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CARBON-FREE SMELTING OF CHROME-CONTAINING FERROALLOY USING FERROALUMOSILICOCALIUM AND FERROSILICOCHROME DUST

Abstract. The study examines carbon-free smelting of chromium-containing ferroalloy using ferroaluminosilicocalcium (***FeAlSiCa***) and ferrosilicochrome dust (***FeSiCr***) as complex metallothermic reductants aimed at reducing the carbon footprint of conventional ferrochrome production. Four charge variants with reductant contents ranging from 10% deficiency to 20% excess relative to stoichiometry were investigated. Smelting was conducted at 1650 °C followed by SEM, EDS, and chemical analyses of the obtained products. ***Cr-Fe*** solid solutions and ***Cr-V-N*** nitride phases were formed, while silicon excess promoted ***Cr-Si*** silicides. Chromium recovery reached 86%, and impurity levels remained low (C ≤ 0.10%). The alloys satisfied ISO 5448-81 requirements. The optimal composition corresponded to a 10% excess of reductants.

Key words: *ferroalloy, ferrochrome, low-carbon ferrochrome, metallothermy, ferroalumosilicocalcium, ferrosilicochrome, calcium, complex reducing agents, carbon footprint.*

Ферроалюмосиликокальций және ферросиликохром шаңын қолдана отырып хром ферроқорытпасын көміртегісіз балқыту

Аңдатпа. Зерттеуде дәстүрлі феррохром өндірісінің көміртегі ізіне тәуелділігін төмендету мақсатында ферроалюмосиликокальций (***FeAlSiCa***) және ферросиликохром шаңы (***FeSiCr***) кешенді металлотермиялық тотықсыздандырғыштар ретінде қолданылған көміртексіз балқыту үдерісі қарастырылды. Тотықсыздандырғыштардың мөлшері стехиометрияға қатысты 10% кемнен 20% артыққа дейін өзгертілген төрт шихта нұсқасы зерттелді. Балқыту 1650 °C температурада жүргізіліп, алынған өнімдер СЭМ, ЭДС және химиялық талдау әдістерімен зерттелді. Нәтижесінде Cr-Fe қатты ерітінділері мен ***Cr-V-N*** нитридтік фазалары түзілді, ал кремнийдің артық мөлшері ***Cr-Si*** силицидтерінің пайда болуына әкелді. Хромның алыну дәрежесі 86%-ға жетті, ал қоспалар мөлшері төмен болды (C ≤ 0,10%). Қорытпалар ISO 5448-81 талаптарына сәйкес келеді. Оңтайлы құрам тотықсыздандырғыштардың 10% артық мөлшеріне сәйкес анықталды.

Түйінді сөздер: *ферроқорытпа, феррохром, төмен көміртекті феррохром, металлотермия, ферроалюмосиликокальций, ферросиликохром, кальций, күрделі тотықсыздандырғыштар, көміртегі ізі.*

Безуглеродная выплавка хромсодержащего ферросплава с применением ферроалюмосиликокальция и пыли ферросиликохрома

Аннотация. В работе исследована возможность безуглеродной выплавки хромсодержащего ферросплава с использованием ферроалюмосиликокальция (***FeAlSiCa***) и пыли ферросиликохрома (***FeSiCr***) в качестве комплексных металлотермических восстановителей с целью снижения углеродного следа традиционного производства феррохрома. Рассмотрены четыре варианта шихты с содержанием восстановителей от 10% недостатка до 20% избытка относительно стехиометрии. Плавка проводилась при 1650 °C, полученные продукты исследованы методами СЭМ, ЭДС и химического анализа. Установлено формирование твердых растворов ***Cr-Fe*** и нитридных фаз ***Cr-V-N***, при избытке кремния образуются силициды ***Cr-Si***. Степень извлечения хрома достигла 86%, содержание примесей было низким (C ≤ 0,10%). Полученные сплавы соответствуют требованиям ISO 5448-81. Оптимальной признана шихта с 10% избытком восстановителей.

Ключевые слова: *ферросплав, феррохром, низкоуглеродистый феррохром, металлотермия, ферроалюмосиликокальция, ферросиликохрома, кальций, комплексные восстановители, углеродный след.*

Introduction

Modern ferrochrome production relies heavily on the carbothermic reduction of chromium oxides, making the process one of the most carbon-intensive in the ferroalloy industry. The use of coke and other carbon-containing reducing agents results in high CO_2 emissions, significant energy costs, and process limitations, particularly in the production of low-carbon ferrochrome for corrosion-resistant steels. Increasing environmental requirements and the transition to low-carbon metallurgy are stimulating the search for alternatives to traditional carbothermic reduction [1–3].

One promising area is the use of metal-thermal reducing agents, which completely eliminate carbon from the process. However, the use of pure ***Al***, ***Si***, or ***Ca*** is limited by their cost and the energy intensity of production. Therefore, interest in complex man-made reducing agents with high reactivity and availability is relevant [4–6].

Ferroaluminosilicocalcium (***FeAlSiCa***) is a reducing agent containing active elements with a high affinity for oxygen – ***Ca***, ***Al***, and ***Si***. Its use allows for lower process temperatures, increased Cr_2O_3 reduction, and a reduced carbon footprint, while simultaneously utilizing metallurgical waste. Research into the mechanisms of reduction, phase formation, and product properties using ***FeAlSiCa*** is an important step toward developing carbon-free smelting technologies for chromium-containing ferroalloys [6–8].

Materials and methods

During the carbon-free smelting of chromium-containing ferroalloy, chromium concentrate, ***FeAlSiCa*** and ***FeSiCr*** dust were used as charge materials.

Chemical analysis of chromium concentrate and metal reducing agents has the following values, %: chromium concentrate: Cr_2O_3 – 52.91; Al_2O_3 – 7.801; SiO_2 – 4.65; ***MgO*** – 17.51; ***CaO*** – 0.58; Fe_2O_3 – 12.91; ***S*** – 0.022; ***P*** – 0.003; calcination loses – 15.021; ***FeAlSiCa***: ***Fe*** – 8.13; ***Al*** – 13.45; ***Si*** – 66.16; ***Ca*** – 10.03; ***C*** – 0.69; ***S*** – 0.017; ***P*** – 0.041; ***Ti*** – 1.08; ***V*** – 0.42; ***FeSiCr***: ***Fe*** – 9.11; ***Al*** – 4.03; ***Si*** – 48.08; ***Ca*** – 1.15; ***C*** – 2.00; ***S*** – 0.056; ***P*** – 0.025; ***Cr*** – 1.1; ***V*** – 38.73.

FeAlSiCa and ***FeSiCr*** were introduced in equal proportions in four variants: 10% deficient reducing agents (variant 1); in a stoichiometric amount sufficient for the complete reduction of the main oxides of ***Cr*** concentrate (variant 2); and also with 10% (variant 3) and 20% (variant 4) excess. A more detailed composition is presented below:

– variant 1, %: 52.3 ***Cr*** concentrate; 7.8 ***FeAlSiCa***; 7.8 ***FeSiCr*** dust; 31.9 lime;

– variant 2, %: 44.7 ***Cr*** concentrate; 8.9 ***FeAlSiCa***; 8.9 ***FeSiCr*** dust; 37.4 lime;

– variant 3, %: 39.0 ***Cr*** concentrate; 9.7 ***FeAlSiCa***; 9.7 ***FeSiCr*** dust; 41.4 lime;

– variant 4, %: 34.6 ***Cr*** concentrate; 10.3 ***FeAlSiCa***; 10.3 ***FeSiCr*** dust; 44.6 lime.

Melting was carried out in alundum crucibles immersed in a ***MgO*** backfill (to protect the furnace chamber from potential splashes resulting from violent exothermic reactions) in a chamber furnace in an air atmosphere at a heating rate of 10 °C/min with an isothermal hold at 1650 °C for 30 minutes, followed by cooling in the furnace to room temperature. The charge was a mixture of ground powders with particle sizes ≤120 µm.

The resulting metal and slag samples were examined using a ZepTools ZEM20 scanning electron microscope (SEM) with an Oxford energy-dispersive spectroscopy (EDS) attachment. Individual elements were analyzed using analytical chemistry methods.

Results

Figure 1 shows SEM images of metals obtained by melting using four different methods of introducing ***FeAlSiCa*** and ***FeSiCr***. The images were obtained in backscattered electron detection mode at a magnification of ×1000.

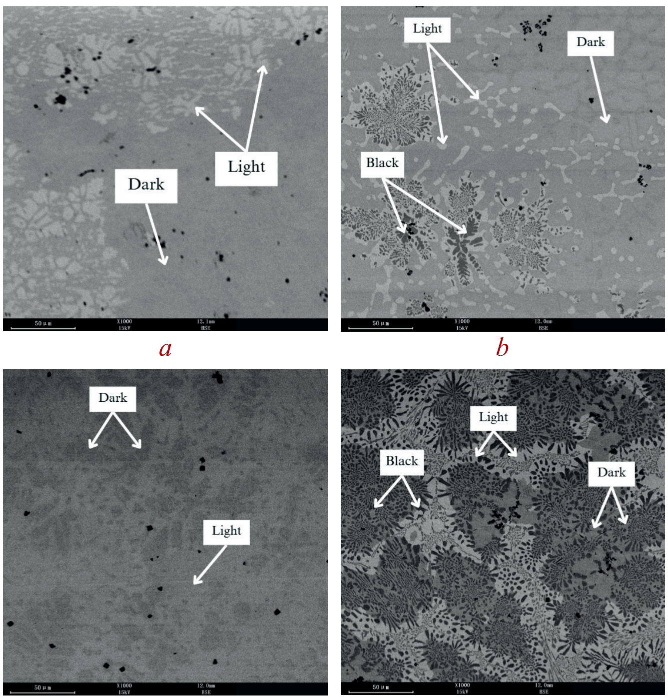

Figure 1. SEM images of metal samples obtained by introducing FeAlSiCa and FeSiCr from batch variants: *1 (a), 2 (b), 3 (c)* **and** *4 (d)*.
Сурет 1. FeAlSiCa және FeSiCr-ді партиялық нұсқалардан енгізу арқылы алынған металл үлгілерінің СЭМ кескіндері: *1 (a), 2 (b), 3 (c)* **және** *4 (d)*.
Рис. 1. Изображения образцов металла, полученные методом СЭМ, с добавлением FeAlSiCa и FeSiCr из пакетных вариантов: *1 (a), 2 (b), 3 (c)* **и** *4 (d)*.

The figure shows that two main phases are formed in variants *1* and *3*, and three in variants *2* and *4*. According to the averaged EDS results for the light and dark areas (Table 4), the light area represents the phase with a lower chromium content, while the dark area has a higher chromium content. Another characteristic of the dark phase is the presence of nitrogen or silicon.

Table 1 also presents the results of EDS when analyzing the total spectrum of the entire observed image.

Table 1
Results of EDS analysis of metal samples*, %
Кесте 1
Металл үлгілерінің ЭДС талдау нәтижелері*, %
Таблица 1
Результаты EDS-анализа образцов металлов*, %

Figure	Plot	Cr	Fe	Si	V	N
Fig. 1, *a* (1st batch variant)	**Sum**	**64.47**	**30.88**	**0.66**	**1.07**	**2.92**
	Light	60.08	38.63	0.89	0.40	-
	Dark	76.66	14.16	-	2.92	6.26
Fig. 1, *b* (2nd batch variant)	**Sum**	**66.31**	**28.52**	**0.14**	**0.91**	**4.12**
	Light	53.61	46.06	0.33	-	-
	Dark	78.09	11.82	-	2.72	7.37
	Black	79.51	9.20	1.87	4.40	5.02
Fig. 1, *c* (3rd batch variant)	**Sum**	**63.53**	**31.87**	**0.92**	**2.05**	**1.63**
	Light	58.58	40.12	0.70	0.60	-
	Dark	85.14	4.87	-	5.01	4.98
Fig. 1, *d* (4th batch variant)	**Sum**	**52.19**	**36.79**	**7.59**	**2.22**	**1.21**
	Light	54.39	37.70	7.28	0.63	-
	Dark	72.46	14.29	12.22	1.03	-
	Black	75.33	9.43	1.78	7.60	5.86

** EDS analysis was carried out on several samples and several areas, and the results were within the error limits of the method used, therefore the results presented in Table 4 can be considered averaged*

Comparing the characteristic microstructure of the studied samples and their composition according to the results of EDS, it can be concluded that the metal samples obtained with options *1* and *3* of introducing reducing agents consist of two phases: a light solid solution of ***Cr-Fe*** and a dark one based on nitrides in the **Cr-V-N** system; in options *2* and *4*, silicides are also formed in the ***Cr-Si*** system (Cr_3Si and Cr_5Si_3), which is explained by the excess of ***Si***, the source of which are reducing agents.

Analyzing the data from the combined spectra, as shown in Table 4, higher chromium contents are observed for charge variants *1* and *2*.

Figure 2 shows a map of the element distribution in a metal sample obtained from charge variant *2*.

Element distribution maps for variants *1* and *3* are not provided, as they exhibit similar distribution patterns, which is also confirmed by the compositions discussed previously (Table 4).

Nitrogen saturation and the formation of chromium and vanadium nitrides at high temperatures are thermodynamically possible; however, their stability decreases with increasing temperature. High temperatures above 1650 °C can be achieved through exothermic reduction reactions [5], which could result in localized overheating followed by rapid cooling, preventing nitrogen decomposition.

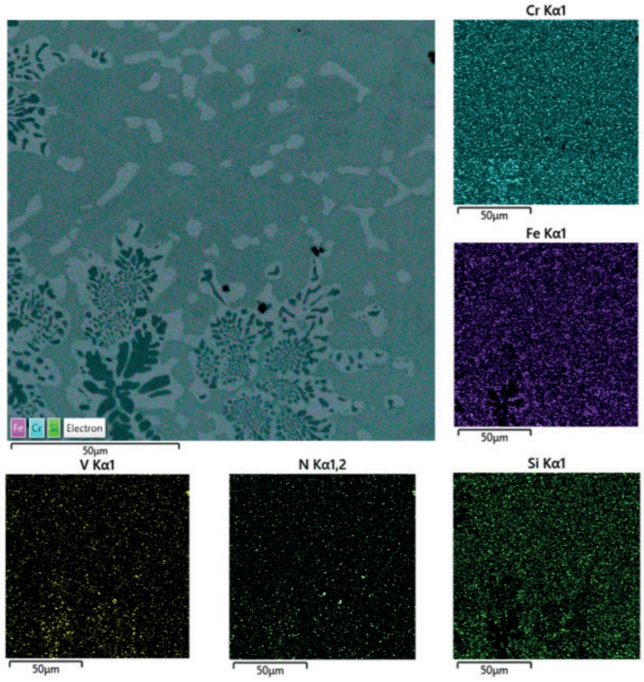

Figure 2. SEM image of a metal sample obtained from the 2nd batch variant in the backscattered electron detection mode, and a distribution map of chromium, iron, silicon, vanadium and nitrogen.
Сурет 2. Кері шашыраңқы электронды анықтау режимінде 2-ші партия нұсқасынан алынған металл үлгісінің SEM кескіні және хром, темір, кремний, ванадий және азоттың таралу картасы.
Рис. 2. Изображение образца металла, полученного из 2-й партии в режиме детектирования обратнорассеянных электронов, полученное с помощью сканирующего электронного микроскопа, и карта распределения хрома, железа, кремния, ванадия и азота.

Figure 3 shows a similar element distribution map for a metal sample obtained from batch variant *4*.

Figure 3 shows that ***Cr*** is distributed over the entire surface of the sample, but is more concentrated in dark areas along with ***Si*** and ***N***. ***V*** is distributed fairly uniformly, primarily rebound with ***N***, and is present to a lesser extent in areas enriched in ***Si***, which is absent from the black phase.

Using analytical chemistry methods, the content of elements difficult to determine by EDS was determined in all metals, and the average content was: ***C*** ≤ 0.10%; ***S*** ≤ 0.02%; ***P*** ≤ 0.03%. Thus, all the metal samples studied were characterized by low contents of these elements. Nitrogen content was determined using titrimetric analysis, which confirmed an average nitrogen content of 2.6; 3.6; 2.6, and 2.1 for metal samples from variants *1*, *2*, *3*, and *4*, respectively.

Ferrochrome samples obtained from batch variants *1*, *2*, and *3* meet the requirements for the ***FeCr60C1N3*** grade (low-carbon nitrogen-containing ferrochrome) according to ISO 5448-81. This makes the obtained metal samples suitable for alloying nitrogen-containing stainless steels. The metal obtained from batch variant 4 is close to the requirement for ***FeCr60C50Si7LP*** (high-carbon ferrochrome) according to ISO 5448-81, but with a low ***C*** content and increased ***N***; it can also be considered as low-carbon nitrogen-containing ferrochrome with an increased ***Si*** content. The metal samples also met the listed requirements for low-carbon ferrochrome grades in terms of ***C***, ***S***, and ***P*** contents.

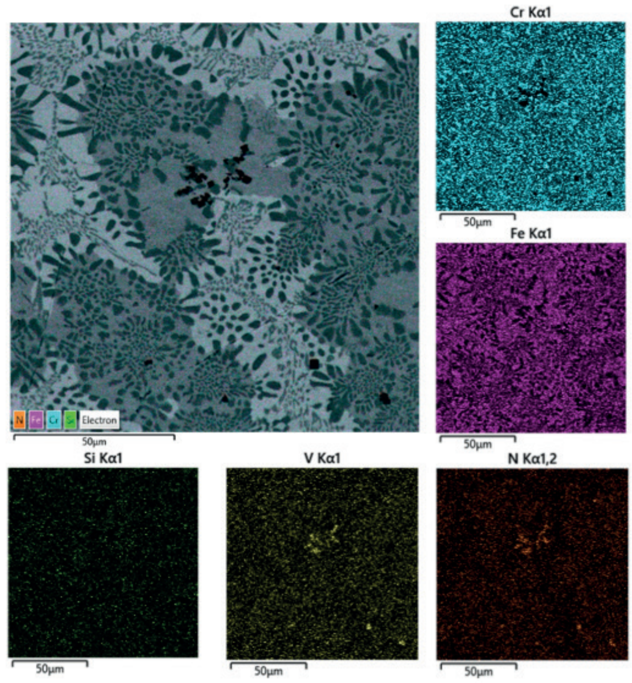

Figure 3. SEM image of a metal sample obtained from the 4th batch variant in EDS mode, distribution map of chromium, iron, silicon, vanadium and nitrogen.
Сурет 3. ЭДС режимінде 4-ші партия нұсқасынан алынған металл үлгісінің SEM кескіні, хром, темір, кремний, ванадий және азоттың таралу картасы.
Рис. 3. Изображение образца металла, полученного из 4-й партии вариантов, полученное с помощью СЭМ в режиме энергодисперсионной спектроскопии (ЭДС), карта распределения хрома, железа, кремния, ванадия и азота.

Discussion

The obtained results can be explained by the thermodynamic and kinetic features of metallothermic reduction in the ***Cr-Fe-Si-Ca-V-N*** system at high temperatures. The formation of ***Cr-Fe*** solid solutions in all charge variants confirms effective reduction of chromium oxides by silicon, aluminum, and calcium contained in ***FeAlSiCa*** and ***FeSiCr***. The presence of ***Cr-V-N*** phases indicates active nitrogen dissolution in the melt, while their stabilization is likely associated with rapid cooling after exothermic reactions, preventing nitrogen degassing.

The formation of Cr_3Si and Cr_5Si_3 silicides in variants with reductant excess is attributed to increased silicon activity. Under moderate reductant content, silicon is primarily consumed in oxide reduction, limiting silicide formation. Thus, the phase composition is strongly governed by the balance between reduction stoichiometry and silicon excess.

The advantages of the proposed approach are related to the use of complex reducing agents that ensure simultaneous participation of ***Si***, ***Al***, and ***Ca***, increasing reduction efficiency. The use of ferrosilicochrome dust promotes partial recycling of metallurgical waste. Moreover, eliminating coke reduces carbon contamination and enables the production of low-carbon ferrochrome suitable for nitrogen alloying. The metallothermic mechanism also provides localized temperature intensification without additional external energy input.

Compared with conventional carbothermic ferrochrome production, the developed approach ensures very low carbon content (≤ 0.10%) and high chromium recovery (up to 86%) without direct carbon input. Stable nitrogen alloying was achieved without additional nitrogen injection, which may simplify industrial application.

However, the study has limitations. Laboratory crucible experiments do not fully reproduce industrial heat and mass transfer conditions. Local overheating may lead to phase inhomogeneity, and controlling silicon content remains challenging. Additionally, the absence of detailed thermodynamic modeling limits precise prediction of phase equilibria.

Further work should focus on optimizing reductant ratios, performing thermodynamic simulations, and scaling the process to pilot conditions. Industrial implementation will require control of reaction intensity and economic evaluation of reductant efficiency.

Overall, carbon-free metallothermic reduction using ***FeAlSiCa*** and ***FeSiCr*** dust represents a promising route for producing low-carbon nitrogen-containing ferrochrome, though further optimization and scaling are necessary.

Conclusions

This study investigated the feasibility of carbon-free smelting of chromium-containing ferroalloy using ferroaluminosilicocalcium (***FeAlSiCa***) and ferrosilicochrome dust (***FeSiCr***) as complex metallothermic reducing agents. It was established that the application of these reductants ensures efficient reduction of chromium oxides with the formation of ***Cr-Fe*** metallic phases and ***Cr-V-N*** nitride phases.

The results demonstrated that the phase composition of the produced alloys depends on the ratio of reductants relative to stoichiometry. Under moderate excess of reductants, predominantly ***Cr-Fe*** solid solutions and nitride phases are formed, whereas a significant excess of silicon leads to the formation of ***Cr-Si*** silicides. Therefore, the balance between reduction capacity and silicon activity is a key factor in controlling alloy structure and properties.

All investigated variants produced alloys with low impurity contents: carbon ≤ 0.10%, sulfur ≤ 0.02%, and phosphorus ≤ 0.03%. Chromium recovery reached up to 86%, which is comparable to industrial practice. According to chemical composition, the obtained alloys meet the requirements of ISO 5448-81 for low-carbon nitrogen-containing ferrochrome, confirming their suitability for alloying corrosion-resistant and nitrogen-containing steels.

The charge composition with a 10% excess of reductants was identified as optimal, providing high chromium recovery, stable phase composition, and compliance with standard specifications.

The obtained results confirm the potential of using ***FeAlSiCa*** and ***FeSiCr*** dust in carbon-free metallothermic ferrochrome production. Further research should focus on thermodynamic modeling of phase equilibria, optimization of charge composition, and scaling the process to pilot and industrial levels.

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REFERENCES

1. *Thongyoug P., Tungtrongpairoj J. Carbothermic Reduction of the Waste Chromium Oxide Rods from Thermal Spray Processes // IOP Conference Series: Materials Science and Engineering. – 2020. – Vol. 965. – Article 012024 (in English)*
2. *Gautam M., Pandey B., Agrawal M. Carbon Footprint of Aluminum Production. In Environmental Carbon Footprints. – Amsterdam: Elsevier, 2018. – P. 197–228 (in English)*
3. *Energy Consumption and Greenhouse Gas Emissions of High-Carbon Ferrochrome Production / W. Wei et al. // JOM. – 2023. – Vol. 75. – P. 1206–1220 (in English)*
4. *Sommerfeld M., Botinha R., Friedrich B. (May 2024). Enabling CO2 Neutral Metallurgy for Ferrochromium Production Using Bio-Based Reducing Agents. Scientific Reports. https://doi.org/10.1038/s41598-024-61700-4 (in English)*
5. *Poluchenie kompleksnyh kal'cijsoderzhashhih ferrosplavov iz otval'nyh metallurgicheskih shlakov i vysokozol'nyh uglej [Production of complex calcium-containing ferroalloys from waste metallurgical slags and high-ash coals], E. N. Mahambetov et al. STAL [STEEL]. – 2019. – No. 10. – P. 18–21 (in Russian)*
6. *Tekhnologiya SVS kompozitsionnykh ferrosplavov chast' I. Metallurgicheskii SVS protsess. Sintez nitridov ferrovanadiya i ferrokhroma [SHS Technology of Composite Ferroalloys, Part I. Metallurgical SHS Process. Synthesis of Ferrovanadium and Ferrochrome Nitrides], M. Kh. Ziatdinov et. al. Izvestiya vysshikh uchebnykh zavedenii [Chernaya Metallurgiya News of Higher Education Institutions. Ferrous Metallurgy]. – 2018. – No. 61 (5). – P. 339–347 (in Russian)*
7. *Mahambetov E. N., Bajsanov A. S., Nabiev A. M. Pererabotka i ispol'zovanie tverdyh tehnogennyh othodov otval'nyh metallurgicheskih shlakov dlja poluchenija kal'cijsoderzhashhih ferrosplavov [Processing and use of solid technogenic waste of metallurgical slags for the production of calcium-containing ferroalloys]. In: Trudy kongressa «Fundamental'nye issledovanija i prikladnye razrabotki processov*

pererabotki i utilizacii tehnogennyh obrazovanij» «TEHNOGEN – 2017» [Proceedings of the congress «Fundamental research and applied development of processes for processing and utilization of man-made formations» «TECHNOGEN – 2017»]. Ekaterinburg, 2017. – P. 144–147 (in Russian)

8. *Fabrication of a complex aluminosilicochrome alloy by a slag-free method / Zh. Ye. Shabanov et. al. // Russian metallurgy (Metally). – 2014. – No. 5. – P. 11–14 (in English)*
9. *Akhmetov A. (2 June, 2025) Carbon-Free Smelting of Ferrochrome Using FeAlSiCa Alloy. Processes. https://doi.org/10.3390/pr13061745 (in English)*
10. *Development of technology of complex aluminum-silicon-chrome alloy with utilization of off grade raw materials / A. Mekhtiev et. al. // Metallurgy. Zagreb. – 2015. – Vol. 54. – No. 1. – P. 157–160 (in English)*
11. *Bartenev A., Issagulov A., Baisanov A. Studying microstructure and phase composition of a newcomplex calcium containing alloy // Metallurgy. – 2016. – Vol. 55. – No. 4. – P. 727–729 (in English)*
12. *Surup G.R., Trubetskaya A., Tangstad M. (November 9, 2020). Charcoal as an Alternative Reductant in Ferroalloy Production: A Review. https://www.mdpi.com/2227-9717/8/11/1432 (in English)*

ПАЙДАЛАНЫЛҒАН ӘДЕБИЕТТЕР ТІЗІМІ

1. *Thongyoug P., Tungtrongpairoj J. Термиялық бүрку процестерінен қалған хром оксиді өзекшелерін карботермиялық тотықсыздандыру // IOP Conference Series: Materials Science and Engineering. – 2020. – Т. 965. – 012024 (ағылшын тілінде)*
2. *Gautam M., Pandey B., Agrawal M. Алюминий өндірісіндегі көміртегі ізі. Қоршаған ортадағы көміртегі іздері. – Амстердам: Elsevier. – 2018. – Б. 197–228 (ағылшын тілінде)*
3. *Жоғары көміртекті феррохром өндірісінің энергия тұтынуы және парниктік газ шығарындылары / W. Wei [және т. б.] // JOM. – 2023. – Т. 75. – Б. 1206–1220 (ағылшын тілінде)*
4. *Sommerfeld M., Botinha R., Friedrich B. (Мамыр, 2024). Биологиялық негіздегі тотықсыздандырғыштарды қолдана отырып, феррохром өндірісі үшін CO2 бейтарап металлургиясын қамтамасыз ету. Scientific Reports. https://doi.org/10.1038/s41598-024-61700-4 (ағылшын тілінде)*
5. *Үйінді металлургиялық қождардан және күлі жоғары көмірден құрамында кальций бар кешенді ферроқорытпаларды алу / Е. Н. Махамбетов [және т. б.] // Болат. –2019. – № 10. – Б. 18–21 (орыс тілінде)*
6. *Композиттік ферроқорытпалардың SHS технологиясы, I бөлім. Металлургиялық SHS процесі. Феррованадий мен феррохром нитридтерінің синтезі / М. Х. Зиатдинов [және т. б.] // Қара Металлургия Жоғары оқу орындарының жаңалықтары. Қара металлургия. – 2018. – № 61 (5). – Б. 339–347 (орыс тілінде)*
7. *Махамбетов Е.Н., Байсанов А.С., Набиев А.М. және т. б. Құрамында кальций бар ферроқорытпаларды алу үшін үйінді металлургиялық қождардың қатты техногендік қалдықтарын өңдеу және пайдалану // «Техногендік түзілімдерді қайта өңдеу және кәдеге жарату процестерінің іргелі зерттеулері және қолданбалы әзірлемелері» «ТЕХНОГЕН – 2017» конгресінің еңбектері. – Екатеринбург, 2017. – Б. 144–147 (орыс тілінде)*
8. *Қожсыз тәсілмен кешенді алюмосиликохром қорытпасын алу / Zh. Ye. Shabanov [және т. б.] // Russian metallurgy (Metally). – 2014. – № 5. – Б. 11–14 (ағылшын тілінде)*
9. *Akhmetov A. (2 маусым, 2025 ж.) FeAlSiCa қорытпасын пайдаланып феррохромды көміртегісіз балқыту. Processes. https://doi.org/10.3390/pr13061745 (ағылшын тілінде)*
10. *Алюминий-кремний-хром күрделі қорытпасы технологиясын кондициялық емес шикізатты пайдалана отырып әзірлеу / A. Mekhtiev [және т. б.] // Metallurgy. Zagreb. – 2015. – Т. 54. – № 1. – Б. 157–160 (ағылшын тілінде)*
11. *Bartenev A., Issagulov A., Baisanov A. Құрамында кальций бар жаңа күрделі қорытпаның микроқұрылымы мен фазалық құрамын зерттеу // Metallurgy. – 2016. – Т. 55. – № 4. – Б. 727–729 (ағылшын тілінде)*
12. *Surup G.R., Trubetskaya A., Tangstad M. (9 қараша 2020 ж.). Ферроқорытпа өндірісіндегі балама тотықсыздандырғыш ретінде көмір қолдану: шолу. https://www.mdpi.com/2227-9717/8/11/1432 (ағылшын тілінде)*

СПИСОК ИСПОЛЬЗОВАННЫХ ИСТОЧНИКОВ

1. *Thongyoug P., Tungtrongpairoj J. Карботермическое восстановление отходов оксида хрома, образующихся в процессе термического напыления // IOP Conference Series: Materials Science and Engineering. – 2020. – Т. 965. – Ст. 012024 (на английском языке)*
2. *Gautam M., Pandey B., Agrawal M. Углеродный след производства алюминия // Environmental Carbon Footprints. – Амстердам: Elsevier, 2018. – С. 197–228 (на английском языке)*

3. *Потребление энергии и выбросы парниковых газов при производстве высокоуглеродистого феррохрома / W. Wei [и др.] // JOM. – 2023. – Т. 75. – С. 1206–1220 (на английском языке)*
4. *Sommerfeld M., Botinha R., Friedrich B. (Май 2024 г.). Обеспечение углеродно-нейтральной металлургии для производства феррохрома с использованием биооснованных восстановителей. Scientific Reports. https://doi.org/10.1038/s41598-024-61700-4 (на английском языке)*
5. *Получение комплексных кальцийсодержащих ферросплавов из отвальных металлургических шлаков и высокозольных углей / Е. Н. Махамбетов [и др.] // Сталь. –2019. – № 10. – С. 18–21 (на русском языке)*
6. *Технология СВС композитных ферросплавов, часть I. Металлургический процесс СВС. Синтез нитридов феррованадия и феррохрома / М. Х. Зиатдинов [и др.] // Известия высших учебных заведений Черной металлургии. Черная металлургия. – 2018. – № 61 (5). – С. 339–347 (на русском языке)*
7. *Махамбетов Е. Н., Байсанов А. С., Набиев А. М. и др. Переработка и использование твердых техногенных отходов отвальных металлургических шлаков для получения кальцийсодержащих ферросплавов // Труды конгресса «Фундаментальные исследования и прикладные разработки процессов переработки и утилизации техногенных образований» «ТЕХНОГЕН – 2017». – Екатеринбург, 2017. – С. 144–147 (на русском языке)*
8. *Получение комплексного алюмосиликохромового сплава бесшлаковым способом / / Zh. Ye. Shabanov [и др.] // Russian metallurgy (Metally). – 2014. – № 5. – С. 11–14 (на английском языке)*
9. *Akhmetov A. (2 июня 2025 г.) Безуглеродная плавка феррохрома с использованием сплава FeAlSiCa. Processes. https://doi.org/10.3390/pr13061745 (на английском языке)*
10. *Разработка технологии сложного сплава алюминий-кремний-хром с использованием некондиционного сырья / A. Mekhtiev [и др.] // Metallurgy. Zagreb. – 2015. – Т. 54. – № 1. – С. 157–160 (на английском языке)*
11. *Bartenev A., Issagulov A., Baisanov A. Исследование микроструктуры и фазового состава нового комплексного кальцийсодержащего сплава // Metallurgy. – 2016. – Т. 55. – № 4. – С. 727–729 (на английском языке)*
12. *Surup G.R., Trubetskaya A., Tangstad M. (9 ноября 2020 г.). Древесный уголь как альтернативный восстановитель в производстве ферросплавов: обзор. https://www.mdpi.com/2227-9717/8/11/1432 (на английском языке)*

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