DOI 10.52209/2706-977X_2025_1_49 IRSTI 53.31.21 UDC 621.791.755

Effect of Boron Additive on the Formation Ferrous Phases in Alloys Al - Fe - Si

Andreyachshenko V.A., Toleuova A.R.*
Abylkas Saginov Karaganda Technical University, Karaganda, Kazakhstan
*corresponding author

Abstract. The article presents an analysis of the diagram of the state of the Al – Fe – Si system using the Thermo-Calc program: polythermal sections were constructed and analyzed in order to determine the concentration limits of the appearance of primary crystals of Fe-containing phases, the mass fractions of phases at certain temperatures were calculated. A search was performed for optimal concentrations and temperatures at which the formation of a highly symmetric Al_8Fe_2Si phase capable of perceiving plastic deformation takes place. The Al-30Fe-9Si-1B system was also investigated. Based on the calculation of the parameters of the primary crystallization of iron in Al – Fe – Si alloys, the possibility of evaluating the effectiveness of modifying this alloy with boron is shown. The boron additive was considered as a modifier contributing to the grinding of aluminium grains and the formation of a wide area of existence of the Al_8Fe_2Si phase. The concentration and temperature ranges at which the maximum number of phases Al_8Fe_2Si and AlB_2 can be achieved have been determined. The minimum amount of the $Al_9Fe_2Si_2$ phase has been calculated, which is undesirable because it leads to a decrease in the mechanical properties of the alloy. From a practical point of view, the complex of proposed studies will allow to scientifically substantiate and develop new technologies for the production and processing of semi-finished products and finished products from aluminium-based alloys and functional materials with a given structure.

Keywords: aluminium, crystallization, boron, phase, polythermic section, modification.

Introduction

Aluminum is one of the key export products of Kazakhstan. The country holds a leading position in Central Asia for its production. However, there are problems associated with this industry (high world market value, high energy costs) [1]. Nevertheless, the prospects for the development of the aluminum industry in Kazakhstan remain quite high. Kazakh companies are actively working to modernize their production facilities and introduce new technologies. This increases production efficiency and reduces energy costs [1].

In the conditions of saving material and energy resources, the issue of recycling aluminum alloys becomes especially relevant, which inevitably leads to an increase in the content of such poorly removed impurities as iron and silicon [2-5]. The increased content of the latter limits the possibility of obtaining such grades of aluminum alloys that are capable of deep drawing, and some operational properties are also reduced. At the same time, recycled aluminum alloys can be very effectively used as raw materials for the production of metal-ceramic materials based on aluminum with an increased content of both iron and silicon. Such metal-ceramic materials have high hardness values and can be used to manufacture products operating under high wear conditions. A distinctive feature of the alloy considered in this paper is the possibility of forming the α-phase, which is characterized by high symmetry of the crystal lattice, which predicts its susceptibility to plastic deformation to a greater extent compared to the β and θ phases, which have monoclinic crystal lattices [6-10].

Considering the increased content of alloying elements in the alloy, significantly exceeding the solubility limits in aluminum, it is quite labor-intensive to obtain such materials by traditional melting. For this purpose, the use of additive manufacturing methods can solve the problem of obtaining metal-ceramic materials.

Often, to ensure the formation of a favorable microstructure, small additives of modifiers are used in aluminum alloys, among which the most common are Ti, Zr, V, TiC, TiB_2, Na, Sr, Sb, Ba [11-15].

Boron is also a well-known modifier of aluminum alloys, which helps to grind the primary crystallizing phases in aluminum alloys, improving the quality of mechanical processing. Aluminum-matrix composite materials alloyed with boron have low specific density, strength, corrosion resistance, good thermal conductivity, and the ability to absorb thermal neutrons. At the same time, there is insufficient literary data showing the effect of boron on the phase composition of aluminum alloys rich in both iron and silicon, and they are mainly fragmentary.

One of the promising areas for producing high-quality aluminum alloys is the additive method of composite material synthesis. The aim of the work was a fundamental study of the Al-Fe-Si system. Search for optimal concentrations and temperatures at which a highly symmetric phase of Al_8Fe_2Si is formed, capable of receiving plastic deformation. Al-30Fe-9Si-1B was also investigated. The boron additive was seen as a modifier, contributing to the grinding of aluminum grains and the formation of a wide range of phase Al_8Fe_2Si. Aluminum alloys, in which boron is used as a modifier (up to 0.04% at melt temperature 690-710°C immediately before casting) and grain shredder are used in the electrical industry. Boron is also introduced to increase electrical conductivity and as a refining additive in aluminum alloys, which are used in the nuclear power industry in the amount of 0095 - 0.1% [16].

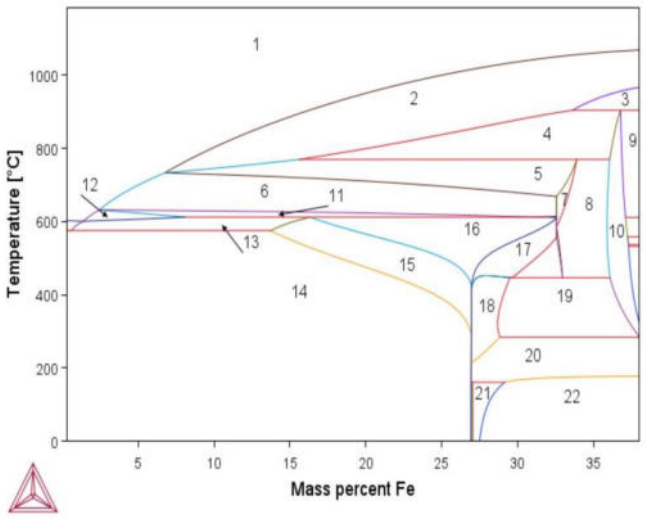
1. Research methodology

At the initial stage, the Al-Fe-Si system from the side of the iron corner was considered. This analysis was carried out using the modern computer program Thermo-Calc.

The Thermo-Calc computer product is a program for calculating phase equilibrium, the basic principle of operation: the algorithm of global minimization of Gibbs energy of multicomponent systems. It is also possible to calculate thermodynamic properties of phases (Gibbs energy, enthalpy, etc.), metastable equilibrium. The main characteristic of this program is its modularity, extensibility, replenishment of the databank of various elements for different systems (metal, salt, oxide, aqueous solutions, etc.). This program also allows the calculation of phase diagrams of multicomponent systems (construction of polythermic and isothermal sections, phase composition calculation, calculation of cooling curves), which was done in this work.

Using the Thermo-Calc program (version TCW8, database TTAL8.2) the aluminum-based system was analyzed to determine the concentration limits of the appearance of primary Fe-containing phase.

The Al-Fe-Si aluminum corner state diagram (Figure 1) is considered as an example. In equilibrium with (Al), in addition to the phases from double systems, there can be two triple connections: Al_8Fe2Si (α) and $Al_9Fe_2Si_2$ (β). In this system there are three three-phase reactions involving (Al): (Al): $L + Al_9Fe_2Si_2 \rightarrow L + Al_9Fe_2Si_2 + (Al)$; $L + Al_9Fe_2Si_2 + (Al) \rightarrow Al_8Fe_2Si + Al_9Fe_2Si_2 + (Al)$; $Al_9Fe_2Si_2 + (Al) \rightarrow Al_9Fe_2Si_2 + (Si) + (Al)$, three three-phase reactions involving liquid phase L and phase θ: $L + \theta + \tau_2 \rightarrow L + \theta + Al_8Fe_2Si$; $L + \theta + Al_8Fe_2Si \rightarrow L + Al_8Fe_2Si$; $L + Al_8Fe_2Si \rightarrow L + Al_8Fe_2Si + Al_9Fe_2Si_2$, the formulations of each phase at a certain temperature are given in the table 1.



Region number	Phase region
1	L
2	L + θ
3	L + θ+ τ_{11}
4	L + θ + τ_2
5	L + θ + Al_8Fe_2Si
6	L + Al_8Fe_2Si
11	L + Al_8Fe_2Si + $Al_9Fe_2Si_2$
12	L + $Al_9Fe_2Si_2$
13	L + $Al_9Fe_2Si_2$ + (Al)
16	Al_8Fe_2Si + $Al_9Fe_2Si_2$ + (Al)
15	$Al_9Fe_2Si_2$ + (Al)
14	$Al_9Fe_2Si_2$ + (Si) + (Al)
17	Al_8Fe_2Si + $Al_9Fe_2Si_2$
18	θ + $Al_9Fe_2Si_2$
7	θ + Al_8Fe_2Si
8	θ +Al_8Fe_2Si + τ_2
9	θ+ τ_{11} + τ_2
10	θ + τ_2
19	θ + $Al_9Fe_2Si_2$ + τ_2
20	θ + $Al_9Fe_2Si_2$ + (Si)
21	θ + $Al_9Fe_2Si_2$ + τ_8
22	θ + $Al_9Fe_2Si_2$

Fig. 1. – Polythermic section of the system Al - 32Fe - 9Si on the side of the iron corner

Primary crystals θ - phase, tend to grow along the orientation [010], forming coarse needles, scales and plate shapes in Al-Fe hypereutectic alloys, which seriously impairs the mechanical properties of alloys [17], [18].

The Al_8Fe_2Si phase has a rather narrow crystallization interval and is suppressed by $Al_9Fe_2Si_2$ phase formation, which is a very undesirable process, as the presence of $Al_9Fe_2Si_2$ phase in the structure causes deterioration of the mechanical properties of the material [19], [20].

Table 1. Phase composition of the system Al-32Fe-9Si

Phase	% mass	Content of the components, %		
		Al	Fe	Si
t = 1072 °C (1 region)				
L	100	81,20	9,75	9,00
t = 925 °C (2 region)				
L	84,5	69,71	19,52	10,63
θ	15,5	59,51	39,60	0,82
t = 928 °C (3 region)				
L	31,27	53,21	29,33	17,38
θ	28,63	58,77	39,71	1,51
τ_{11}	40,09	51,11	40,69	8,18
t = 831 °C (4 region)				
L	24,93	71,37	14,99	13,63
θ	40,25	59,17	39,39	1,42
τ_2	34,80	51,05	33,89	15,05
t = 730 °C (5 region)				
L	8,88	84,45	6,63	8,90
θ	12,79	59,60	39,21	1,17
Al_8Fe_2Si	78,23	57,11	32,55	10,33
t = 671 °C (6 region)				
L	70,61	87,71	3,75	8,53
Al_8Fe_2Si	29,38	57,50	32,55	9,94
t = 665 °C (7 region)				
θ	6,08	59,64	39,15	1,19
Al_8Fe_2Si	93,91	57,91	32,56	9,52
t = 648 °C (8 region)				
θ	23,96	59,34	39,16	1,49
Al_8Fe_2Si	43,25	57,67	32,55	9,76
τ_2	32,77	52,44	33,91	13,64
t = 828 °C (9 region)				
θ	41,76	58,53	39,57	1,89
τ_{11}	16,63	51,11	40,69	8,18
τ_2	41,60	49,44	33,87	16,68
t = 571 °C (10 region)				
θ	51,97	58,00	39,23	2,75
τ_2	48,02	50,16	33,88	15,94
t = 618 °C (11 region)				
L	61,99	90,20	1,97	7,81
Al_8Fe_2Si	28,91	58,07	32,56	9,36
$Al_9Fe_2Si_2$	9,08	58,28	26,90	14,81

Phase	% mass	Content of the components, %		
		Al	Fe	Si
t = 624 °C (12 region)				
L	97,37	89,03	2,16	8,79
$Al_9Fe_2Si_2$	2,62	57,64	26,89	15,45
t = 589 °C (13 region)				
L	25,09	88,17	1,12	10,7
$Al_9Fe_2Si_2$	34,68	57,46	26,89	15,64
(Al)	40,22	98,76	0,00	1,22
t = 379 °C (14 region)				
$Al_9Fe_2Si_2$	52,15	63,49	26,95	9,54
(Si)	3,74	0,00	0,00	100
(Al)	44,10	99,79	0,00	0,20
t = 491 °C (15 region)				
$Al_9Fe_2Si_2$	81,11	62,32	26,94	10,73
(Al)	18,88	99,68	0,00	0,31
t = 550 °C (16 region)				
Al_8Fe_2Si	30,58	60,35	32,59	7,05
$Al_9Fe_2Si_2$	59,49	61,78	26,94	11,27
(Al)	9,91	99,67	0,31	0,00
t = 494 °C (17 region)				
Al_8Fe_2Si	49,72	60,32	32,59	7,08
$Al_9Fe_2Si_2$	50,27	62,09	26,94	10,96
t = 362 °C (18 region)				
θ	6,38	57,98	38,99	3,02
$Al_9Fe_2Si_2$	93,61	63,60	26,96	9,43
t = 367 °C (19 region)				
θ	33,68	56,72	38,96	4,31
$Al_9Fe_2Si_2$	46,53	63,16	26,95	9,88
τ_2	19,78	50,88	33,89	12,55
t = 229 °C (20 region)				
θ	30,66	53,03	38,82	8,14
$Al_9Fe_2Si_2$	69,01	64,00	26,96	9,03
(Si)	0,31	0,00	0,00	100
t = 120 °C (21 region)				
θ	6,70	51,64	38,75	9,59
$Al_9Fe_2Si_2$	93,18	64,11	26,96	8,92
τ_8	0,11	20,10	50,26	29,62
t = 93 °C (22 region)				
θ	49,58	52,15	38,77	9,07
$Al_9Fe_2Si_2$	50,41	64,11	26,96	8,92

To evaluate the morphology of the obtained phases, an alloy of the Al-Fe-Si system with a basic composition was synthesized. The technological conditions of the synthesis are presented in detail in [21, 22]. For metallographic analysis, microsections were prepared using a standard technique, using cutting, grinding, and polishing operations. The microstructure was studied immediately after synthesis, without additional processing in the "as prepared" state. The synthesized ingot has two main regions: the intermetallic region, which occupies the bulk of the material, and the eutectic region (Figure 2).

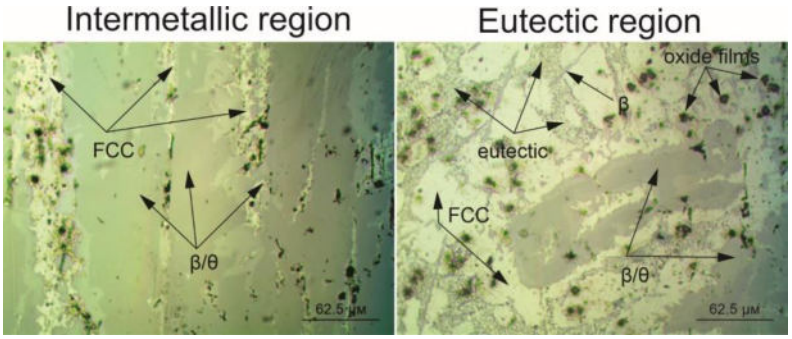
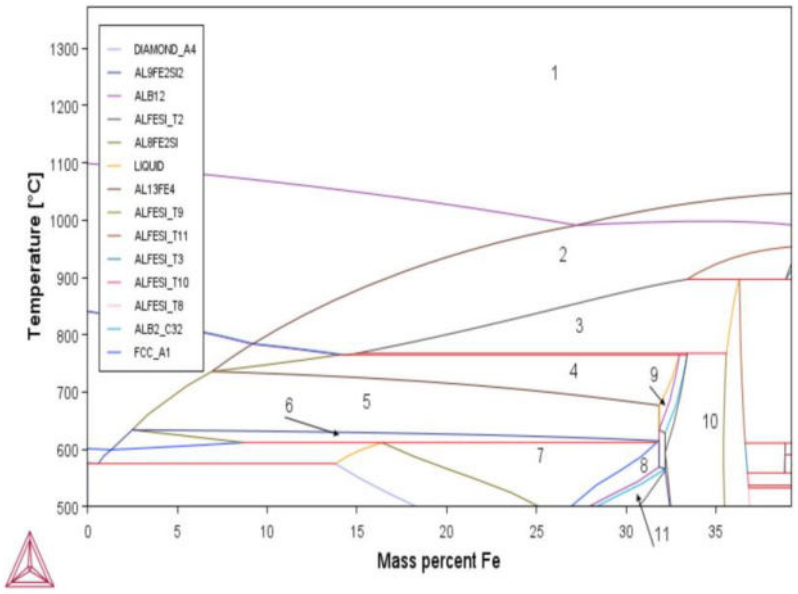


Fig. 2. – Microstructure of the alloy system Al-Fe-Si

Metallographic analysis shows that the structure of the material predominantly contains a combination of β/θ phases, with the growth of the β phase occurring on the primary crystals of the θ phase, which is in good agreement with the results of computer modeling for region 22 (Figure 1). At the same time, thin sections of the FCC solid solution of silicon and iron in aluminum were detected, formed as products of decomposition and phase transformation as a result of nonequilibrium cooling conditions during synthesis. The obtained results demonstrate the validity of using this approach to modeling for the purpose of predicting the phase composition of the alloy during its modification.

In this connection, the effect of boron on the formation and formation of the Al_8Fe_2Si phase was further considered. As an example, a diagram of the state of Al-Fe-Si-B (Figure 3) was constructed.



Region number	Phase region
1	L
2	L
3	L + θ + AlB_2 + τ_2
4	L + θ + Al_8Fe_2Si + AlB_2
5	L + Al_8Fe_2Si + AlB_2
9	θ + Al_8Fe_2Si + AlB_2
6	L + Al_8Fe_2Si + $Al_9Fe_2Si_2$+ AlB_2
7	Al_8Fe_2Si + $Al_9Fe_2Si_2$+ AlB_2+ (Al)
8	Al_8Fe_2Si + $Al_9Fe_2Si_2$+ AlB_2
10	θ + Al_8Fe_2Si + AlB_2 + τ_2
11	Al_8Fe_2Si + $Al_9Fe_2Si_2$+ AlB_2

Fig. 3. – Polythermic section of the system Al-30Fe-9Si-1B

In this system, with the participation of the θ phase, there are four three-phase reactions with the formation of Al_8Fe_2Si and AlB_2: L + θ + AlB_2 + τ_2 → L + θ + Al_8Fe_2Si + AlB_2; L + θ + Al_8Fe_2Si + AlB_2 → L + Al_8Fe_2Si + AlB_2; L + Al_8Fe_2Si + AlB_2 → θ + Al_8Fe_2Si + AlB_2. There is one four-phase reaction involving (Al): L + Al_8Fe_2Si + $Al_9Fe_2Si_2$+ AlB_2 → Al_8Fe_2Si + $Al_9Fe_2Si_2$+ AlB_2+ (Al). The Al_8Fe_2Si phase has three three-phase reactions: Al_8Fe_2Si + $Al_9Fe_2Si_2$+ AlB_2 → θ + Al_8Fe_2Si + AlB_2 + τ_2; θ + Al_8Fe_2Si + AlB_2 + τ_2 → Al_8Fe_2Si + $Al_9Fe_2Si_2$+ AlB_2. The formulations of each phase at a certain temperature are given in table 2. As seen from the reactions, the separation of phase Al_8Fe_2Si and AlB_2 goes through the entire temperature range.

Table 2. Phase composition of the system Al-30Fe-9Si-1B

Phase	% mass	Content of the components, %			
		Al	Fe	Si	B
t = 1236 °C (1 region)					
L	100	64,21	25,78	9,00	1,00
t = 1236 °C (2 region)					
L	100	64,21	25,78	9,00	1,00
t = 818 °C (3 region)					
L	44,65	72,57	14,10	13,12	1,89
θ	33,80	59,21	39,37	14,1	0,00
AlB_2	2,85	17,21	0,00	0,00	82,78
τ_2	18,68	51,20	33,9	14,89	0,00
t = 730 °C (4 region)					
L	23,54	84,25	6,73	8,93	0,07
θ	8,13	59,6	39,21	1,18	0,00
Al_8Fe_2Si	64,09	57,1	32,55	10,34	0,00
AlB_2	4,22	55,51	0,00	0,00	4,48
t = 685 °C (5 region)					

Phase	% mass	Content of the components, %			
		Al	Fe	Si	B
t = 568 °C (7 region)					
Al_8Fe_2Si	30,53	59,72	32,58	7,69	0,00
$Al_9Fe_2Si_2$	51,75	60,97	26,93	12,08	0,00
AlB_2	4,24	55,51	0,00	0,00	44,48
(Al)	13,46	99,56	0,01	0,41	0,00
t = 568 °C (8 region)					
Al_8Fe_2Si	79,22	58,98	32,57	8,44	0,00
$Al_9Fe_2Si_2$	16,38	60,04	26,92	13,02	0,00
AlB_2	4,39	55,51	0,00	0,00	44,48
t = 677 °C (9 region)					
θ	4,64	59,66	39,16	1,17	0,00
Al_8Fe_2Si	90,92	57,8	32,55	9,63	0,00
AlB_2	4,42	55,51	0,00	0,00	44,48
t = 628 °C (10 region)					
θ	22,45	59,31	39,15	1,54	0,00

L	61,31	86,94	4,37	8,63	0,04
Al_8Fe_2Si	34,76	57,39	32,55	10,05	0,00
AlB_2	3,91	55,51	0,00	0,00	44,48
t = 625 °C (6 region)					
L	60,90	89,26	2,23	8,47	0,02
Al_8Fe_2Si	31,08	57,80	32,55	9,63	0,00
$Al_9Fe_2Si_2$	4,06	57,79	26,89	15,31	0,00
AlB_2	3,93	55,51	0,00	0,00	44,48

Al_8Fe_2Si	38,90	57,9	32,56	9,53	0,00
AlB_{12}	3,23	17,21	0,00	0,00	82,78
τ_2	35,40	52,49	33,91	13,58	0,00
t = 520 °C (11 region)					
Al_8Fe_2Si	68,86	59,46	32,58	7,95	0,00
$Al_9Fe_2Si_2$	27,97	61,02	26,93	12,04	0,00
AlB_{12}	3,16	17,21	0,00	0,00	82,78

2. Results and Discussing

One of the main criteria for producing alloys based on aluminium is the process of modification (grinding of grains of cast aluminium with the introduction of special additives). The process of grinding aluminum grain at crystallization is the result of special interaction of transition metals with aluminium [23], [24]. The ideal modifier is a particle that satisfies the following requirements: it should be effectively crushed grain at a minimum concentration; in the melt is thermally stable and dispersed; it has a minimum structural difference with the lattice of the modifying alloy; do not lose their modifying properties when melting. None of the modifiers currently known have a complete set of these properties [16], [25], [26]. One such modifier in aluminum alloys is boron, which is a transition metal. It has good refining effect on Al-Si alloys [27], [28].

Analyzing the polythermic section of the system Al - 32Fe - 9Si on the side of the iron angle sections, we can conclude that the phase of interest to us Al_8Fe_2Si has a fairly wide crystallization interval at a temperature from 730 C to 490 °C, but its formation is suppressed by the formation of phase $Al_9Fe_2Si_2$. For example, at 494 °C (table 2, 17 region), the phase region consists of Al_8Fe_2Si (49.72%) and $Al_9Fe_2Si_2$ (50.27%). However, with the drop in temperature, a phase transition is underway with the disappearance of the Al_8Fe_2Si phase, which is completely transitioned to the $Al_9Fe_2Si_2$ phase.

The $Al_9Fe_2Si_2$ phase is known to be the most harmful, reducing the mechanical properties of aluminum alloys. In particular, the plate or needle phase of $Al_9Fe_2Si_2$ not only cleaves the matrix, but also contributes to the formation of casting defects such as pores and shrink pores. These phases easily cause stress concentration and crack propagation, thus becoming the weakest sites in the alloys Al-Si [29], [30], [31]. Therefore, a section of the system Al-30Fe-9Si-1B was built and the main optimal phase compositions were determined.

Boron is an effective grain shredder in Al-Si alloys, but the mechanism responsible for the effect of boron on the formation and growth of phases rich in iron is still under discussion [31]. The mechanism of primary grinding of boron grains in the Al matrix in the alloy is based on the formation of particles AlB_2 as a result of eutectic reaction (table 3, region 3). And the formation of this phase has a fairly wide temperature crystallization interval (818 - 520 °C). It can also be concluded that this phase contributes to the formation of the Al_8Fe_2Si phase with a fairly good phase composition (min 31.08%, max 90.92%). Phase AlB_2 is crystallized by eutectic reaction at 818 C (table 4, area 3). Since the AlB_2 and Al_8Fe_2Si phases have different crystallographic lattices, it can be assumed that the AlB_2 phase is the catalyst for the onset of phase Al_8Fe_2Si [32], [33], [34].

Conclusions

Quantitative analysis of the phase diagram Al - Fe - Si as the basis of the high-strength alloy was carried out using the program Thermo-Calc (version TCW8, database TTAL8.2). The standard alloy Al - 32Fe - 9Si was considered, built a polythermic section, calculated the temperature of phase transformations. The phase composition obtained during modeling was compared with the real phase composition, and the microstructure of the alloy was studied. Optimum concentrations of iron and silicon were determined for Al_8Fe_2Si phase crystallization. The mass fractions of each phase are calculated at certain temperatures.

A polythermic cut Al-30Fe-9Si-1B was also calculated. The concentration and temperature regions at which the maximum number of Al_8Fe_2Si and AlB_2 phases can be achieved have been determined. The minimum number of phase $Al_9Fe_2Si_2$ is calculated, which is undesirable because it leads to a decrease in the mechanical properties of the alloy.

The data presented in this article are the initial stage in carrying out research on the development of technology for the synthesis of composite ceramic materials of the AlxFeySi system using an additive method to improve the quality of the structure of materials based on them. In the future, a complete thermodynamic analysis will be carried out to select the optimal concentrations of alloying elements in order to develop a rational mode of heat treatment of the alloy under study.

In the future, using the above described thermodynamic calculations to identify and modify phases rich in iron in Al-Fe-Si alloys, it is planned to experiment with the addition of boron by the method of additive synthesis.

Acknowledgement. The work was done with the support of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant AP19675471)

References

[1] Kazakhstan guide in the country. https://kazakhstangid.ru/ao-alyuminiy-kazahstana, 2024

[2] Zhou B, Liu B, Zhang S, Lin R, Jiang Y, Lan X. Microstructure evolution of recycled 7075 aluminum alloy and its mechanical and corrosion properties. Journal of Alloys and Compounds, 2021; 879. – p. 160407. https://doi.org/10.1016/j.jallcom.2021.160407

[3] Sun Y. The use of aluminum alloys in structures: Review and outlook //Structures. 2023. 57. – p. 105290. https://doi.org/10.1016/j.istruc.2023.105290

[4] Yu Y, Zhang X, Wang C, Hu J, Zhou D, Yang C, Zhang D. The influence of deformation-dependent prior chip boundary on microstructure and tensile properties in a solid-state recycled AA6063 aluminum alloy. Journal of Materials Processing Technology, 2025, 336 – p. 118693. https://doi.org/10.1016/j.jmatprotec.2024.118693

[5] Krolo J, Špada V, Bilušić M, Čatipović N. Welding of Solid-State-Recycled Aluminum Alloy: Comparative Analysis of the Mechanical and Microstructural Properties. Applied Sciences, 2025, 15(3) – p. 1222. https://doi.org/10.3390/app15031222

[6] Andreyachshenko V, Toleuova A. On the influence of iron and silicon content on the phase composition of the Al-Fe-Si system. Kompleksnoe Ispolzovanie Mineralnogo Syra= Complex use of mineral resources, 2025, 332(1), pp. 98-107. https://doi.org/10.31643/2025/6445.09

[7] Andreyachshenko V, Naizabekov A. The technology of equal channel angle backpressure extrusion for deformation iron and aluminium alloys. In Proceedings of the 3rd International Conference on NANOCON-2011, 2011. – pp. 246-252.

[8] Andreyachshenko V, Isheva Y, Mazhit A, Imangazinova D. ECAP-treated aluminium alloy AA2030: microstructure and mechanical properties. Materials & Technologies/Materiali in Tehnologije, 2019. 53(6). – pp. 805-810. 10.17222/mit.2018.250

[9] Andreyachshenko V.A. Evolution of the AA2030 alloy microstructure in the ECAP process. Metallic Materials/Kovové Materiály, 2022. 60(2) – 79-87. 10.31577/km.2022.2.79

[10] Andreyachshenko V, Bartenev I, Malashkevichute-Brillant Y. Synthesis of an aluminum alloy rich in iron and silicon by surfacing with a consumable electrode. Acta Metallurgica Slovaca, 2024, 30(3) – 133-136. https://doi.org/10.36547/ams.30.3.2065

[11] Ammar HR, Samuel E, Elsharkawi E, Doty HW, Songmene V, Samuel FH. Effect of Be, Sr, Mn, Mg, Cr and Si Addition on Neutralization and Fragmentation of β-Al5SiFe Phase in Al-(6–10)% Si Alloys. International Journal of Metalcasting, 2025 – pp. 1-24. https://doi.org/10.1007/s40962-024-01540-0

[12] Nagaraj C, Dutt KM, Manjunath GK, Sharath PC, Sollapur SB, Arunkumar DT. Effect of multidirectional forging on grain structure and mechanical properties of hypereutectic Al–20% Si alloys with added refiners and modifiers. Canadian Metallurgical Quarterly, 2024 – pp. 1-15. https://doi.org/10.1080/00084433.2024.2413245

[13] Man'ko T. Influence of Modification of Cast and Deformed Alloys on Mechanical Properties of Compositions. Journal of Rocket-Space Technology, 2024, 33(4-28) – pp. 94-97. https://doi.org/10.15421/452430

[14] Zheng Q, Chen T, Li D, Wu J. Synergistic optimization of α-Al grain and eutectic Si structures for Al-Si alloys via a newly designed Al-Ce-B alloy. Materials Science and Engineering: A, 2025, 925 – p. 147867. https://doi.org/10.1016/j.msea.2025.147867

[15] Grejtak T, Shyam A, Blau PJ, Qu J. Additively manufactured and cast high-temperature aluminum alloys for electric vehicle brake rotor application. Wear, 2025 – p. 205961. https://doi.org/10.1016/j.wear.2025.205961

[16] Aluminum alloy modification. https://studref.com/519893/tehnika/modifitsirovanie_alyuminievyh_splavov

[17] Zhongping Q, Changming F, Chamini L. M, Yun W, Zhongyun F. Effects of Si solution in θ-Al13Fe4 on phase transformation between Fecontaining intermetallic compounds in Al alloys. Journal of Alloys and Compounds, 2023. – p. 1-13. https://doi.org/10.1016/j.jallcom.2022.167587

[18] Que Zh, Fang Ch, Mendis ChL., Wang Yu., Fan Zh. Effects of Si solution in θ-Al13Fe4 on phase transformation between Fe-containing intermetallic compounds in Al alloys. Journal of Alloys and Compounds, 2023 https://doi.org/10.1016/j.jallcom.2022.167587.

[19] Jin L, Liu K, Chen XG. Evolution of Fe-Rich Intermetallics in Al-Si-Cu 319 Cast Alloy with Various Fe, Mo, and Mn Contents. Metall Mater Trans B, 2019. – p. 1896–1907. https://doi.org/10.1007/s11663-019-01584-2

[20] Nová K, Novák P, Průša F, Kopeček J, Čech J. Synthesis of Intermetallics in Fe-Al-Si System by Mechanical Alloying. Metals, 2019 https://doi.org/10.3390/met9010020

[21] Aiken AZ, Andreyachshenko VA. Evolution of microstructure and properties in Fe, Si-Rich Al-Fe-Si alloy. AIP Conference Proceedings, 2024, 3251(1) – p. 040006 https://doi.org/10.1063/5.0234067

[22] Andreyachshenko V, Ulyeva G. Heat treatment effect on the intermetallic Al-Fe-Si alloy microstructure. Acta Metallurgica Slovaca, 2024, 30(4) – pp. 156–160. https://doi.org/10.36547/ams.30.4.2092

[23] Yang W, Gao F, Ji Sh. Formation and sedimentation of Fe-rich intermetallics in Al–Si–Cu–Fe alloy. Transactions of Nonferrous Metals Society of China, 2015. – p. 1704-1714 https://doi.org/10.1016/S1003-6326(15)63776-1

[24] Lan X, Kai L, Wang J, Yang M, Lu Q, Du Y. Developing Al–Fe–Si alloys with high thermal stability through tuning Fe, Si contents and cooling rates. Intermetallics, 2022 https://doi.org/10.1016/j.intermet.2022.107505.

[25] Becker H, Bergh T, Vullum PE, Leineweber A, Li Y. Effect of Mn and cooling rates on α-, β-and δ-Al–Fe–Si intermetallic phase formation in a secondary Al–Si alloy. Materialia, 2019 https://doi.org/10.1016/j.mtla.2018.100198
[26] Song DF, Zhao YL, Wang Z et al. 3D Fe-Rich Phases Evolution and Its Effects on the Fracture Behavior of Al–7.0Si–1.2Fe Alloys by Mn Neutralization. Acta Metall. Sin. (Engl. Lett.), 2022. – p. 163–175 https://doi.org/10.1007/s40195-021-01299-x
[27] Fang CM, Que ZP, Fan Z. Crystal chemistry and electronic structure of the β-AlFeSi phase from first-principles. Journal of Solid State Chemistry, 2021 https://doi.org/10.1016/j.jssc.2021.122199
[28] Orozco-González P, Castro-Román M, Muñiz-Valdez R, Luna-Álvarez S, Equihua-Guillén F, Hernández-Rodríguez A, Baltazar-Hernández VH, Alvarado-Hernández F. Formation and crystal structure of the τ phase in the Al-Fe-Mn-Si system. Materials Letters, 2016. – p. 277-279 https://doi.org/10.1016/j.matlet.2016.05.139
[29] Naizabekov A.B., Andreyachshenko V.A. Evaluation of possible mechanical property improvement for alloy of the Al-Fe-Si-Mn system by equal-channel angular pressing. Metallurgist, 2013; 57(1-2) – pp.159-163. doi 10.1007/s11015-013-9706-0
[30] Yu JM, Wanderka N, Rack A, Daudin R, Boller E, Markötter H, Manzoni A, Vogel F, Arlt T, Manke I, Banhart J. Influence of impurities, strontium addition and cooling rate on microstructure evolution in Al-10Si-0.3Fe casting alloys. Journal of Alloys and Compounds, 2018. – p. 818-827. https://doi.org/10.1016/j.jallcom.2018.06.372
[31] Song D, Zhao Y, Jia Y, Huang G, Zhang Z, Zhou N, Li X, Zheng K, Fu Y, Zhang W. Effect of B addition on the formation of Fe-rich phases in Al-Si-Fe alloys. Journal of Alloys and Compounds, 2022 https://doi.org/10.1016/j.jallcom.2022.167426
[32] Toleuova A.R., Dostayeva A.M., Zharkevich O.M., Abdullina S.A., Adilkanova M.A., Serikbayev D. Calculating and experimental studying phase transformations in the Al-Zr-Fe-Si system alloys //Metalurgija, 2020. – p. 543 – 546
[33] Jiang H, Liu YC, Wei C, Zhang YH, Gao ZM. Influence of minor Co on the formation of intermetallic phases in the Al91Fe7Si2 alloy. Journal of Alloys and Compounds, 2008. – p. 92-97 https://doi.org/10.1016/j.jallcom.2007.11.019.
[34] Kishor M., Chopra K., Ayyagari K.P.R. Tackling Fe-rich Intermetallics in Al-Si Alloy: A Critical Review. Trans Indian Inst Met, 2023 https://doi.org/10.1007/s12666-023-03205-8

Information of the authors

Andreyachshenko Violetta Alexandrovna, PhD, associate professor, Head of the Testing Laboratory Engineering Profile “Comprehensive Development of Mineral Resources”, Abylkas Saginov Karaganda Technical University
e-mail: Vi-ta.z@mail.ru

Toleuova Ainagul Rymkulovna, PhD, associate professor, docent of the department Nanotechnology and metallurgy, Abylkas Saginov Karaganda Technical University
e-mail: rymkul.ainagul@gmail.com