



2022 (Vol. 23)



FOUNDERS:

“Ore & Metals” Publishing house
Nosov Magnitogorsk State Technical University

PUBLISHER:

“Ore & Metals” Publishing house

Established in 2006.

The “CIS Iron and Steel Review” journal is registered in the Russian Federal Service for Supervision of Communications, Information Technology, and Mass Media for Compliance with the Law in Mass Communications and Cultural Heritage Protection (Certificate PI No. FS77-73962 dated 19.10.2018)

Trade mark and the title “CIS Iron and Steel Review” are exclusively property of “Ore and Metals” Publishing House

The official information edition of the Federal Curricular Union “Technologies of Materials”

EDITORIAL BOARD

Chief editor: **Tsirulnikov Evgeny**

Deputy Chief Editors: **Kosyrev Konstantin, Vorobiev Alexandr**

Members of Editorial Board: Belenky Anatoly (Russia), Bleck Wolfgang (Germany), Bobarikin Yuriy (Belarus), Boriskin Oleg (Russia), Butorina Irina (Russia), Chichenev Nikolay (Russia), Chukin Mikhail (Russia), Elanskiy Dmitriy (Russia), Galkin Sergey (Russia), Goli-Oglu Evgeny (Denmark), Gordon Yakov (Canada), Illarionov Ilya (Russia), Kaputkina Lyudmila (Russia), Kazakov Alexandr (Russia), Kolikov Alexandr (Russia), Kolokoltsev Valeriy (Russia), Korchunov Alexey (Russia), Kushnarev Alexey (Russia), Leushin Igor (Russia), Mazur Igor (Russia), Savenok Anatoliy (Belarus), Scheller Piotr (Germany), Serebryakov Andrey (Russia), Sultanguzin Ildar (Russia), Tkachenko Stanislav (Russia), Travyanov Andrey (Russia), Volynkina Ekaterina (Russia), Vydrin Alexandr (Russia), Yatsenko Elena (Russia), Zyuban Nikolay (Russia)

EDITORIAL STAFF

Responsible Secretary: **Rakhmanova Elena**

EDITORIAL ADDRESS

Actual address: Moscow, Leninskiy prospekt 6, bld. 2, office 617

Mailing address: P.O. Box No. 71, Moscow, 119049, Russia

Phone/fax: +7-495-638-4518, +7-495-955-0175

E-mail: chermet@rudmet.ru; tsirulnikov@rudmet.ru

Web-site: www.rudmet.ru

Computer design and make-up by “Izdatelstvo UMC UPI” JSC

Volume: 15.5 printer’s sheets (124 pages)

Printed: 12.07.2022 by “Kancler” Printing house

Circulation: 40 copies. Open price

© Design and make-up. AO “Издательский дом “Руда и Металлы”,
“CIS Iron & Steel Review”, 2022

© Cover picture: Evgeny Tsirulnikov

All rights reserved. This publication or its parts may not be reproduced in any form without written permission of the publisher.

Reference to “CIS Iron and Steel Review” is strictly required in the case of any reproduction.

Advertisers are responsible for reliability of advertising information.

Authors are responsible for reliability of scientific and technical information.

“Реклама” note means that material is published as sponsored statement (advertisement).

IN SCOPUS SINCE 2014!

In 2014, the journal “CIS Iron and Steel Review” was included into the international bibliographic and abstract database Scopus, which is an instrument for tracking of scientific articles’ citedness.

The Ministry of education and science of Russian Federation considers the Scopus database as a criterion of estimation of efficiency of activity of higher education institutes. The journal “CIS Iron and Steel Review” is located in the first quartile (Q1) of Scopus (Scimago version) since 2017.

ISSN 2072-0815



CONTENTS

Preparation of raw materials

V. V. Lvov, T. N. Aleksandrova, V. B. Kuskov, A. E. Pelevin. Study of possibility of magnetic hydrocyclone use in concentration cycles of oxidized ferriferous quartzites 4

Ironmaking

P. I. Chernousov, A. E. Karpalev, A. V. Kramar, V. O. Podusovskiy. Comprehensive index of compound blast furnace smelting 9

E. P. Pototskiy, T. S. Lazareva. Investigation of factors affecting the safety of a blast furnace operation 15

Casting and Foundry

N. I. Gabelchenko, A. A. Belov, N. A. Kidalov, S. R. Polyak. Use of experimental casting equipment for research of castings crystallized through individual cooling procedures 19

Rolling and other Metal Forming Processes

V. M. Kolokoltsev, N. A. Feoktistov, A. S. Savinov, E. V. Skripkin. Development of new composition for sHSS steel used for hot rolling mill rolls at Magnitogorsk Iron and Steel Works 24

A. B. Moller, O. N. Tulupov, S. A. Levandovskiy, D. A. Nazarov. Providing steel with an approximate application of the mechanical properties of wire rod 5.5-6.5 mm from steel grades 70-75 based on a conventional twin of the Stelmor process 28

I. K. Andrianov. Minimization of dies volume using uniform distribution of hollows in the conditions of multi-cycle fatigue dependence on temperature 33

V. F. Danenko, L. M. Gurevich. On calculation of stress-strain state of steel closed ropes in extension and twisting. Part 2. Influence of torsion on the stress-strain state of closed rope 39

Tubemaking

G. P. Zhigulev, M. M. Skripalenko, V. A. Fadeev, M. N. Skripalenko, V. N. Danilin. Modelling of the sheet forming while 3-roller bending process 45

V. N. Shinkin. Analytical calculation of sheet curvature in four-roll mills at tubes production 50

Coatings application and Corrosion protection

A. G. Sokolov, E. E. Bobylev. Features and regularities in formation of diffusion nickel-copper coatings on steels in the medium of low-melting liquid-metal solutions .. 56

- N. A. Serdiuk, E. I. Pryakhin, A. V. Sivenkov. Technological basis for the process of application of diffusion coatings in liquid metal melts with use of electric furnaces with air atmosphere 61

Metal Science and Metallography

- D. A. Gorlenko, D. V. Konstantinov, M. A. Polyakova, M. Dabalá. TRIP steels: the features of chemical composition and structure, prospects of application (overview) 67
- A. A. Akberdin, A. S. Kim, A. S. Orlov, R. B. Sultangaziev. Diagram of the phase composition of the Fe - Si - Al system and its isothermal sections 76
- N. A. Kozyrev, R. E. Kryukov, V. E. Gromov, Yu. A. Shlyarova. Structure, defect substructure and fracture surface of low-carbon alloy steel welds 81
- A. E. Balanovskiy, M. G. Shtaiger, V. V. Kondratyev, A. I. Karlina. Determination of rail steel structural elements via the method of atomic force microscopy. 86

Powder Metallurgy

- E. V. Ageev, E. V. Ageeva, A. Yu. Altukhov. Structure and properties of additive products manufactured from electroerosion powders 92

Refractory materials

- E. A. Sidorina, A. Z. Isagulov, I. D. Kashcheev, K. G. Zemlyanoy. Study of aluminosilicate refractories after operation in the presence of fluorine-containing wastes 98

Quality of Products

- A. V. Kudrya, E. A. Sokolovskaya, D. F. Kodirov, E. V. Bosov, G. V. Kotishevskiy. On necessity of taking into account statistical nature of the objects using Big Data in metallurgy 105

Power Engineering

- S. V. Kartavtsev, E. G. Neshporenko, S. V. Matveev. Primary diagnosis of energy efficiency in an integrated steel plant, based on intensive energy-saving methodology. Part 2 113

Ecology and Recycling

- S. V. Panchenko, M. I. Dli, M. V. Chernovalova, N. S. Kulyasov. Thermophysical processes in dry granulation of metallurgical slags. 119

Diagram of the phase composition of the Fe - Si - Al system and its isothermal sections

A. A. Akberdin, Dr. Eng., Prof., Head of the Bor laboratory¹;

A. S. Kim, Dr. Eng., Chief Researcher of the Bor laboratory¹;

A. S. Orlov, Dr. Eng., Senior Researcher of the Bor laboratory¹, e-mail: wolftailer@mail.ru;

R. B. Sultangaziev, Dr. Eng., Senior Researcher of the Bor laboratory¹

¹Chemical and Metallurgical Institute named after Zh. Abishev (Karaganda, Kazakhstan)

The diagram of the phase composition of the Fe – Si – Al system and its isothermal sections within the temperature range of 300–3000 K are plotted. Thermodynamic data of Fe₃Si, Fe₂Si, Fe₅Si₃, FeSi, FeSi₂ silicides, FeAl, FeAl₂, FeAl₃, Fe₂Al₅ aluminides and Al₂Fe₂Si, Al₃FeSi, Al₂FeSi, Al₁₁Fe₃Si₆, Al₁₄Fe₃Si₃ ternary compounds are used. The diagram consists of 20 elementary triangles of coexisting phases, the number of which decreases to 6 at the temperature 1900 K and more. At the temperatures above 2900 K, the equilibrium of the condensed phases is disturbed due to the transition of such metal components of the low-melting aluminum corner of the diagram as Al, Al₂, Fe, Si and Si₂, leading to losses of valuable elements, to the gas phase.

Crystallization fields are assessed by calculating the squares of elementary triangles, as well as the prevalence of each compound in the phase space by taking into account its participation in the construction of adjacent triangles. Using our own method, the mathematical model of the diagram was created in the form of equations for dependence of the amount of the formed phase on the chemical composition of examined metal. The computer program was developed based on the established equations. The examples of calculation of the phase composition of two grades of ferrosilicon FeSi65 and FeSi75, which are the most common in metallurgy, as well as two grades of ferrosilicoaluminum FeSi45Al15 and FeSi55Al20 are presented. Correspondence of the calculated and instrumentally found phase composition of the industrial metal has been revealed. Presence of mathematical models makes it possible to accelerate selection of the metal with the required composition and properties from the set of planned for smelting.

Key words: iron, silicon, aluminum, diagram, phases, thermodynamics, mathematical model.

DOI: 10.17580/cisr.2022.01.14

Introduction

The phase equilibrium diagram of the Fe – Si – Al system is a subject of permanent attention of researchers. This interest is connected with its necessity for analysis and improvement of technological processes in production of several metals. First of all, ferrosilicon can be mentioned here, which is widely used in metallurgy and is described by Fe – Si binary system in its main components. More strict requirements to steel quality set the task to produce ferrosilicon with extra low content of impurities (especially Al) [1]. The ternary diagram Fe – Si – Al is used for this purpose. It was also the base for creation of the complex ferroalloy ferrosilicoaluminum (FSA) [2, 3].

Fe – Al binary system arises especial interest, and not only because of ferroaluminum production on its base [4], but also due to possibility of Fe aluminides synthesis with special properties [5–7]. Si – Al system is considered as simple eutectic one, but it is also examined because it is often included in multi-component systems [8].

Technical literature describes the phase equilibrium diagrams Fe – Si – Al, but they varied noticeably one from another. Some sources do not take them into account at all [9]. The other ones suggest presence of such phases as Al₈Fe₂Si, Al₅FeSi, Al₄FeSi [10], Al₃Fe₃Si₂, Al₁₂Fe₆Si₅, Al₉Fe₅Si₅, Al₃FeSi₂, Al₁₅Fe₆Si₅, Al₄FeSi [11], as well as

Al₂Fe₂Si, Al₃FeSi, Al₂FeSi, Al₁₄Fe₃Si₃, Al₁₁Fe₃Si₆ [12]. It was planned to search them using the bases of thermodynamic data, which are conventional in the scientific community, not using separate investigations.

Determination of the kind and quality of forming phases for metal with required properties is considered as one of multiple destinations of the diagrams. Usually it is executed using the lever rule. However, analysis of metals variety is accompanied with simple but labour-intensive calculations. The mathematical model of the diagram was created in this work using the self method [13]; corresponding software was developed as well. When chemical composition is preset from the remote control panel, the computer provides metal phase composition in mass. %.

To examine the temperature relationship of phase composition, isothermal diagram sections were built within the temperature range 300–3000 K. It is noted that at the temperature 2900 K and higher, equilibrium of condensed phases is violated due to transition of metal components of the low-melting aluminum corner of the diagram in the gas phase. Thereby it is recommended not to overheat the melt and to operate with closed dry top throat for catching fumes and their return in the process.

So, the updated diagram of phase composition of the Fe – Si – Al system was built in this work, its isothermal sections are presented, mathematical model of the diagram

was created and corresponding software for numerical calculations was developed as well.

Methods and materials

Theoretical (calculating) methods of diagrams building was used in this work. The computer («Triangle») and thermodynamic-diagram methods, which have widely prevalence in researching practice [14–16], were applied. The self-developed balance method [13] was used for mathematical description of the phase composition diagram. Use of the described approach allows to delete restrictions for number of components under examination, because the mathematical model operates not only in 3D space (where diagrams are usually reflected), but also multi-dimensional space.

Obtained results and their analysis

The ternary system Fe – Si – Al consists of three binary partial systems: Fe – Si, Fe – Al and Si – Al. Presence of such silicides as Fe_3Si , Fe_5Si_3 , FeSi , FeSi_2 and Fe_2Si was taken into account in the system Fe – Si. The system Fe – Al includes four Fe aluminides [17]: FeAl , FeAl_2 , FeAl_3 , Fe_2Al_5 , which are accepted for diagram building. No binary compounds were found in the system Si – Al. The problem of presence of ternary compounds is especial one for the examined system; they are not taken into account in general in several researches [9]. Other authors suggested presence of such phases as $\text{Al}_8\text{Fe}_2\text{Si}$, Al_5FeSi , Al_4FeSi [10] or $\text{Al}_3\text{Fe}_3\text{Si}_2$, $\text{Al}_{12}\text{Fe}_6\text{Si}_5$, $\text{Al}_9\text{Fe}_5\text{Si}_5$, Al_3FeSi_2 , $\text{Al}_{15}\text{Fe}_6\text{Si}_5$, Al_4FeSi [11]. Information about five other compounds $\text{Al}_2\text{Fe}_2\text{Si}$, Al_3FeSi , Al_2FeSi , $\text{Al}_{14}\text{Fe}_3\text{Si}_3$, $\text{Al}_{11}\text{Fe}_3\text{Si}_6$ is presented in the data base of SGT complex [12]. As soon as these data were obtained by efforts of scientific teams from several countries and they are mutually agreed, they were used for diagram building.

It is recommended to show on the triangle of compositions (Fig. 1) all compounds which were found in the technical literature, when using thermodynamic-diagram method. It will provide general picture of phase building of the system.

Analysis of phase chemical composition helps to reveal that FeSi_2 and $\text{Al}_{11}\text{Fe}_3\text{Si}_6$ have equal Fe to Si relation (0.994), and ternary compound $\text{Al}_{11}\text{Fe}_3\text{Si}_6$ can be considered as the product of chemical reaction



where $\Delta G_{298,15\text{K}} = -52.44$ KJ/mol. It allows to make the line $\text{FeSi}_2 - \text{Al}$ on the diagram. The line $\text{FeSi} - \text{Al}$ includes three ternary compounds: Al_2FeSi , Al_3FeSi and $\text{Al}_{14}\text{Fe}_3\text{Si}_3$.

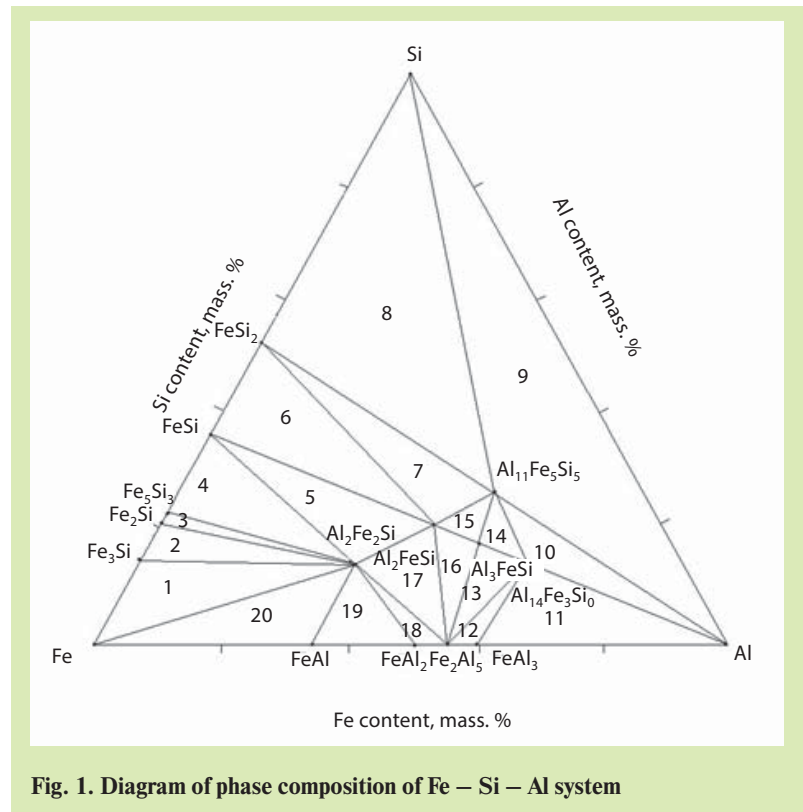


Fig. 1. Diagram of phase composition of Fe – Si – Al system

They and FeSi have also equal Fe to Si relation (1.988), what stipulates their presence on the line $\text{FeSi} - \text{Al}$.

Coupled co-existence of other phases was evaluated by calculation of Gibbs energy variation for corresponding reactions. So, in the quadrangle of substances $\text{FeSi} - \text{FeSi}_2 - \text{Al}_2\text{FeSi} - \text{Al}_{11}\text{Fe}_3\text{Si}_6$ (Fig. 1), the reaction written along its diagonals



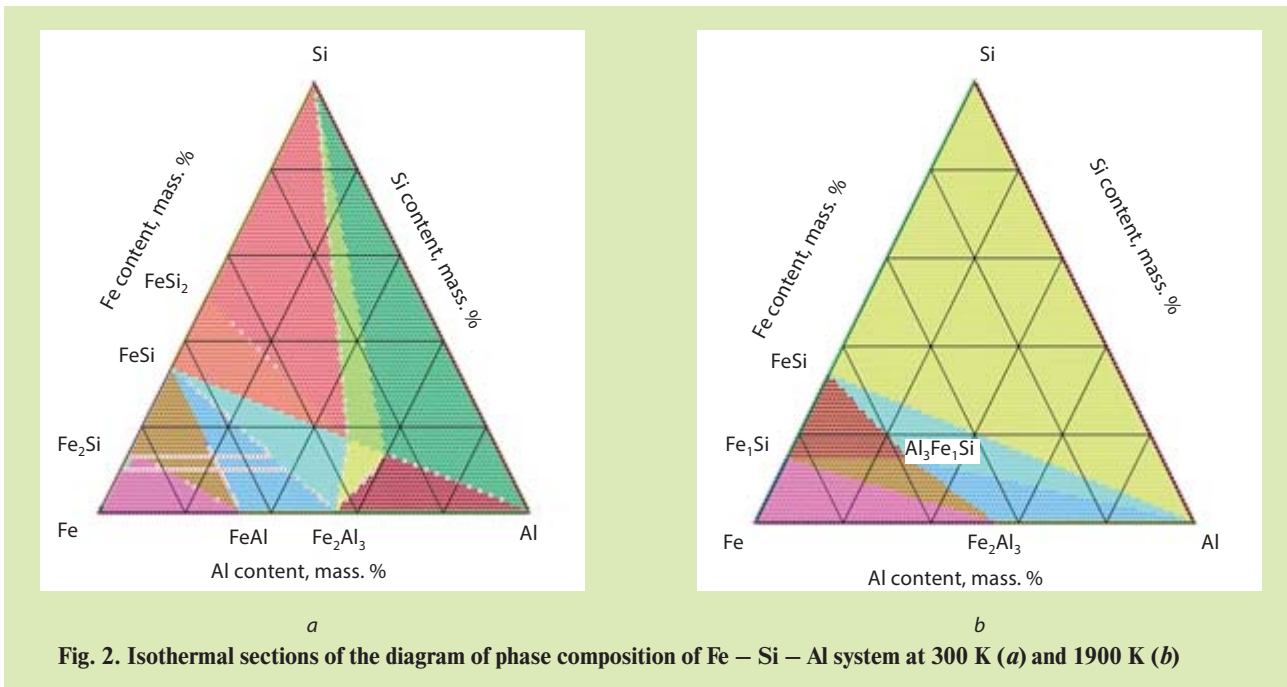
Passes in straight direction with $\Delta G_{298,15\text{K}} = -279.31$ KJ/mol. As a result, its products were assessed as co-existing ones, and they were connected by direct line on the diagram. Conduction of this procedure with other compounds allowed to make complete triangulation of the studied system with establishment of 20 elementary triangles of co-existing phases in it (Fig. 1).

Table 1 presents the numbers of all triangles, their squares (S), equations for determination of number of phases depending on chemical composition of initial metal (Fe_0 , Si_0 , Al_0), as well as prevalence of each phase in the field of the diagram (W) according to [16].

Triangle No. 8 $\text{FeSi}_2 - \text{Al}_{11}\text{Fe}_3\text{Si}_6 - \text{Si}$ occupies maximal square in the examined system, while triangle No. 3 $\text{Al}_2\text{Fe}_2\text{Si} - \text{Fe}_2\text{Si} - \text{Fe}_5\text{Si}_3$ occupies minimal square. The phase $\text{Al}_{11}\text{Fe}_3\text{Si}_6$ has the most existence possibility (W) in the system Fe – Si – Al, and the phase Fe_2Si is characterized by minimal existence possibility.

Temperature relationship of phase composition was studied using “Triangle” program via building isothermal

Table 1. Characteristics of Fe – Si – Al system				
Triangle No.	S, sq. un.	Equations	Phases	W, %
1	0.02133	$Al_2Fe_2Si = 3.5907 \cdot Al_0$ $Fe_3Si = 6.9638 \cdot Si_0 - 3.6260 \cdot Al_0$ $Fe = Fe_0 - 5.9638 \cdot Si_0 + 1.0353 \cdot Al_0$	Fe	3.34
2	0.00994	$Fe_3Si = 3.2061 \cdot Fe_0 - 13.9458 \cdot Si_0 + 0.0032 \cdot Al_0$ $Al_2Fe_2Si = 3.5906 \cdot Al_0$ $Fe_2Si = -2.5061 \cdot Fe_0 + 14.9458 \cdot Si_0 - 2.5938 \cdot Al_0$	Si	15.54
3	0.00311	$Al_2Fe_2Si = 3.5906 \cdot Al_0$ $Fe_2Si = 7.5016 \cdot Fe_0 - 24.8608 \cdot Si_0 - 2.5847 \cdot Al_0$ $Fe_5Si_3 = -6.5016 \cdot Fe_0 + 25.8608 \cdot Si_0 - 0.0059 \cdot Al_0$	Al	10.88
4	0.02070	$Al_2Fe_2Si = 3.5906 \cdot Al_0$ $Fe_5Si_3 = 3.2548 \cdot Fe_0 - 6.4727 \cdot Si_0 - 3.3676 \cdot Al_0$ $FeSi = -2.2548 \cdot Fe_0 + 7.4727 \cdot Si_0 + 0.777 \cdot Al_0$	Fe_3Si	1.54
5	0.01895	$Al_2Fe_2Si = 3.4697 \cdot Fe_0 - 6.9 \cdot Si_0 + 0.0008 \cdot Al_0$ $FeSi = -0.0003 \cdot Fe_0 + 2.989 \cdot Si_0 - 1.5558 \cdot Al_0$ $Al_2FeSi = -2.4694 \cdot Fe_0 + 4.911 \cdot Si_0 + 2.555 \cdot Al_0$	$FeSi$	5.35
6	0.02878	$FeSi = 3.0047 \cdot Fe_0 - 2.9868 \cdot Si_0 - 1.5551 \cdot Al_0$ $Al_2FeSi = 2.5555 \cdot Al_0$ $FeSi_2 = -2.0047 \cdot Fe_0 + 3.9868 \cdot Si_0 - 0.0004 \cdot Al_0$	$FeSi_2$	11.71
7	0.01938	$Al_2FeSi = 4.9397 \cdot Fe_0 - 4.9101 \cdot Si_0 - 0.001 \cdot Al_0$ $FeSi_2 = 0.1825 \cdot Fe_0 + 1.8126 \cdot Si_0 - 1.1324 \cdot Al_0$ $Al_{11}Fe_3Si_6 = -4,1222 \cdot Fe_0 + 4,0975 \cdot Si_0 + 2,1334 \cdot Al_0$	$FeAl$	2.43
8	0.10154	$FeSi_2 = 2.006 \cdot Fe_0 - 1.1328 \cdot Al_0$ $Al_{11}Fe_3Si_6 = 2.1326 \cdot Al_0$ $Si = -1.006 \cdot Fe_0 + 1 \cdot Si_0 + 0.0002 \cdot Al_0$	Fe_2Al_5	2.45
9	0.10090	$Al_{11}Fe_3Si_6 = 3.7764 \cdot Fe_0$ $Si = -1.0056 \cdot Fe_0 + 1 \cdot Si_0$ $Al = -1.7708 \cdot Fe_0 + 1 \cdot Al_0$	Al_3FeSi	1.51
10	0.01382	$Al_{11}Fe_3Si_6 = -3.7818 \cdot Fe_0 + 7.5157 \cdot Si_0$ $Al = -2.7395 \cdot Fe_0 + 0.9632 \cdot Si_0 + 1 \cdot Al_0$ $Al = -2.7395 \cdot Fe_0 + 0.9632 \cdot Si_0 + 1 \cdot Al_0$ $Al_{14}Fe_3Si_3 = 7.5213 \cdot Fe_0 - 7.4789 \cdot Si_0$	$Al_{14}Fe_3Si_3$	4.04
11	0.02516	$Al = -1.4491 \cdot Fe_0 - 1.601 \cdot Si_0 + 1 \cdot Al_0$ $Al_{14}Fe_3Si_3 = 7.4682 \cdot Si_0$ $FeAl_3 = 2.4491 \cdot Fe_0 - 4.8672 \cdot Si_0$	$Al_{11}Fe_3Si_6$	18.74
12	0.00286	$Al_{14}Fe_3Si_3 = 7.4683 \cdot Si_0$ $FeAl_3 = -12.2371 \cdot Fe_0 - 21.0921 \cdot Si_0 + 10.1342 \cdot Al_0$ $Fe_2Al_5 = 13.2371 \cdot Fe_0 + 14.6238 \cdot Si_0 - 9.1342 \cdot Al_0$	Al_2FeSi	6.93
13	0.00655	$Al_{14}Fe_3Si_3 = -5.6342 - 2,2432 \cdot Si_0 + 4.666 \cdot Al_0$ $Fe_2Al_5 = 2.2068 \cdot Fe_0 - 4.388 \cdot Si_0 + 0.0006 \cdot Al_0$ $Al_3FeSi = 4.4274 \cdot Fe_0 + 7.6312 \cdot Si_0 - 3.6666 \cdot Al_0$	Al_2Fe_2Si	9.44
14	0.00323	$Al_{11}Fe_3Si_6 = -3.7795 \cdot Fe_0 + 7.5148 \cdot Si_0 - 0.0008 \cdot Al_0$ $Al_{14}Fe_3Si_3 = -5.2616 \cdot Fe_0 - 2.9841 \cdot Si_0 + 4.6661 \cdot Al_0$ $Al_3FeSi = 10.0411 \cdot Fe_0 - 3.5307 \cdot Si_0 - 3.6653 \cdot Al_0$	$FeAl_2$	1.03
15	0.00316	$Al_{11}Fe_3Si_6 = -3.778 \cdot Fe_0 + 7.5156 \cdot Si_0 - 0.0022 \cdot Al_0$ $Al_3FeSi = -0.9852 \cdot Fe_0 - 9.7843 \cdot Si_0 + 6.1131 \cdot Al_0$ $Al_2FeSi = 5.7632 \cdot Fe_0 + 3.2687 \cdot Si_0 - 5.1109 \cdot Al_0$	$FeAl_3$	2.19
16	0.00641	$Al_3FeSi = -7.3772 \cdot Fe_0 + 2.9314 \cdot Si_0 + 6.1094 \cdot Al_0$ $Al_2FeSi = 6.1712 \cdot Fe_0 + 2.4569 \cdot Si_0 - 5.1107 \cdot Al_0$ $Fe_2Al_5 = 2.206 \cdot Fe_0 - 4.3883 \cdot Si_0 + 0.0013 \cdot Al_0$	Fe_2Si	1.02
17	0.01196	$Al_2FeSi = -2.4704 \cdot Fe_0 + 5.8909 \cdot Si_0 + 2.0458 \cdot Al_0$ $Fe_2Al_5 = 0.0002 \cdot Fe_0 - 3.5119 \cdot Si_0 + 1.8279 \cdot Al_0$ $Al_2Fe_2Si = 3.4706 \cdot Fe_0 - 1.380 \cdot Si_0 - 2.8737 \cdot Al_0$	Fe_5Si_3	1,86
18	0.00354	$Fe_2Al_5 = -8.8381 \cdot Fe_0 + 17.5636 \cdot Si_0 + 9.1474 \cdot Al_0$ $Al_2Fe_2Si = 6.8965 \cdot Si_0$ $FeAl_2 = 9.8381 \cdot Fe_0 - 23.4601 \cdot Si_0 - 8.1474 \cdot Al_0$	-	-
19	0.00972	$Al_2Fe_2Si = 6.8965 \cdot Si_0$ $FeAl_2 = -1.9656 \cdot Fe_0 - 0.0031 \cdot Si_0 + 4.0694 \cdot Al_0$ $FeAl = 2.9656 \cdot Fe_0 - 5.8934 \cdot Si_0 - 3.0694 \cdot Al_0$	-	-
20	0.02142	$Al_2Fe_2Si = 6.8965 \cdot Si_0$ $FeAl = -5.8977 \cdot Si_0 + 3.0703 \cdot Al_0$ $Fe = 1 \cdot Fe_0 + 0.0012 \cdot Si_0 - 2.0703 \cdot Al_0$	-	-



sections of the Fe – Si – Al diagram with 200 K interval. Several obtained data are presented on the Fig. 2.

Only stable binary compounds Fe_2Al_3 , FeSi , Fe_3Si , as well as the ternary compound $\text{Al}_2\text{Fe}_2\text{Si}$, are saved at the increased temperatures (1900 K). Within the temperature range 1900–2700 K the phase composition of the Fe – Si – Al system stabilizes, and it includes 6 elementary triangles of co-existing phases. At the temperatures 2900 K and higher, equilibrium of condensed phases is violated due to transition of low-melting aluminium diagram corner in the gas phase of metal components.

Fig. 3 displays the temperature relationship between metal phase composition in the aluminium corner, containing 90Al, 5Si and 5Fe (mass. %), which is built on semi-logarithmic coordinates. The condensed phases are marked with “c” index, e.g. Al (c), while gas phases don’t have such index.

It can be seen, that increased amount of Al, Al_2 , Fe, Si and Si_2 , which leads to losses of valuable elements of melting metal, can be observed outside the temperature 2800 K in the gas phase.

The concluded equations (see Table 1) allow to calculate metal phase composition in the total area of Fe – Si – Al diagram. It is shown in the Table 2 on the example of two grades of ferrosilicon (FS75 and FS65) and two grades of ferrosilicoaluminium FeSi45Al15 and FeSi55Al20

Conclusions

Both grades of ferrosilicon FS75 and FS65 are located in the triangle field $\text{Al}_3\text{FeSi} - \text{FeSi}_2 - \text{Si}$ with their phase composition. FeSi_2 and Si, which were instrumentally revealed in industrial metal ingots [18], dominate in the structure in this case. Role of loboite (FeSi_2) in ferrosilicon

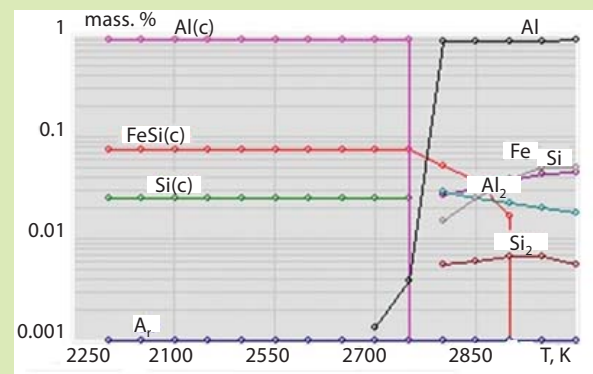


Fig. 3. Relationship between metal phase composition in the aluminium corner, containing 90Al, 5Si and 5Fe (mass. %), and temperature

and ferrosilicoaluminium is an especial one. It is connected with decomposition (dispersion) of these metals during their storage due to transition of high-temperature form of Fe disilicide in low-temperature form, accompanied by volume increase by 17 %. In correspondence with the diagram (Fig. 1), it can be avoided via work in the triangle $\text{Al}_{11}\text{Fe}_3\text{Si}_6 - \text{Si} - \text{Al}$ or below the line $\text{FeSi} - \text{Al}$, where this phase is absent. However, the authors of [18] noted that loboite is not considered as a trigger of ferrosilicon dispersion, while the observing process can be connected with presence of excessive phases based on aluminium, calcium, ferrum, phosphorus, which are instable in wet atmosphere. This problem needs further investigation.

Thereby, the phase composition diagrams for Fe – Si – Al system were built after calculation, their isothermal sections were presented and the mathematical model was

Table 2. Compositions of ferroalloys

No.	Alloy	Alloy composition, mass. %					
		Chemical			Phase		
		Fe	Si	Al	Si	FeSi ₂	Al ₁₁ Fe ₃ Si ₆
1	FeSi75	24	75	1	50.86	47.01	2.13
2	FeSi65	33	65	2	31.8	63.93	4.27
3	FeSi45Al15	40	45	15	4.76	63.25	31.99
4	FeSi55Al20	25	55	20	29.85	27.49	42.66

created. Applicability of this model for analysis of phases forming in silicon and silicon-aluminium ferroalloys was shown. 

This research is funded by the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan (Grant No. AP09259368).

REFERENCES

1. Khurmetbek Zh., Karbaev M., Akberdin A. A. Production of ferrosilicon with low aluminium content. *The input of youth science in Kazakhstan-2050 strategy realization: Proceedings of the Republican student scientific conference. Part 2.* Karaganda. 2016. 398 p.
2. Baisanov S., Tolymbekov M., Takenov T., Chekimbaev A. Development and mastering of the technology of ferrosilicoaluminium production. *Physical-chemical and technological problems of metallurgical production in Kazakhstan. Collection of works. Chemical-metallurgical institute named after Zh. Abishev.* Almaty. Iskander. 2002. Vol. 1. pp. 41-53.
3. Ovcharuk A. N., Taran A. Yu., Rudenko V. K. Ferrosilicoaluminium melting from secondary materials of abrasive production. *Metallurgicheskaya i gornorudnaya promyshlennost.* 2010. No. 3. pp. 37-41.
4. Udovichenko Yu. P., Onishchenko A. A., Parenchuk I. V., Parenchuk V. V. Ferroaluminium as a new ferroalloy for the iron and steel industry. *Energosnabzhenie.* 2004. No. 8. pp. 12-16.
5. Tomida S., Nakata K. Fe-Al composite layers on aluminum alloy formed by laser surface alloy iron powder. *Surface and Coatings Technology.* 2003. Vol. 174-175. No. 1. pp. 559-563.
6. Godlewska E., Szczepanik S., Mania R., Krawiarzand J., Koziński S. FeAl materials from intermetallic powders. *Intermetallics.* 2003. Vol. 11. No. 4. pp. 307-312.
7. Seliverstov I. A., Trotsan G. N., Smirnov I. V. Study of structure and properties of Fe – Al based plasma coatings. *Naukoviy visnik Khersonskoy derzhavnoy morskoy akademii.* 2014. Vol. 10. No. 1. pp. 249-254.
8. Moiseev G. K., Ilyinykh N. I., Kulikova T. V. Thermodynamic researches of Al – Si system melts taking into account existence of “small” clusters. 1. Interval 1000-1600 K. *Rasplavy.* 2005. No. 4. pp. 27-33.
9. Isagulov A. Z., Baisanov S. O., Baisanov A. S., Azotte A., Shabanov E. Zh. Analytical expressions of Fe – Al – Si – Cr system and phase composition of aluminosilicochromium complex alloy. *Trudy universiteta.* 2016. Vol. 63. No. 2. pp. 18-22.
10. Mondolfo L. F. Structure and properties of aluminium alloys. Moscow. *Metallurgiya.* 1979. 639 p.
11. Bannykh O. A. Phase composition diagrams for binary and multi-component Fe-based systems. Moscow. *Metallurgiya.* 1986. 224 p.
12. Dinsdale A. T. SGTE data for pure elements. *Calphad.* 1991. Vol. 15. pp. 317-425.
13. Akberdin A. A. Balance method for calculation of phase composition in multi-component systems. *Kompleksnoe ispolzovanie mineralnogo syrya.* 1995. No. 3. pp. 92-93.
14. Udalov Yu. P. Use of software complexes of calculating and geometric thermodynamics in designing of technological processes for inorganic substances. A manual. St. Petersburg. St. Petersburg state technological institute (Technical university). 2012. 147 p.
15. Tyushnyakov S. N., Selivanov E. N. Thermodynamic simulation of phase forming during cooling of zinc-bearing copper-melting slag. *Butlerovskie chteniya.* 2015. Vol. 43. No. 9., pp. 102-107.
16. Bereznoy A. S. Multi-component systems of oxides. Kiev. *Naukova dumka.* 1970. 572 p.
17. Ilyinykh N. I., Moiseev G. K., Kulikova T. V., Shunyaev K. Yu., Leontyev L. I., Lisin V. L. Thermodynamic parameters of Fe – Al melts. *Izvestiya Chelyabinskogo nauchnogo tsentra.* 2003. Vol. 19. Iss. 2. pp. 32-36.
18. Zubov V. L., Gasik M. I. Ferrosilicon electrometallurgy. Dnepropetrovsk. *Systemnye tekhnologii.* 2002. 704 p.