal furnace».

Evaluation of the completeness of solutions to the tasks. The assigned tasks were completed in full. As a result of research, a technology has been developed for smelting calcium-containing ferroalloys using dump metallurgical slags and high-ash coals. A metallurgical assessment of high-ash coal, in particular the coal of the Saryadyr deposit, was carried out for suitability for smelting a calcium-containing ferroalloy. In order to determine the optimal phase region for the smelting of the calcium-containing ferroalloy, thermodynamic analysis was carried out. To simulate the process of reduction of silicon, aluminum and calcium during carbothermal alloy smelting using the ASTRA-4 software package, the optimal consumption of solid carbon (O/C_{solid} = 1,04-1,16) and the nature of the reduction processes were determined. In a 200 kVA ore-thermal furnace, the fundamental possibility of obtaining a calcium-containing ferroalloy from dump metallurgical slags and high-ash coals has been established. A pilot batch of alloy (over 0,55 tons) has been

produced. Pilot tests were carried out under the conditions of Kyrylysmet LLP at ArcelorMittal Temirtau JSC for the modification of steel with a calcium-containing ferroalloy. 14 scientific papers have been published, including 3 articles in journals indexed by the Scopus database, 4 articles in journals recommended by the CCSES MES RK, 1 article in the RSCI journal, 5 reports at international conferences and 1 patent of the RK.

Assessment of the technical and economic efficiency of implementation

To date, the Republic of Kazakhstan has not established the production of ferroalloys with calcium (silicocalcium, aluminosilicocalcium, etc.), due to the lack of a rational technology for their production. Industrial enterprises that need an effective steel deoxidizer such as silicocalcium have to buy it abroad. Within the framework of the dissertation work, a technology is proposed for obtaining a calcium-containing ferroalloy from metallurgical slags and high-ash coals, which can replace the imported and expensive silicocalcium. The estimated cost of the alloy is $ 900-1100, in comparison with the purchased silicocalcium, the price of which is more than $ 2000. The low cost of the proposed alloy is not due to the scarcity of the raw materials used.

Recommendations and baseline data for the specific use of the results

The resulting calcium-containing ferroalloy can be used as a deoxidizer and modifier of steel and cast iron, this is confirmed by pilot tests under the conditions of Kyrylysmet LLP of ArcelorMittal Temirtau JSC and QazQarbon LLP. Also, a calcium-containing ferroalloy can be used as a reducing agent for smelting refined ferroalloys and ligatures.

Assessment of the scientific level of the work performed in comparison with the best achievements in the field

Research work on the smelting of calcium-containing ferroalloys was carried out earlier using blast-furnace slag, iron ore, quartzite, coal and coke in the composition of the charge. The complexity of regulating the process for four to five charge components did not allow reaching a stable technological regime, so the work was suspended. In this dissertation work, a technology for smelting a calcium-containing ferroalloy by a single-stage slag-free, easily controlled method with a high calcium recovery and with complete elimination of iron ore and coke from the charge mixture is proposed. The use of dump metallurgical slags and high-ash coal are proposed as charge materials.