alloys

MDPI

Article

Additional Extraction of Aluminum and Silicon During Integrated Bauxite Processing in Kazakhstan

P. O. Bykov [1,2], M. M. Suyundikov [1], A. V. Bogomolov [1], A. B. Kuandykov [1,*], A. K. Zhunusov [1] and N. K. Kulumbaev [1]

[1] Metallurgy Department, Toraighyrov University, Pavlodar 140008, Kazakhstan
[2] University Administration, Innovative University of Eurasia, Pavlodar 140000, Kazakhstan
* Correspondence: azeka200892@mail.ru

Abstract

In this paper, we experimentally investigated the integrated processing of high-iron Kazakh bauxites by reducing smelting of ore–coke–lime briquettes to produce an Fe-Al-Si metallic alloy, which is of potential interest for steel deoxidation, together with calcium-aluminate slag, which is of potential interest for alumina extraction. Briquettes containing bauxite, metallurgical coke (10–20 wt.%), and freshly calcined lime (10 wt.%, constant) were melted in a muffle furnace at a temperature of 1200–1450 °C. Complete separation of metal and slag was achieved at 1400–1450 °C, whereas at 1200–1350 °C, separation remained incomplete. Changing the coke/bauxite mass ratio in the charge from 0.125 to 0.286 increased the total content of metallic Si, Al and Fe in the recovered metallic product from 77.1 to 98.66 wt.%, according to X-ray fluorescence (XRF) analysis after two-stage magnetic separation; the metallic product obtained with a coke/bauxite ratio of 0.286 in the charge contained 72.8% Fe, 23% Al and 2.86% Si (with minor impurities of Ti, Mn and Cr), while the associated slag was represented mainly by CaO (59.5%) and Al2O3 (34.0%). These slag characteristics indicate its potential suitability for alumina extraction or as a filler for structural concrete. The proposed route represents a potentially low-waste alternative for processing high-iron bauxites that are poorly suited to the classical Bayer process, avoiding the direct formation of red mud and supporting Kazakhstan's transition toward closed-loop bauxite processing.

Keywords: bauxite; ferro-aluminum-silicon alloy; reduction smelting; ore-lime briquettes; slag; alumina; magnetic separation; closed-loop processing; recycling

1. Introduction

Aluminum is the second most important structural metal after steel, and its consumption continues to grow in industries such as transportation, mechanical engineering, construction, and electrical engineering [1,2], which increases the demand for aluminum metal and, consequently, requires primary producers to continually improve the degree of metal extraction from bauxite ore [3–6].

This growth is supported by a significant amount of research aimed at expanding the use of aluminum and its alloys as structural materials [3–6]. Abro et al. [3] investigated the effect of aluminum additives in combination with nitrogen on the heat treatment behavior and second-phase particle formation in microalloyed steel. Sunar and Cetin [4] studied the fabrication of metal structures based on reinforced open-cell aluminum foams strengthened with boron carbide. Gazi et al. [5] investigated the formability of A5010 aluminum alloy

Check for updates

Received: 14 July 2026
Revised: 30 August 2026
Accepted: 2 September 2026
Published: 14 September 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

sheets under various incremental forming and deformation conditions. Bykov et al. [6] studied the recycling of spent filters from primary aluminum refining ash waste as a filler for concrete production, demonstrating the potential for recycling aluminum industry waste in the construction industry.

The success of such applied research increases the demand for aluminum metal and, consequently, puts pressure on its availability on the global market, requiring primary aluminum producers to continually improve the degree of metal extraction from bauxite ore.

Globally, the ore base for alumina production is primarily represented by high-quality low-silica and low-iron bauxites suitable for direct processing using the Bayer hydrometallurgical process [7,8]. In Kazakhstan, however, alumina and aluminum production is based on domestic bauxite deposits located in the north of the country, which are characterized by a relatively complex mineralogical and chemical composition, in particular, an increased content of iron and silica oxides and a low silicon modulus [9–15]. Such high-iron, high-silica bauxites are processed by the Bayer process with reduced efficiency and lead to the formation of significant volumes of waste in the form of sludge.

Table 1 shows the average chemical composition of bauxite from the three main Kazakh deposits used as raw material in this work, and Table 2 shows their mineralogical composition.

Table 1. Average chemical composition of Kazakhstani bauxites (main elements), % [9].

Field	Al_2O_3	SiO_2	Fe_2O_3	CaO	FeO	μSiO_2, un.
Belinskoye	41.40	10.3	21.2	1.27	2.88	4.02
Ayatskoe	44.60	10.7	18.3	0.53	2.06	4.17
Krasnooktyabrskoye	42.00	10.9	19.4	0.96	5.41	3.85

Table 2. Mineralogical composition of Kazakhstani bauxites, % [9].

Field	Kaolinite	Chamosite	Gibbsite	Goethite	Anatase	Quartz	Siderite	Hematite
Belinskoye	15.0	1.95	52.3	2.7	2.7	1.0	2.4	18.4
Ayatskoe	14.4	1.65	56.6	2.6	2.3	1.2	1.4	16.7
Krasnooktyabrskoye	22.6	2.0	50.9	2.8	2.4	1.2	4.7	11.5

As can be seen from Tables 1 and 2, the largest proportion of chemical elements in the composition of Kazakhstani bauxites is represented by iron, silicon, and aluminum minerals, with hematite, goethite, and siderite together accounting for a significant iron oxide load, along with aluminum-containing gibbsite and kaolinite.

These environmental aspects are also reflected in the regulatory and strategic policy of Kazakhstan, which establishes requirements for the minimization of industrial waste and stimulates the transition of resource-intensive industries, including non-ferrous metallurgy, to closed, low-waste production cycles [16,17]. Red mud is recognized worldwide as one of the largest types of industrial waste in terms of volume: on average, 1–1.5 tons of red mud are generated per 1 ton of alumina produced by the Bayer process, and the accumulated global reserves are estimated at billions of tons, with a limited degree of their industrial utilization [18,19]. The high alkalinity (pH often above 12) and fine dispersion of red mud make its storage a constant source of land alienation, groundwater and soil pollution, and a risk to public health due to dusting [20]. These circumstances have stimulated extensive research into the utilization of red mud—in the production of building materials, environmental remediation, catalysis and, most relevant to the present work, in the pyrometallurgical extraction of iron and other valuable elements by carbothermic

reduction followed by magnetic separation [20–24]. Carbothermic reduction of red mud or high-iron bauxite residues at temperatures of 1300–1600 °C, as shown in the literature, allows the production of metallic iron with a degree of extraction, typically in the range of 90–98%, along with calcium-alumina silicate slag, which, depending on the composition, can be used for the extraction of alumina, the production of cement clinker, or used as a building filler [20,23,24].

A common feature of most published studies on red mud utilization [18–24] is that they consider the mud that has already formed after the Bayer leaching stage, i.e., they are dealing with an already formed hydrometallurgical waste. An alternative strategy, applied in the present work, is to process the highest iron bauxite ore by pyrometallurgical reduction smelting before Bayer leaching, which allows the production of an Fe-Al-Si metallic alloy of potential interest as a steelmaking deoxidizing additive, along with an alumina-containing slag directly from the ore, without forming red mud at all. This approach is particularly relevant for Kazakh bauxites, the iron and silicon content of which makes them unsuitable for classical processing by the Bayer method [9–15] due to the low silicon modulus of bauxite and the high iron and kaolin content.

It should be noted that reduction smelting of iron-rich bauxite ore followed by metal-slag or magnetic separation has already been reported; for example, Zhang et al. [25] developed a semi-smelting reduction and magnetic separation route for iron-rich bauxite, achieving an iron recovery of 96.84% and an alumina-slag Al_2O_3 grade of 43.98%. Thus, the novelty of this study lies not in the general concept of pyrometallurgical processing before the Bayer stage as such, but in the application of the ore–coke–lime briquettes technology specifically to high-iron, high-silicon Kazakh bauxites, aimed at the simultaneous production of Fe-Al-Si metal alloy and slag rich in CaO-Al_2O_3, potentially suitable for further use in the production of steel, alumina or the production of structural concrete.

The objective of the study was to conduct laboratory studies on the integrated processing of high-iron and high-silicon Kazakhstani bauxites by reducing smelting of ore–coke–lime briquettes to produce Fe-Al-Si metallic alloy of potential interest for steel deoxidation and a slag of potential interest for alumina production.

To achieve this goal, the following objectives were set in the study: to characterize representative Kazakh bauxites; to develop a laboratory technology for reducing smelting to obtain silicon–aluminum alloys and high-alumina slag, which are of potential interest for subsequent use in steel deoxidation and the production of alumina or structural concrete.

2. Materials and Methods of Research

2.1. Source Materials

The raw materials used for the production of ore–coke–lime briquettes were pre-ground bauxite of the −0.4. . .+0.63 mm fraction (Table 3), metallurgical coke (Table 4), and freshly calcined lime (Table 5). The presence of kaolin in Kazakh bauxite made it possible to exclude bentonite and other binders from the raw material composition. The initial materials were crushed using a jaw crusher DShch 80–150 (Vibrotechnik, Saint Petersburg, Russia), ground using a Herzog vibratory grinder, and samples were prepared using a Herzog laboratory press. The chemical composition of bauxite, metallurgical coke, and freshly calcined lime was determined by X-ray spectral analysis using a multi-channel X-ray spectrometer SRM-35 (Granat group, Orel City, Russia).

Table 3. Chemical composition of bauxite in experimental studies (main elements), %.

Al_2O_3	SiO_2	Fe_2O_3	CaO	FeO	μSiO_2, un.
47.10	10.7	20.1	0.88	6.30	3.84

Table 4. Chemical composition of metallurgical coke, %.

Component	C	S	L.O.I.
Metallurgical coke	79.02	0.53	20.45

Table 5. Chemical composition of freshly burnt lime, %.

Component	CaO	SiO_2	MgO	$Al_2O_3 + Fe_2O_3$	S	L.O.I.
Freshly burned lime	89	1.9	1.2	1.3	0.12	6.48

2.2. Briquette Production

The raw materials were dosed, mixed, and formed into cylindrical briquettes using a hydraulic press at a pressing force of 30 kN. The green briquettes were pre-dried at 110 °C for 60 min to achieve sufficient strength for subsequent loading into the furnace for reduction smelting. The finished briquettes had a diameter of 27 mm, a height of 20 mm, and a mass of 17 ± 0.02 g each (Figure 1).



Figure 1. General view of characteristic ore-lime briquettes.

Samples from three experimental series, differing in the ratio of bauxite, metallurgical coke, and lime, were prepared and tested. The amount of water added to ensure green strength of the briquettes remained constant for all series (Table 6).

Table 6. Composition (dry matter, mass%) of components of ore–coke–lime briquettes depending on the series of experiments.

Component	Series No.1	Series No.2	Series No.3
Bauxite	70	75	80
Metallurgical coke	20	15	10
Lime	10	10	10
Water (over 100%)	15	15	15

The amount of metallurgical coke was varied between the series in order to establish its effect on the degree of reduction of iron, silicon and aluminum, based on the requirement for maximum reduction of iron, silicon and aluminum and taking into account the experience of previously published studies of reduction smelting and waste recycling [23–26]. Because bauxite content was reduced from 80 to 70 wt.% as coke increased from 10 to 20 wt.% (Table 5), coke was not varied as a strictly independent parameter; expressed as a coke-to-bauxite mass ratio, the three series correspond to 0.125 (Series No 3), 0.20 (Series No 2) and 0.286 (Series No 1). The amount of freshly burned lime (10%, constant for all series) was selected to ensure a sufficiently fluid slag and effective separation of metal and slag during reduction smelting by regulating the basicity of the resulting calcium-alumina silicate slag.

2.3. Recovery Smelting

Briquettes of each of the three series were subjected to reduction melting in a muffle furnace in the temperature range of 1200–1450 °C in an air atmosphere, with the accumulation of reduction products in a graphite crucible (Figure 2). Two briquettes per melt were loaded into a standard graphite crucible with a capacity of 0.1 kg. The furnace heating rate was 10 °C/min, the holding time at the operating temperature was 30 min, and cooling was carried out together with the furnace to a temperature of 300 °C. Although the furnace chamber itself contained air, the crucible cover and the excess coke in the charge are expected to have limited bulk oxidation of the charge: combustion of coke at the charge surface, together with the Boudouard reaction, generates a locally CO/CO_2-rich atmosphere within the crucible that is reducing with respect to the metal oxides, consistent with the behavior reported for similar covered-crucible carbothermic reduction system. The graphite crucible itself is a potential additional carbon source, and its contribution to the overall carbon balance was not separately quantified in this study.

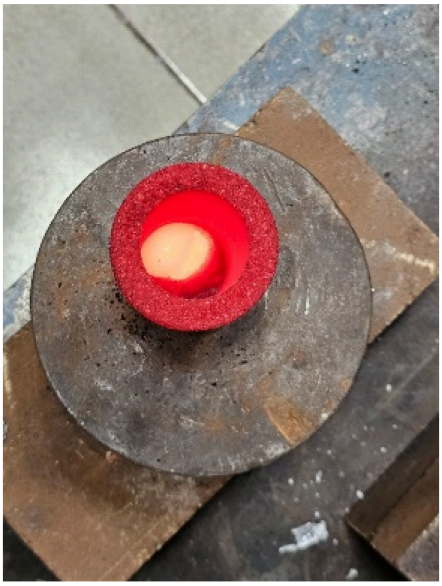


Figure 2. Results of the reduction smelting of ore–coke–lime briquettes: metallic silicon–aluminum–iron alloy and associated slag.

2.4. Magnetic Separation

After the reduction smelting, the products were subjected to crushing and two-stage magnetic separation on a laboratory magnetic separator SMS-20-PM1 (ITOMAK company, Novosibirsk, Russia)to separate the metallic phase from the slag: in the first stage, permanent magnets were used, in the second—a magnetic field with a strength of 2 T.

2.5. Chemical Analysis and Calculation of the Degree of Recovery

The chemical composition of the separated metal and slag products was determined by X-ray fluorescence analysis (XRF) using a ProSpector 2 LE portable spectrometer (Elvatech, Kyiv, Ukraine) (serial number P1775). The metal portion was measured in the “alloys” mode, and the slag phase was measured in the “oxides” mode. For the main components (Fe, SiO_2, CaO, Al_2O_3, MgO, MnO), the absolute measurement error did not exceed ±0.05–0.15%; for trace elements (P, S, Cu, Ni, Cr) it was ±0.01–0.03%.

The degree of reduction of each element (Fe, Al, Si) was calculated as the ratio of the mass of the given element transferred to the metallic product to its total mass in the

bauxite, expressed as a percentage, in accordance with the approach traditionally used for the reduction smelting processes of iron-containing raw materials [24]:

$$\alpha_{Me}\ (\%) = (m_{Me,met} / m_{Me,charge}) \times 100 \quad (1)$$

where $m_{Me,met}$ is the mass of the element Me (Si, Al or Fe) in the resulting metal product, $m_{Me,charge}$ is the mass of the same element in the initial charge of briquettes.

In each series, 5 samples were tested.

In each series of experiments, five samples were tested, and the arithmetic mean of the results and the standard deviation of the Fe, Al, and Si content in the metal product and slag were calculated. In the tables, the numerical values are presented as arithmetic means; standard deviations do not exceed 3%.

3. Results

3.1. The Effect of Temperature on the Separation of Metal and Slag

At reduction temperatures of 1200–1350 °C, the processes of metal oxide reduction and separation of the resulting metallic and slag phases did not proceed fully: the melt remained partially solid, and the metallic and non-metallic fractions were visually indistinguishable. At 1300–1350 °C, partial melting occurred, creating favorable conditions for phase separation; metallic phases were partially observed in the melt products. At 1400–1450 °C, maximum separation of metal and slag was achieved, i.e., metallic phases interspersed with slag were clearly visible in the melt product. Part of the metallic phase of the Fe-Al-Si alloy accumulated at the bottom of the graphite crucible, and the lower-density slag collected above it. Further increases in temperature did not improve the experimental results and led to the boiling of the melt, so they were not investigated in this study. Thus, the practical value of operating temperatures for reduction melting is 1400–1450 °C.

3.2. Effect of Coke Content on the Metal Yield

Table 7 shows the results of the yield of condensed products (metal and slag) of the smelting process in the optimal temperature range of 1400–1450 °C, calculated for 1 kg of the initial bauxite.

Table 7. Results of the yield of condensed products (metal and slag) of melting at 1400–1450 °C, kg.

Product Name	Series No.1 (Coke/Bauxite Mass Ratio 0.286)	Series No.2 (Coke/Bauxite Mass Ratio 0.2)	Series No.3 (Coke/Bauxite Mass Ratio 0.125)
Input:			
Bauxite	1.000	1.000	1.000
Metallurgical coke	0.286	0.200	0.125
Lime	0.143	0.133	0.125
Dry charge	1.429	1.333	1.250
Output:			
Metallic part	0.256	0.227	0.201
Slag	0.745	0.773	0.810

As can be seen from Table 7, the coke/bauxite ratio in the briquette charge significantly affects the metallization of iron, aluminum, and silicon. As the coke content in the briquette increases, the yield of the metal fraction increases from 0.201 kg at a ratio of 0.125 to 0.227 kg at a ratio of 0.20 and 0.256 kg at a ratio of 0.286, calculated per 1 kg of bauxite in the charge.

It is also clear that the losses are as follows: Series 1—0.428 kg, Series 2—0.333 kg, Series 3—0.239 kg. These losses are associated with coke combustion and gasification, CO/CO_2 release, moisture loss, etc.

3.3. Chemical Composition of the Metal Product and Slag

Two-stage magnetic separation of crushed reduction products made it possible to isolate the metallic Fe-Al-Si phase from the slag.

As can be seen from Table 8, the metal product obtained under optimal conditions (1400–1450 °C, coke/bauxite mass ratio 0.286) consisted mainly of iron (72.8%) and aluminum (23.0%), with a smaller proportion of silicon (2.86%) and trace amounts of titanium, manganese, and chromium; in total, the metals Si, Al, and Fe accounted for up to 98.66% of the product. In the slag (Table 9), CaO (59.5%) and Al_2O_3 (34.0%) predominated, with lower contents of SiO_2, Fe_2O_3, MgO, BaO, and MnO, which reflects the addition of lime introduced to increase the fluidity of the slag and to separate the metal and slag (Section 2.2).

Table 8. Chemical composition of the isolated metal product, X-ray fluorescence (XRF) analysis, % (arithmetic mean deviation +3.0% for n = 5).

Fe	Al	Si	Ti	Mn	Cr
72.8	23.0	2.86	0.81	0.38	0.15

Table 9. Chemical composition of associated slag, X-ray fluorescence (XRF) analysis, % (arithmetic mean deviation +3.0% for n = 5).

CaO	Al_2O_3	Fe_2O_3	SiO_2	MgO	BaO	MnO	L.O.I.
59.5	34.0	2.69	1.65	1.4	0.37	0.04	0.35

An analysis of the experimental results shows that the maximum recovery of Fe, Al, and Si in the optimal temperature range of 1400–1450 °C is αFe = 98.32% + 3.0%, αAl = 27.07% + 3.0%, and αSi = 14.64% + 3.0%. These values are valid for a coke/bauxite mass ratio in the charge of 0.286.

This confirms that the coke/bauxite mass ratio in the briquette charge is the key process parameter determining the degree of metallization at a given temperature. However, when selecting the optimal coke additive for industrial applications, it is also necessary to consider the balance between the degree of metal recovery and the associated costs of the reagent (coke), etc.

4. Discussion

The observed temperature dependence of metal–slag separation (incomplete at 1200–1350 °C, complete at 1400–1450 °C) is consistent with the behavior described for the carbothermic reduction of other iron-containing aluminosilicate materials, where coalescence and precipitation of metal droplets requires the formation of a sufficient amount of liquid phase in the slag [22,24]. For example, in the reduction smelting of high-iron bauxite residue studied by Wang et al. [24], the proportion of liquid phase in a similar slag of the Al_2O_3-SiO_2-CaO(-Na_2O) system depended significantly on both temperature and basicity, with almost complete melting required for effective separation of metal and slag. The addition of lime and the operating window of 1400–1450 °C established in this study can be explained within the same concept: the introduced CaO sufficiently reduces the liquidus temperature of the aluminosilicate slag, allowing separation to be achieved without the need to reach the temperatures used in the reduction smelting of red mud (up

to 1500–1600 °C in [22,24]) or in its carbothermic reduction for the purpose of titanium extraction (1600 °C in [23]).

The basicity of the resulting slag can be quantified using the traditional binary basicity index B = %CaO/%SiO_2. Applying this definition to the composition of the slag obtained with a coke/bauxite mass ratio in the charge of 0.286 (Table 9: CaO = 59.5%, SiO_2 = 1.65%) gives B = 36, i.e., a highly basic slag with a predominance of calcium aluminates; accordingly, the low residual SiO_2 content reflects the reduction of part of the silica into the metallic phase under these conditions. The lime addition of 10 wt.% (constant for all series, Table 6) was chosen based on the fact that freshly calcined lime (89% CaO, Table 5) reliably shifted the slag system CaO-Al_2O_3-SiO_2 towards the observed behavior of the liquid phase at 1400–1450 °C.

The degree of Fe, Al, and Si recovery achieved in this study is comparable to the iron extraction values reported for the carbothermic reduction of red sludge and other high-iron bauxite residues, which, under optimized conditions, typically amount to 90–98% [20,23,24]. This demonstrates that the studied technology of ore–lime briquettes is competitive with red sludge-based reduction methods in terms of metal extraction, while also enabling the direct processing of bauxite ore without the prior generation of alkaline waste.

The high CaO (59.5%) and Al_2O_3 (34.0%) content in the resulting slag, coupled with a low residual iron content, favors two alternative routes for its subsequent utilization, similar to those proposed in the literature for red mud processing slags. Slags of this type, rich in calcium and aluminum, are suitable for alumina extraction by hydrometallurgical and other methods (e.g., sintering or leaching), as demonstrated for similar Bayer and reduction slags [19,21,22]. The choice between slag processing directions—or their combination—requires a separate technical and economic assessment.

From the perspective of process design, the increase in the degree of reduction with an increase in coke addition (Section 3.2) indicates a trade-off between the efficiency of metallization and coke consumption, and consequently, the cost of the process; therefore, the selection of the optimal coke dosage for industrial implementation should be based on comprehensive technical and economic optimization, not just on maximizing the degree of reduction, which is also noted in studies of coke consumption in related processes of iron ore pellet production and reduction smelting [26]. The elevated operating temperature (1400–1450 °C) and the associated energy consumption are additional factors that must be taken into account when conducting a technical and economic assessment of the proposed technology on a pilot or industrial scale. The proposed integrated processing technology also aligns with the broader environmental context in Kazakhstan, where the Environmental Code and the national concept of a “green economy” encourage the minimization of industrial waste and the transition of resource-intensive industries to closed production cycles [16,17]. By obtaining an Fe-Al-Si metal alloy, which is potentially valuable as a deoxidizing additive, and slag, which is potentially valuable for alumina production, directly from bauxite ore, this process could minimize the generation of alkaline bauxite waste, in contrast to the classical processing of the same ores using the Bayer method with subsequent reclamation of red sludge [18–24]. The broader environmental aspects of bauxite mining and processing in Kazakhstan, including land use and waste management, are discussed in [27] and provide a useful context for assessing the environmental benefits of the proposed approach.

It should be noted that this study has a number of limitations that determine the priority areas for further work. The experiments were conducted on a laboratory scale using briquettes of fixed geometry; to scale up to pilot and industrial levels, it will be necessary to verify that the identified temperature patterns and patterns of coke influence are preserved at larger batch volumes and under continuous or semi-continuous furnace operation. In this

study, the coke/bauxite mass ratio in the charge was varied between 0.125, 0.2, and 0.286; a more systematic parametric study—for example, examining the interactions between temperature and the coke/bauxite mass ratio in the charge, briquette size, lime dosage, and the possible role of an inert atmosphere in the furnace—combined with a kinetics and material balance study similar to that conducted for the red mud reduction smelting [24] would allow a more accurate determination of the optimum process parameters. Although the resulting slag composition (Table 9) has the potential to be suitable for alumina recovery, the present work did not include slag leaching or sintering tests; such tests, along with a feasibility study of the proposed technology compared to the traditional Bayer process for bauxite processing, will allow for a more detailed development of a closed-loop strategy for bauxite ore processing in Kazakhstan.

Thus, the novelty of this work lies in determining the optimal temperature range of 1400–1450 °C and a coke/bauxite mass ratio of 0.286 in the batch of ore–coke–lime briquettes to achieve maximum extraction of Fe, Al, and Si during the integrated processing of high-iron and high-silicon Kazakhstani bauxites using the reduction smelting method.

5. Conclusions

1. Characterization of Kazakhstani bauxites (Belinskoye, Ayatskoye, and Krasnooktyabrskoye deposits) confirmed that the largest proportion of their chemical composition is represented by iron, silicon, and aluminum minerals, which limits the efficiency of conventional Bayer processing and justifies the need for an alternative pyrometallurgical technology.

2. Reduction smelting of ore–coke–lime briquettes at 1400–1450 °C ensured maximum separation of metal and slag, i.e., the smelting product clearly contained metallic phases embedded in the slag. Part of the metallic phase of the Fe-Al-Si alloy accumulated at the bottom of the graphite crucible, while the lower-density slag collected above it.

3. Analysis of the experimental results shows that the maximum degree of reduction of Fe, Al, and Si in the optimal temperature range of 1400–1450 °C is αFe = 98.32%, αAl = 27.07%, and αSi = 14.64%. These values are valid for a coke/bauxite mass ratio in the charge of 0.286.

4. The resulting metallic product (up to 98.66% metallic Si, Al, and Fe; 72.8% Fe, 23.0% Al, 2.86% Si) is an Fe-Al-Si alloy of potential interest as a steelmaking deoxidizing additive.

5. The associated slag (59.5% CaO, 34.0% Al_2O_3) is a potential secondary raw material for alumina production, pending confirmatory leaching/sintering tests, and could support the implementation of a closed-loop processing cycle for high-iron Kazakh bauxites without the formation of alkaline bauxite waste (red mud).

6. The proposed technology represents a technically feasible alternative to the classic Bayer-sintering method for processing high-iron bauxites of complex composition and requires further study on a pilot scale, including systematic kinetic, balance, and feasibility studies, to justify industrial implementation.

Author Contributions: Conceptualization—P.O.B. and A.K.Z.; methodology—P.O.B. and A.V.B.; validation—A.B.K. and A.K.Z.; formal analysis—A.B.K. and A.V.B.; study execution—M.M.S., A.K.Z. and N.K.K.; resources—A.V.B. and N.K.K.; data handling—P.O.B. and N.K.K.; manuscript drafting—M.M.S.; review and editing—P.O.B. and A.V.B.; visualization—A.B.K. and N.K.K.; scientific supervision—P.O.B.; project administration—M.M.S.; funding acquisition—P.O.B. All authors have read and agreed to the published version of the manuscript.

Funding: The study was carried out with grant funding from the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan under the competition for grant funding of scientific and (or) scientific and technical projects for 2024–2026, project AP23487674

"Complex processing of bauxites of Kazakhstan with additional extraction of iron using alternative reducing agents in the implementation of the low-carbon development strategy".

Data Availability Statement: The original contributions presented in this study are included in the article material. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Hou, Q.; Wu, X.; Li, Z.; Feng, S.; Kong, D.; Wang, S.; Ma, X.; Miao, Y.; Qiao, H.; Li, X.; et al. Artificial intelligence enabled microstructure prediction in Al alloy casting. *J. Mater. Sci. Technol.* **2026**, *241*, 21–34. [CrossRef]
2. Bykov, P.O.; Kuandykov, A.B.; Zhunusov, A.K.; Tolymbekova, L.B.; Suyundikov, M.M. Complex processing of primary aluminum to remove impurities of non-ferrous metals. *Metalurgija* **2023**, *62*, 293–295.
3. Abro, S.H.; Moria, H.A.; Chandio, A.; Al-Khazaal, A.Z. Understanding the effect of aluminum addition on the forming of second phase particles on grain growth of micro-alloyed steel. *Eng. Technol. Appl. Sci. Res.* **2020**, *10*, 5153–5156. [CrossRef]
4. Sunar, T.; Cetin, M. An experimental study on boron carbide reinforced open cell aluminum foams produced via infiltration technique. *Eng. Technol. Appl. Sci. Res.* **2018**, *8*, 3640–3645. [CrossRef]
5. Ghazi, S.K.; Salloom, M.Y.; Bedan, A.S. Experimental evaluation of a system to control the incremental forming of aluminum alloy type 1050. *Eng. Technol. Appl. Sci. Res.* **2024**, *14*, 16943–16949. [CrossRef]
6. Bykov, P.O.; Kuandykov, A.B.; Kaliyeva, A.B.; Siemens, E. Processing of used aluminium production granular to produce concrete. *Eng. Technol. Appl. Sci. Res.* **2025**, *15*, 19885–19890. [CrossRef]
7. Ahmad, I.; Hartge, E.-U.; Werther, J.; Wischnewski, R. Bauxite washing for the removal of clay. *Int. J. Miner. Metall. Mater.* **2014**, *21*, 1045–1051. [CrossRef]
8. Lever, G. Identification of organics in Bayer liquor. In *Essential Readings in Light Metals*; Springer Nature: Berlin, Germany, 2016; Volume 1, pp. 184–190. [CrossRef]
9. Ibragimov, A.T.; Budon, S.V. *Development of Alumina Production Technology from Bauxite in Kazakhstan*; House of the Press: Pavlodar, Kazakhstan, 2010; 304p.
10. Power, G.; Grafe, M.; Klauber, C. Bauxite residue issues: I. Current management, disposal and storage practices. *Hydrometallurgy* **2011**, *108*, 33–45. [CrossRef]
11. Zhunusova, G.; Zhunusov, A.; Bykov, P.; Bakirov, A.; Zayakin, O.; Kenzhebekova, A. Research of physicochemical properties of ferrous sands from alumina production. *Acta Metall. Slovaca* **2024**, *30*, 161–166. [CrossRef]
12. Kenzhaliyev, B.K.; Kuldeyev, E.I.; Abdulvaliyev, R.A.; Pozmogov, V.A.; Beisembekova, K.O.; Gladyshev, S.V.; Tastanov, E.A. Prospects of aluminum industry development in Kazakhstan. *News Natl. Acad. Sci. Repub. Kazakhstan Ser. Geol. Tech. Sci.* **2017**, *3*, 151–160.
13. Ibragimov, A.T.; Budon, S.V.; Ambarnikova, G.A.; Mikhailova, O.I.; Eremina, M.G. Bauxite Processing Method. Innovative Patent of the Republic of Kazakhstan No. 19915, 15 August 2008.
14. Ibragimov, A.T.; Tastanov, E.A.; Eremina, M.G. Extraction of ferruginous sands as a method of processing substandard bauxites. *Complex Use Miner. Complex Use Miner. Resour.* **2009**, *6*, 11–17.
15. Zhunussova, A.K.; Bykov, P.O.; Zhunusov, A.K.; Kenzhebekova, A.Y. Research of the production of iron ore sinter from bauxite processing waste. *Complex Use Miner. Complex Use Miner. Resour.* **2024**, *2*, 73–81. [CrossRef]
16. Parliament of the Republic of Kazakhstan. *Environmental Code of the Republic of Kazakhstan Dated 01.02.2021*; No. 400-VI ZRK No. 400-VI ZRK (as amended 7 May 2023); Parliament of the Republic of Kazakhstan: Astana, Kazakhstan, 2023.
17. Parliament of the Republic of Kazakhstan. *Concept for the Transition of the Republic of Kazakhstan to a "Green Economy", Approved by Decree of the President of the Republic of Kazakhstan Dated May 30, 2013*; No. 577; Parliament of the Republic of Kazakhstan: Astana, Kazakhstan, 2013.
18. Wang, L.; Sun, N.; Tang, H.; Sun, W. Review on comprehensive utilization of red mud and prospect analysis. *Minerals* **2019**, *9*, 362. [CrossRef]
19. Khairul, M.A.; Zanganeh, J.; Moghtaderi, B. The composition, recycling and utilisation of Bayer red mud. *Resour. Conserv. Recycl.* **2019**, *141*, 483–498. [CrossRef]
20. Habibi, H.; Piruzian, D.; Shakibania, S.; Pourkarimi, Z.; Mokmeli, M. The effect of carbothermal reduction on the physical and chemical separation of the red mud components. *Miner. Eng.* **2021**, *173*, 107216. [CrossRef]
21. Li, X.; Xiao, W.; Liu, W.; Liu, G.; Peng, Z.; Zhou, Q.; Qi, T. Recovery of alumina and ferric oxide from Bayer red mud rich in iron by reduction sintering. *Trans. Nonferrous Met. Soc. China* **2009**, *19*, 1342–1347. [CrossRef]
22. Klauber, C.; Gräfe, M.; Power, G. Bauxite residue issues: II. Options for residue utilization. *Hydrometallurgy* **2011**, *108*, 11–32. [CrossRef]

23. Stopic, S.; Kostić, D.; Schneider, R.; Sievers, M.; Wegmann, F.; Kaya, E.E.; Perušić, M.; Friedrich, B. Recovery of titanium from red mud using carbothermic reduction and high pressure leaching of the slag in an autoclave. *Minerals* **2024**, *14*, 1151. [CrossRef]
24. Wang, K.; Zhang, T.-A.; Dou, Z.-H.; Liu, Y.; Lv, G.-Z. Cleaner production of metallurgical-grade iron from high-iron bauxite residue via smelting reduction. *Materials* **2025**, *18*, 3288. [CrossRef] [PubMed]
25. Zhang, Y.; Gao, Q.; Zhao, J.; Li, M.; Qi, Y. Semi-smelting reduction and magnetic separation for the recovery of iron and alumina slag. *Minerals* **2019**, *9*, 223. [CrossRef]
26. Borra, R.; Dwarapudi, S.; Kapure, G.; Tathavadkar, V.; Denys, M.B. Effect of alumina on slag-metal separation during iron nugget formation. *Ironmak. Steelmak.* **2013**, *40*, 443–451. [CrossRef]
27. Yesenbayev, A.; Kolesnikov, A.; Naukenova, A.; Eremenko, O.; Issengaliyeva, G. Environmental assessment of the consequences of bauxite mining in Kazakhstan. *MIAB Min. Inf. Anal. Bull.* **2025**, *6*, 82–93. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.