

Impurity behavior in low-temperature sintering products of ironmaking dust in the presence of ammonium chloride

G. M. Koishina · E. E. Zholdasbay · A. A. Argyn · I. N. Nursainov · N. K. Dosmukhamedov

Received: 29 October 2024 / Revised: 12 January 2025 / Accepted: 10 February 2025

© Springer Science+Business Media, LLC, part of Springer Nature 2025

Abstract

In this study, the elemental composition of dust from the melting of scrap metal in an electric arc furnace was analyzed using an X-ray fluorescence energy dispersive spectrometer (RLP-21) to determine the concentrations of impurities at their lower detection limits. A wide range of impurities was identified in the dust: Cu, Fe, Ti, Cr, Ni, Cd, Mn, Sn, Si, Ca, K, S, Cl. Using the Olympus BX51 microscope, new data on the forms of impurities in dust have been obtained. It was shown that impurities in the dust are present in the form of oxides. Based on the new results, a thermodynamic analysis of the reactions between dust components and ammonium chloride under low-temperature sintering conditions (573–1073 K) was performed. It was found that almost all impurities, except chromium, concentrate in the clinker as solid oxides during the sintering process. A high potential for the removal of titanium and tin as gaseous chlorides in the vapor phase was identified. Laboratory experiments were conducted on sintering dust with NH_4Cl under optimal process conditions (temperature—773 K, NH_4Cl consumption—1.5 times the stoichiometric amount required for lead chlorination, sintering time—60 min). Based on these experiments, the quantitative proportions of impurities in the resulting clinker were determined. It was found that during sintering tin and titanium are volatilized in significant amounts (more than 30% of their total content in the initial dust). The results obtained are fundamental for the development of selective lead extraction technology from dust. They will be used to develop an integrated chlorination process for the treatment of ironmaking dust with selective recovery of valuable metals into marketable products.

Keywords Dust · Impurities · Thermodynamics · Gibbs free energy · Ammonium chloride · Sintering · Clinker

Introduction

A critical analysis of the current state of steel and ferroalloy production reveals a number of common and intensifying technological and environmental problems [1–5]. One major concern is the accumulation of zinc-containing dust from electric arc furnaces (EAFs), whose growing volumes have reached a critical level of environmental impact. The production of 1 ton of steel generates approximately 25–30 kg of dust. According to literature data, approximately 5.6 billion tons of dust have accumulated globally [1]. As a result of the activities of metallurgical plants in Russia, 1 million tons of dust are generated annually. Due to the lack of a rational processing technology, the dust is stockpiled, occupying large areas and causing environmental damage. Up to 800,000 tons of iron, 500,000 tons of zinc, and 150,000 tons of lead are lost annually with the dust. The

Translated from *Metallurg*, No. 4, pp. 90–95, April, 2025. Russian DOI: https://doi.org/10.52351/00260827_2025_4_90



data presented indicate that the accumulated quantities of dust could be used as an additional source of raw materials for ferrous and non-ferrous metallurgical enterprises to extract valuable metals [1]. The high content of lead and other accompanying elements complicates the processing according to the existing plant schemes due to excessive accumulation of lead and zinc in the technological production, which significantly reduces the production efficiency and, consequently, the quality of the obtained products.

There is a considerable amount of research in the scientific literature on the use of zinc-containing dust [6–11]. Each study and its results, despite their originality, address a specific issue—extraction of zinc and lead from the dust using different methods and solutions. However, the organization of dust processing technologies does not consider the possibility of comprehensive extraction of other accompanying elements from the dust. The presence and subsequent behavior of these elements significantly affect the technological parameters of the processes. Moreover, the redistribution of valuable elements in products leads to their losses, which reduces the complexity of raw material utilization and recovery of valuable elements.

Hydrometallurgical methods of dust processing, which are widely discussed in the scientific literature [12–15], do not require detailed consideration. It should be noted that the essence of hydrometallurgical methods is based on the selective dissolution of the valuable component (zinc) in the form of its sulfate, using sulfuric acid as a solvent. A significant disadvantage of hydrometallurgical processes is the significant dissolution of iron, which is present in the dust in much higher quantities than zinc. Iron readily dissolves in sulfuric acid and easily enters the solution. The presence of iron in the solution negatively affects the process of cleaning the solution of Cu, Cd, and Co. To date, the process of iron removal from solutions remains a costly operation and one of the most problematic tasks in hydrometallurgical processes. The presence of iron ions in the solution significantly affects the technological parameters of the zinc electrowinning process: it increases the specific energy consumption, reduces the quality of the obtained metal, and promotes anode corrosion [12, 13].

The presented data indicate the need to search for new technologies for processing zinc-containing dusts, taking into account the peculiarities of their formation, elemental and phase composition, and other parameters. It should be noted that the majority of studies in the scientific literature on the development of processing technologies were conducted for zinc-containing dust from electric arc furnaces (EAFs). However, there is a lack of research focused on the development of technologies for dust generated during the recycling of secondary ferrous steel scrap. In any case, the organization of dust processing technology in the iron and steel industry should aim to extract valuable metals into target products, regardless of its technological origin. This process must also ensure a high degree of environmental sustainability in production.

In this study, the behavior of accompanying elements and their quantitative proportions in the final clinker obtained by low-temperature sintering of zinc-containing dust from ferrous scrap recycling in the presence of ammonium chloride were investigated. The distribution of impurities among the sintered products is of great interest. The behavior of impurities during the process affects the rate of lead oxide reduction and the formation of lead vapors, which ultimately determines the quality of the final product. The obtained results are of fundamental importance for analyzing and organizing the subsequent clinker processing stages, which focus on the selective extraction of zinc. These operations represent the final stage of the overall technological scheme in the developed complex chlorination process for iron and steel dust utilization.

Materials and methods

The starting material was dust derived from processing secondary ferrous scrap (such as rails and pipes) in an electric arc furnace at KazFerroSteel LLP [16]. This dust underwent magnetic separation, yielding a magnetic fraction constituting approximately 29% of the total sample. The non-magnetic fraction was used for subsequent laboratory analysis. Comprehensive investigations into the composition of the magnetic and non-magnetic fractions have been reported elsewhere [16, 17]. However, those studies did not examine the behavior of accompanying elements due to the challenges associated with detecting their low concentrations in the dust.

Research method. The elemental composition of the initial dust was analyzed using an X-ray fluorescence energy dispersive spectrometer (RLP-21) [18]. The study determined the concentrations of a wide range of accompanying elements at their lower detection limits in the studied dust, which allowed the identification of several interesting patterns in their behavior during the sintering process.

Additional information on the forms of impurities in the initial dust was obtained using an Olympus BX51 microscope. These results were used in the thermodynamic analysis of the reactions between accompanying elements in the dust and ammonium chloride that occur during sintering at low temperature intervals of 300–600 °C.

HSC Chemistry 8.1.5 software from Outotec Technologies (licensee: KazNTU) was used for the thermodynamic evaluation of the impurity behavior. The thermodynamic calculations involved determining the change in Gibbs free energy (ΔG^0_T) of impurity chlorination reactions as a function of temperature. The standard states of the accompanying impurities were assumed to be: crystalline solid oxides ($\text{MeO}_{(s)}$), chlorides of impurities in crystalline ($\text{Me}_x\text{Cl}_{y(s)}$) and gaseous states ($\text{Me}_x\text{Cl}_{y(g)}$). For the standard states of chlorides of nonferrous metals, $\text{MeCl}_{2(s)}$ and $\text{MeCl}_{2(g)}$ have been adopted, where Me stands for Cu, Pb, Zn. The default state of ammonium chloride was taken as solid ammonium chloride ($\text{NH}_4\text{Cl}_{(s)}$).

The quantitative ratios of impurities in the clinker obtained after sintering were determined on the basis of the results of laboratory experiments carried out under the previously established optimum sintering parameters: temperature—500 °C, NH_4Cl consumption—1.5 times the stoichiometrically required quantity (SCR) for lead chlorination, sintering time—60 min [17].

The experiments were carried out three times under identical conditions. The results obtained showed good convergence and were used as a basis for formulating conclusions on the evaluation of the impurity behavior during low-temperature sintering of dust with ammonium chloride and for determining their quantitative ratios in the clinker.

Results and discussion

Investigation of the elemental composition and forms of accompanying elements in dust. The detailed chemical composition and the standard deviations of the elements in the EAF dust, as determined using the RLP-21 spectrometer, are presented in Fig. 1.

The results obtained for the main elements (Zn, Pb, Fe) are in good agreement with the data on the composition of the non-magnetic fraction of the dust reported in literature [16, 17]. A wide range of impurities was identified in the initial dust (Fig. 1), which is characteristic of EAF dust. Comparative analysis of the results of numerous studies of the elemental composition of EAF dust reveals a common pattern in the presence of these impurities. According to the literature, EAF dust consists primarily of metal oxides, with only a small fraction (~10%) present as ferrites, sulfates, sulfides, and chlorides [5]. The concentration of the elements in the dust varies widely [2, 4, 5], and the composition of the dust depends on the technology used to produce it and the composition of the raw materials.

In the context under consideration, the dust we studied does not deviate from the norms established in the technical literature. The results of the analysis of the composition of the dust, obtained with the microscope Olympus BX51, which provides high quality fluorescence observations due to its built-in reflected light illuminator that minimizes distortions, allows identification of different forms of accompanying elements in the dust.

To study the phase composition of the initial dust, two opaque thin sections were prepared. These sections revealed host rocks in the form of carbonaceous aleurolites with a general grain size ranging from 10 to 40 μm and grains covered with a brown film (Fig. 2).

Fig. 1 Elemental composition of the non-magnetic fraction of zinc-containing dust

content of elements in the sample (file ..\Product.spr)

Sample: Powder			Filler: Mu= 0.45			Sigma: 2		
Element	Cu	0.2819±0.0028%	Element	Al	<0.01%	Element	P	0.0137±0.0075%
Element	Si	5.704±0.025%	Element	Cl	0.316±0.023%	Element	Fe	17.078±0.072%
Element	S	0.590±0.055%	Element	Pb	4.607±0.015%	Element	K	0.562±0.013%
Element	Ca	0.674±0.021%	Element	V	<0.004%	Element	Mn	0.6234±0.0071%
Element	Zn	42.556±0.096%	Element	Ni	0.0380±0.0015%	Element	Ge	0.0144±0.0040%
Element	As	<0.0001%	Element	Br	0.1317±0.0017%	Element	Sr	0.00549±0.00046%
Element	Ti	0.1007±0.0085%	Element	Zr	0.00235±0.00060%	Element	Mo	0.00365±0.00061%
Element	Cr	0.2809±0.0031%	Element	Ag	117,1±3.3 g/s	Element	Sn	0.1108±0.0047%
Element	Co	0.0131±0.0081%	Element	Ba	<0.01%	Element	W	<0.001%
Element	Ga	0.0117±0.0036%						
Element	Se	0.0033±0.0012%						
Element	Rb	0.01333±0.00084%						
Element	Y	<0.0001%						
Element	Nb	<0.0001%						
Element	Pd	6.5±3.1 g/s						
Element	Cd	206.4±8.3 g/s						
Element	Sb	0.0184±0.0059%						
Element	Ta	<0.001%						

Total content: 73.80% Number of elements: 39 D0.00
 Date: Time:
 Information: Exposition: 150s (P0.00)



Fig. 2 Forms of metal occurrence in dust

Sulfur is present in the form of a small number of sulfides (sphalerite, pyrite, galena). The occurrence of sulfides is very sparse. Most of the sulfides are present in the free state. Iron is present in the form of oxides (limonite, hematite).

Pyrite occurs as rare grains of irregular shape with sizes ranging from 2 to 10 μm . Galena is represented by grains of various shapes with sizes ranging from 2 to 20 μm . Sphalerite occurs as medium and small inclusions with sizes ranging from 2 to 20 μm , often irregular.

Iron oxides (limonite and goethite) are present as rare, irregularly shaped grains ranging in size from 2 to 10 μm .

Native gold, characterized by its isometric form, bright yellow color and clean surface, was identified with a visible grain size of 4 μm (Fig. 2).

Accessory elements were detected in the studied samples in the form of their respective oxides. From the comprehensive elemental composition shown in Fig. 1, accessory elements with concentrations higher than 0.1% were selected for further analysis. These elements, which we consider highly significant, are likely to contribute significantly to the quality of the products obtained during sintering, such as lead fumes and clinker.

The additional results on the forms of Pb and Fe, combined with previously established data on the forms of Zn in dust, indicate that Zn in dust is not only present in the form of ferrites, but also as an oxide [17].

Table 1 Calculated values of Gibbs free energy (ΔG°_T) for the chlorination reactions of accompanying element oxides with ammonium chloride

No.	Reaction	ΔG°_T , kJ/mol					
		573	673	773	873	973	1073
1	$\text{TiO}_2 + 4\text{NH}_4\text{Cl} = \text{TiCl}_4(\text{g}) + 4\text{NH}_3 + 2\text{H}_2\text{O}$	-614.34	-723.1	-833.2	-944.5	-1057.0	-1170.7
2	$\text{CuO} + 2\text{NH}_4\text{Cl} = \text{CuCl}_2(\text{s}) + \text{H}_2\text{O} + 2\text{NH}_3$	-29.71	-78.92	-129.3	-180.7	-233.1	-286.4
3	$\text{Cu}_2\text{O} + 2\text{NH}_4\text{Cl} = 2\text{CuCl}(\text{g}) + \text{H}_2\text{O} + 2\text{NH}_3$	204.94	127.1	48.83	-29.74	-108.6	-187.7
4	$\text{CaO} + \text{NH}_4\text{Cl} = \text{CaCl}_2(\text{s}) + 2\text{NH}_3 + \text{H}_2\text{O}$	-501.73	-563.4	-626.8	-691.7	-757.9	-826.1
5	$\text{FeO} + 2\text{NH}_4\text{Cl} = \text{FeCl}_2(\text{s}) + 2\text{NH}_3 + \text{H}_2\text{O}$	-38.95	-86.42	-134.7	-183.8	-234.8	-289.9
6	$\text{PbO} + 2\text{NH}_4\text{Cl} = \text{PbCl}_2(\text{g}) + 2\text{NH}_3 + \text{H}_2\text{O}$	-26.23	-92.23	-158.8	-225.8	-293.4	-361.3
7	$\text{K}_2\text{O} + 2\text{NH}_4\text{Cl} = 2\text{KCl}(\text{s}) + 2\text{NH}_3 + \text{H}_2\text{O}$	-478.9	-527.2	-576.3	-626.1	-676.7	-729.5
8	$\text{MnO} + 2\text{NH}_4\text{Cl} = \text{MnCl}_2(\text{s}) + 2\text{NH}_3 + \text{H}_2\text{O}$	-59.63	-107.5	-156.3	-205.9	-258.3	-313.6
9	$\text{NiO} + 2\text{NH}_4\text{Cl} = \text{NiCl}_2(\text{s}) + 2\text{NH}_3 + \text{H}_2\text{O}$	-25.54	-74.82	-122.9	-171.9	-221.6	-272.0
10	$\text{SnO}_2 + 4\text{NH}_4\text{Cl} = \text{SnCl}_4(\text{g}) + 4\text{NH}_3 + 2\text{H}_2\text{O}$	56.17	-57.41	-172.1	-287.9	-404.7	-522.5
11	$\text{Cr}_2\text{O}_3 + 6\text{NH}_4\text{Cl} = \text{CrCl}_3(\text{s}) + 6\text{NH}_3 + \text{H}_2\text{O}$	772.31	650.03	526.69	402.3	276.89	150.47
12	$\text{CdO} + 2\text{NH}_4\text{Cl} = \text{CdCl}_2(\text{s}) + 2\text{NH}_3 + \text{H}_2\text{O}$	-95.7	-144.47	-194.53	-247.0	-302.99	-359.94

These results were used in the subsequent thermodynamic analysis of the interactions between impurities and ammonium chloride.

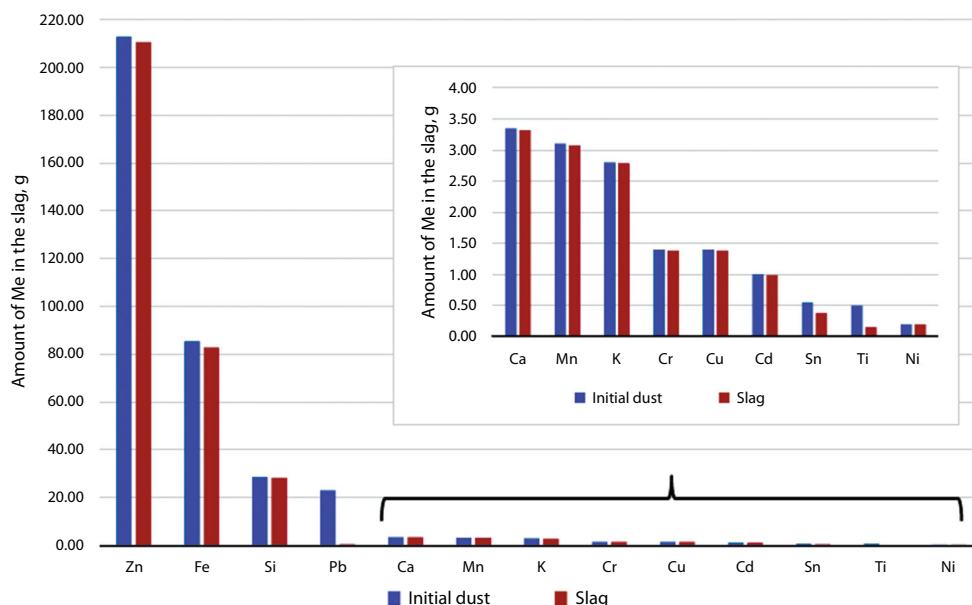
Thermodynamic interactions between trace element oxides and ammonium chloride under low-temperature sintering conditions. The results of thermodynamic calculations are summarized in Table 1, which demonstrate the feasibility of practically all reactions involving the interaction of metal oxides with ammonium chloride in the studied temperature range of 573–1073 K. The exception is reaction (3), for which the thermodynamic feasibility begins at a higher temperature (above 873 K). The formation of chlorides of accompanying elements is characteristic of all reactions. The high probability of the formation of chlorides of Ti, Pb, and Sn as sublimates by reactions (1), (6), and (10) is noteworthy because these reactions are accompanied by large negative values of Gibbs free energy. This indicates that under optimal technological parameters for the sintering process ($T = 773$ K, $t = 60$ min, NH_4Cl consumption = 1.5 times the stoichiometric amount), selective extraction of lead can be expected, along with the presence of titanium and tin in the sublimates. In particular, at the optimal process temperature of $T = 773$ K, the values of ΔG°_T for the formation reactions of gaseous lead and tin chlorides are close to each other: $\Delta G^\circ_{773\text{K}} = -158.8$ kJ/mol and $\Delta G^\circ_{773\text{K}} = -172.1$ kJ/mol, respectively. In contrast, the established value of $\Delta G^\circ_{773\text{K}} = -833.2$ kJ/mol for the formation reaction of gaseous titanium chloride indicates a preferential sublimation of titanium chloride according to reaction (1). However, considering the low and approximately equal initial concentrations of titanium and tin in the dust (0.1% and 0.11%, respectively), it can be concluded that their presence in the lead sublimates obtained during sintering does not significantly affect the quality of the final product.

Other accompanying impurities present in the initial dust interact with ammonium chloride according to reactions (2), (4), (5), (7)–(9) and (12) to form solid chlorides and concentrate in the clinker. The probability of formation of solid chlorides from impurities, as indicated by the large negative values of ΔG°_T for their formation reactions, is very high over the entire temperature range studied. The thermodynamic probability of chromium chloride formation is virtually non-existent, as indicated by the large positive values of ΔG°_T for reaction (11).

The results obtained fully confirm the conclusions drawn in [17] regarding the selective extraction of lead from dust in the form of pure lead sublimates, which can then be processed using known technologies to produce marketable lead.

Table 2 Elemental composition of the initial dust and clinker

Products	Quantity, g	Element content, wt %															
		Zn	Pb	Cu	Fe	Ti	Cr	Ni	Cd	Mn	Sn	Si	Ca	K	S	Cl	Imp.
Dust	500	42.6	4.6	0.28	17.1	0.1	0.28	0.04	0.2	0.62	0.11	5.7	0.67	0.6	0.6	0.31	26.3
Clinker	468.27	46.2	0.08	0.3	18.6	0.03	0.3	0.04	0.22	0.67	0.08	6.2	0.73	0.6	–	0.62	25.4

Fig. 3 Quantitative proportions of impurities in clinker

In order to verify the established patterns, laboratory experiments were carried out on low temperature sintering of the non-magnetic fraction of the dust together with ammonium chloride under optimal technological parameters.

The primary objective of this research was to determine the quantitative proportions of accompanying elements in the condensed solid product (clinker) obtained during low-temperature sintering of dust together with ammonium chloride.

Determination of the quantitative proportions of accompanying elements in clinker. As mentioned above, the experiments were carried out under optimal technological parameters, using the setup and methodology described in reference [17].

The initial sample weight was 500 g. After the required holding time (60 min) of the initial charge consisting of the non-magnetic fraction of dust and ammonium chloride at a temperature of 500 °C, the crucible containing the sample was removed from the furnace. The resulting clinker was then separated and analyzed for major and trace metal contents. The results of the three parallel experiments showed good agreement in clinker yield and in the content of the elements. The final results were based on the average element content obtained from the three experiments. The average clinker composition is shown in Table 2.

Quantitative proportions of heavy non-ferrous metals and impurities in the clinker were calculated on the basis of the obtained results (Fig. 3).

It was found that the amount of zinc in the obtained clinker was 210.62 g compared to 212.5 g in the initial sample. The slight decrease in zinc content indicates minimal removal of zinc during sintering as its chloride. The amount of iron in the clinker remained virtually the same as in the initial sample—85.35 g.

As shown in Fig. 3, lead is virtually absent from the clinker. This indicates that essentially all of the lead present in the initial dust (23 g) is removed as its chloride during sintering.

The nearly equal amounts of Ca, Mn, K, Cu, Cd, and Ni in the initial dust and in the clinker indicate that these elements remain in the clinker primarily as solid chlorides. Chromium is present in the clinker in the form of its oxide. A decrease in the amount of tin was observed, from 0.55 g in the initial dust to 0.38 g in the clinker. A similar trend was observed for titanium, which decreased from 0.5 g to 0.16 g. The lower titanium content in the clinker suggests that the chlorination of titanium during sintering is more intense than that of tin. Sulfur is oxidized in the presence of oxygen and passes into the gas phase. The results obtained fully confirm the conclusions drawn from the thermodynamic analysis of the interactions between impurities and ammonium chloride.

Conclusion

Results obtained in this work show that the initial dust contains a wide range of impurities—Cu, Fe, Ti, Cr, Ni, Cd, Mn, Sn, Si, Ca, K, S, Cl. The results showed that the impurities in the starting material are mainly present in the oxide form.

Thermodynamic analysis of the interactions between impurity oxides present in the dust and ammonium chloride revealed that under low-temperature sintering conditions only titanium and tin transform into sublimates. The obtained results are fully confirmed by obtained experimental data. The quantitative proportions of impurities in the clinker obtained after sintering were determined. It was shown that the main impurities concentrate in the clinker in the form of their solid chlorides during the sintering process.

The tin content decreased from 0.55 g in the initial dust to 0.38 g in the clinker. Similarly, the titanium content reduced from 0.5 g to 0.16 g. The lower titanium content in the clinker suggests that titanium undergoes more intense chlorination during sintering than tin. These low levels of titanium and tin in the clinker, relative to the lead content forming the main matrix of lead sublimates, are unlikely to significantly affect the quality of the lead sublimates. However, high concentrations of titanium and tin in the sublimates suggest that increasing their content in the initial dust could impact lead behavior during sintering. Therefore, additional measures may be necessary to mitigate their presence in the final lead sublimates.

Funding The research was conducted within the framework of grant funding from the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan for 2023–2025, under the priority direction *Rational use of water resources, flora and fauna, and ecology* of the project AP19679572 *Development of a new technology for the utilization of zinc dust from steelmaking with the production of marketable products*.

References

1. Leont'ev LI (2011) Technogenic waste of ferrous and non-ferrous metallurgy and environmental problems. *Ekol Promyshlen* 4:32–35
2. Mchado JG, Brehm FA, Carlos AM, Carlos AS. (2006) Characterization study of electric arc furnace dust phases. *Mater Res* (1):30–36. <https://doi.org/10.1590/S1516-14392006000100009>
3. Chakrabarti AK (2012) Steel Making. PHI Pvt Ltd, New Delhi
4. Simonyan L.M., Khilko A.A., Lysenko A.A. et al (2010) Electric steel-making dust as a dispersed system *Izvestiya vuzov Ferrous metallurgy* 11:68–75
5. Stovpchenko AP et al (2009) Theoretical and experimental studies of the composition and reducibility of electric arc furnace dust. *Elektrometallurgiya* 8:29–36
6. Pereskoka VV (2010) Reductive-thermal treatment of electric arc furnace electrostatic precipitator dust. *Vestn Priazovsk Gos Tekh Univ Ser: Tekh Nauki* 21:13–16
7. Demin AV (2015) Search for methods of electric arc furnace dust utilization at Belarus Metallurgical Plant. *Litye Metall* 3:76–80
8. Kikuchi S et al (2010) ITmk3 Process. *Kobelco Technol Rev* 29:77–84
9. Money KL (2013) Processing steel wastes pyrometallurgically at Inmetco. *JOM* (1):28–35. <https://doi.org/10.1002/9781118788073.ch34>

10. Borlee J et al (1999) Economopoulos COMET: a coal-based process for the production of high quality DRI from iron ore fines. *Rev Met* (3):331–340. <https://doi.org/10.1051/metal/199996030331>
11. Clelland JM (2003) Recycling ferrous and nonferrous waste streams with FASTMET. *JOM* (8):30–34. <https://doi.org/10.1007/s11837-003-0101-3>
12. Arkhipova LV, Fedorov AN (2015) Zinc leaching from steelmaking dust using NaOH. In: 70-e Dni Nauki Studentov NITU “MISiS”. ID MISiS, Moscow, pp 93–95
13. Kukurugya F (2015) Behavior of zinc, iron and calcium from electric arc furnace (EAF) dust in hydrometallurgical processing in sulfuric acid solutions: thermodynamic and kinetic aspects. *Hydrometallurgy* (15):20–32. <https://doi.org/10.1016/j.hydromet.2015.03.008>
14. Sarka L (2009) Selective leaching of zinc from zinc ferrite with hydrochloric acid. *Hydrometallurgy* 95(3-4):179–182
15. Veres J (2011) Zinc recovery from iron and steel making wastes by conventional and microwave assisted leaching. *Acta Montan Slov* 16(3):185–191
16. Koishina GM, Zholdasbay EE, Argyn AA, Kurmanseitov MB, Dosmukhamedov NK (2024) Iron extraction from electric arc furnace steel scrap melting dust by magnetic separation. *Metallurg* 7:109–113
17. Dosmukhamedov NK, Koishina GM, Zholdasbay EE, Kurmanseitov MB (2024) Lead extraction in low-temperature dust roasting during metal scrap melting in electric arc furnace together with ammonium chloride. *Cis Iron Steel Rev* 28(2):104–109
18. Lezin AN, Efimenko SA (2009) X-ray radiometric laboratory device RLP–21. *Prib Tekh Eksp* 1:180–181

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

Authors and Affiliations

G. M. Koishina¹ · E. E. Zholdasbay² · A. A. Argyn² · I. N. Nursainov¹ · N. K. Dosmukhamedov¹

✉ G. M. Koishina
gulzada.koishina@mail.ru

E. E. Zholdasbay
zhte@mail.ru

A. A. Argyn
aidarargyn@gmail.com

I. N. Nursainov
ilyasnursainov@gmail.com

N. K. Dosmukhamedov
nurdos@bk.ru

¹ Satbayev University, Almaty, Kazakhstan

² Zhezkazgan university named after O. Baikonurav, Zhezkazgan, Kazakhstan