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HYDROMETALLURGICAL PROCESSING OF EAF DUST: ZINC EXTRACTION AND RECYCLING IRON RESIDUE IN STEELMAKING




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Abstract. *Electric arc steel smelting furnace dust (EAP dust) is one of the most problematic waste in modern metallurgy from an ecological and technological point of view due to its high dispersity, high content of zinc, lead, and other associated elements. In recent years, as a result of the increase in the share of zinc-containing secondary raw materials in the metal charge, the amount of this dust has also increased. In this study, a hydrometallurgical method of complex processing of PE PE dust based on sulfuric acid leaching was considered. A spent sulfuric acid electrolyte containing H_2SO_4 (120-160 g/l) and Zn (30-50 g/l) was used as the solvent reagent. The leaching process was carried out at a temperature of 60-65 °C, in a solid-liquid ratio of 1:6, for 120-240 minutes. The research results showed that zinc-containing phases accelerate the dissolution kinetics, reduce energy consumption, and provide the possibility of effective extraction of zinc from the solution and subsequent obtaining the cathode metal by electrolysis. In addition, it has been substantiated that the iron-containing residue formed after leaching can be returned to the steelmaking process as a charge additive. The proposed technology is a resource-saving, energy-efficient, and environmentally friendly alternative to traditional pyrometallurgical methods of processing EAP dust. This approach serves the implementation of the principles of a circular economy through the processing of metallurgical waste, the restoration of zinc, and the return of iron components to production.*

Keywords: *electric arc furnace dust, zinc, hydrometallurgy, sulfuric acid leaching, electrolysis, secondary resources, comprehensive processing.*

ГИДРОМЕТАЛЛУРГИЧЕСКАЯ ПЕРЕРАБОТКА ПЫЛИ ЭДП: ИЗВЛЕЧЕНИЕ ЦИНКА И РЕЦИКЛИНГ ЖЕЛЕЗОСОДЕРЖАЩЕГО ОСТАТКА В СТАЛЕПЛАВИЛЬНОМ ПРОИЗВОДСТВЕ

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Аннотация. *Пыль электродуговой сталеплавильной печи (ДСП) является одним из наиболее экологически и технологически проблемных отходов в современной металлургии из-за высокой дисперсности, высокого содержания цинка, свинца и других сопутствующих элементов. В последние годы в результате увеличения доли цинксодержащего вторичного сырья в металлической шихте увеличивается и количество этой пыли. В данной исследовательской работе рассмотрен гидрометаллургический метод комплексной переработки пыли ЭПЭ, основанный на сернокислотном выщелачивании. В качестве растворяющего реагента использовали отработанный сернокислый электролит, содержащий H_2SO_4 (120-160 г/л) и Zn (30-50 г/л). Процесс выщелачивания проводили при температуре 60-65 °C, в соотношении твердое-жидкое 1:6, в течение 120-240 минут. Результаты исследования показали, что цинксодержащие фазы интенсифицируют кинетику растворения, снижают энергозатраты и обеспечивают возможность эффективного извлечения цинка из раствора с последующим получением катодного металла электролизом. Кроме того, обоснована возможность возврата железосодержащего остатка, образующегося после выщелачивания, в качестве добавки к шихте в процессе выплавки стали. Предлагаемая технология является ресурсосберегающим, энергоэффективным и экологически чистым альтернативным решением по сравнению с традиционными пирометаллургическими методами переработки пыли ЭПЭ. Данный подход служит реализации принципов циркулярной экономики путем переработки металлургических отходов, восстановления цинка и возврата железных компонентов в производство.*

Ключевые слова: *пыль электродуговой печи, цинк, гидрометаллургия, сернокислотное выщелачивание, электролиз, вторичные ресурсы, комплексная переработка.*

PO‘LAT ERITISH PECHI CHANGLARINI GIDROMETALLURGIK QAYTA ISHLASH: RUXNI AJRATIB OLISH VA TEMIR TARKIBLI QOLDIQ MAXSULOTLARDAN QAYTA FOYDALANISH

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Annotatsiya. *Elektr yoyli po‘lat eritish pechi changi (EYPE changi) yuqori dispersligi, tarkibida rux, qo‘rg‘oshin va boshqa yo‘ldosh elementlarning ko‘pligi sababli zamonaviy metallurgiyada ekologik va texnologik jihatdan eng muammoli chiqindilardan biri hisoblanadi. So‘nggi yillarda metall shixtasida rux saqlovchi ikkilamchi xomashyolar ulushining ortib borishi natijasida ushbu chang miqdori ham ko‘paymoqda. Mazkur tadqiqot ishida EYPE changini kompleks qayta ishlashning sulfat kislotali tanlab eritishga asoslangan gidrometallurgik usuli ko‘rib chiqildi. Erituvchi reagent sifatida tarkibida H_2SO_4 (120–160 g/l) va Zn (30–50 g/l) bo‘lgan ishlatilgan sulfat kislotali elektrolit qo‘llanildi. Tanlab eritish jarayoni 60–65 °C haroratda, qattiq-suyuqlik nisbatida 1:6, 120–240 daqiqa davomida olib borildi. Tadqiqot natijalari rux tarkibli fazalarning eritish kinetikasini jadallashtirishi, energiya sarfini kamaytirishi hamda ruxni eritmadan samarali ajratib olish va keyinchalik elektroliz orqali katod metallini olish imkoniyatini ta’minlashini ko‘rsatdi. Bundan tashqari, tanlab eritishdan keyin hosil bo‘ladigan temir tarkibli qoldiqni po‘lat eritish jarayoniga shixta qo‘shimchasi sifatida qaytarish mumkinligi asoslandi. Taklif etilayotgan texnologiya EYPE changini qayta ishlashning an’anaviy pirometallurgik usullariga nisbatan resurs tejamkor, energiya jihatdan samarali va ekologik toza muqobil yechim hisoblanadi. Ushbu yondashuv metallurgiya chiqindilarini qayta ishlash, ruxni qayta tiklash va temir komponentlarini ishlab chiqarishga qaytarish orqali aylanma iqtisodiyot tamoyillarini amalga oshirishga xizmat qiladi.*

Kalit so‘zlar: *elektr yoyli pech changi, rux, gidrometallurgiya, sulfat kislotali tanlab eritish, elektroliz, ikkilamchi resurslar, kompleksqayta ishlash*

Introduction

Modern steel metallurgy is characterized by a steady increase in production volumes, which is accompanied by a growing amount of industrial waste. One of the most complex and environmentally hazardous types of such waste is dust from electric arc furnaces (EAF), which is generated during the smelting of scrap metal and iron-containing semi-finished products. According to various estimates, for every ton of steel melted in arc furnaces, 15 to 25 kg of dust is formed, containing zinc, lead, cadmium, chlorine, and other elements classified as hazardous substances.

The problem of processing EAF dust has become particularly relevant in recent decades due to the increase in the proportion of galvanized scrap in the metallic charge. The zinc coating, evaporating in the high-temperature zone of the arc furnace, concentrates in the dust-gas phase and is captured by gas cleaning systems. As a result, the ZnO content in the dust can reach 20-40%, and in some cases even exceed 50%, making this waste a valuable secondary source of zinc.

On the other hand, the direct return of EAF dust to the steelmaking process without preliminary processing is impossible due to the accumulation of zinc, which causes intensive dust formation, increases the load on gas cleaning systems, and deteriorates the operational performance of the furnace. Therefore, processing EAF dust to extract zinc and return the iron-containing component is an important scientific and technical task, having both economic and environmental significance.

Pyrometallurgical methods for processing zinc-containing dust are the most widespread in industrial practice. A classic example is the Waelz process, in which dust mixed with a carbon-containing reducing agent is subjected to high-temperature treatment in a rotary kiln. Zinc and lead are reduced and volatilized, and then captured as oxides in the gas purification system [1-3].

Despite its relative simplicity and industrial development, the Waelz process is characterized by a number of drawbacks, including high energy consumption, the formation of secondary waste, and the production of so-called "dirty" zinc oxide, which requires additional processing.

In recent years, there has been a proliferation of proposals for more intensive pyrometallurgical technologies, including plasma processes (e.g. Plasmadust, Tetronics) and vacuum processing methods (e.g. VHR process, Japan) [4-6]. These technologies have been demonstrated to provide a high degree of zinc recovery; however, they require significant capital investments and complex equipment, which limits their widespread application.

The hydrometallurgical methods for processing EAF dust are based on the conversion of zinc and associated metals into a solution with subsequent selective extraction. The principal reagents employed in the leaching process are solutions of sulfuric acid, ammonium chloride, acetic acid, and complexing systems [7-10].

The utilisation of NH_4Cl solutions in the leaching process has been demonstrated to yield zinc extraction efficiencies ranging from 60 to 80 per cent. Nevertheless, a substantial proportion of the zinc remains in the form of poorly soluble zinc ferrites, thereby impeding the efficacy of the process [11]. Sulfuric acid leaching, particularly under autoclave conditions, has been demonstrated to yield a higher degree of zinc extraction (up to 95-98%), yet necessitates elevated temperatures and pressures, as well as corrosion-resistant equipment [12-14].

A thorough analysis of extant literature data indicates that the primary issue encountered during hydrometallurgical processing of EAF dust pertains to the dissolution of $ZnFe_2O_4$ ferrite phases, which exhibit stability under conventional leaching conditions. A promising approach to solving this problem is the intensification of the process by increasing the temperature, using preheated material, and optimising the electrolyte composition [13-17].

Materials and Methods

The object of research was the dust from electric arc furnaces formed during the smelting of scrap metal and hot briquetted iron. The dust is characterized by high dispersity, developed specific surface area, and complex phase composition (Table 1).

The majority of zinc is present in the form of oxide and ferrites, while iron is predominantly in oxide phases, creating conditions for selective extraction of zinc using hydrometallurgical methods.

The proposed method for processing electric arc furnace (EAF) dust consists of the following main stages: feeding hot dust into a leaching reactor; sulfuric acid leaching of zinc; separation of the pulp into solid and liquid phases; multi-stage purification of the resulting electrolyte; electrolytic production of cathode zinc; and recycling of the

Table 1

Chemical composition of dust, wt. %:

Analyzed result (FP method, Scatter)

No.	Component	Result (mass%)	Unit	Stat. Err.	LLD	LLQ
1	SO3	1.73	mass%	0.0056	0.0117	0.0351
2	K2O	1.95	mass%	0.0158	0.0131	0.0393
3	CaO	33.8	mass%	0.0527	0.0102	0.0306
4	Cr2O3	0.148	mass%	0.0023	0.0032	0.0096
5	MnO	1.29	mass%	0.0064	0.0060	0.0180
6	Fe2O3	32.1	mass%	0.0117	0.0114	0.0342
7	Co2O3	(0.0586)	mass%	0.0068	0.0206	0.0617
8	CuO	0.129	mass%	0.0020	0.0029	0.0088
9	ZnO	2	mass%	0.0207	0.0013	0.0040
10	Ga2O3	0.0402	mass%	0.0016	0.0040	0.0121
11	As2O3	0.0411	mass%	0.0032	0.0081	0.0244
12	Rb2O	0.0142	mass%	0.0004	0.0007	0.0020
13	SrO	0.0086	mass%	0.0003	0.0004	0.0013
14	ZrO2	0.269	mass%	0.0035	0.0018	0.0053
15	Ag2O	0.0083	mass%	0.0005	0.0006	0.0017
16	CdO	0.0655	mass%	0.0013	0.0027	0.0082
17	SnO2	0.0556	mass%	0.0012	0.0006	0.0017
18	BaO	0.0431	mass%	0.0016	0.0028	0.0085
19	Ir2O3	0.0451	mass%	0.0026	0.0072	0.0215
20	PbO	1.22	mass%	0.0045	0.0022	0.0065
21	Yb2O3	0.0248	mass%	0.0023	0.0057	0.0170

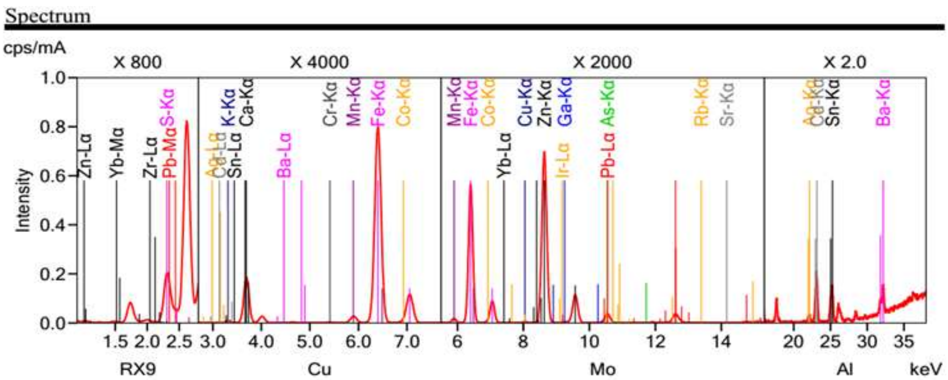

Fig.1. Spectral analysis of primary samples

iron-containing residue back into the steelmaking process.

A distinctive feature of the technology is the use of hot dust at a temperature of 200-300°C, which is fed into a tank with mechanical stirring without preliminary cooling.

The leaching agent used was spent sulfuric acid electrolyte containing:

H_2SO_4 - 120-160 g/l;

Zn - 30-50 g/l.

The leaching process was carried out under the following conditions: a temperature of 60–65 °C, a solid-to-liquid ratio of 1:6, and a leaching duration of 120–240 min.

Based on the data presented in Table 2 and Figure 3, it can be seen that as a result of the initial leaching, the degree of iron and zinc leaching increased by 47-50%. By controlling the sulfuric acid concentration, it is possible to ensure high efficiency of the process.

These conditions ensure sufficient aggressiveness of the medium for the dissolution of ZnO and partial decomposition of zinc ferrites without significant transfer of iron into the solution.

After leaching, the electrolyte was purified from impurities in three successive stages: hydrolytic purification to precipitate iron and aluminum; cementation for the removal of copper, cadmium, and lead; and final chemical purification to adjust the electrolyte composition to meet the requirements for subsequent electrolysis.

The purified solution was directed to the electrolysis department, where cathode zinc was produced using standard technology. Solutions containing 50-60 g/l Zn and 100-120 g/l H_2SO_4 were reused, which increases the closure of the water-reagent cycle.

Fig.2. Primary samples

Results

The results of this study confirm the possibility of using the sulfuric acid hydrometallurgical method for the selective extraction of zinc from the dust of the electric arc furnace (EDF), followed by electrolysis and purification of the electrolyte. Direct use of hot dust (200-300 °C) without preliminary cooling provides additional intensification of the process and contributes to improving the kinetics of zinc dissolution. This is an important technological feature of the proposed approach.

EDP dust is a complex technogenic material with a heterogeneous mineralogical composition and high variability depending on the operating conditions, steel grade, and additives. While iron was mainly associated with oxide phases, zinc in the investigated dust predominated in oxide forms and in the structure of zinc ferrites. Since ZnO dissolves readily in acidic environments, while iron oxides dissolve poorly in controlled leaching conditions, this distribution promotes the selective extraction of zinc through sulfuric acid leaching.

In the hydrometallurgical processing of EDP dust, zinc ferrite ($ZnFe_2O_4$) is usually considered one of the main factors limiting zinc extraction. Zinc ferrite has a stable spinel structure and shows low reactivity in dilute sulfuric acid. Nevertheless, partial decomposition of ferrites can occur under sufficiently aggressive conditions, such as elevated temperature, optimal acid concentration, and increased contact time. This increases the zinc transfer to the solution. At the same time, proper control of leaching parameters can reduce iron dissolution; this is important for reducing impurities during subsequent electrolyte purification.

One of the most important results of this work is demonstrating the intensification of leaching when hot dust is fed into a reactor with mechanical stirring at temperatures between 200 and 300 °C. Before leaching, the dust is typically cooled during conventional hydrometallurgical processing, resulting in higher energy consumption and lower kinetic activity. Supplying hot dust, on the contrary, quickly increases the thermal potential of the system, reduces the time required to achieve the desired leaching temperature (60-65°C), and improves the mass distribution.

Increasing the temperature at the initial stage of pulp formation leads to faster dissolution of ZnO and accelerated diffusion of reagents and products in the liquid phase. In addition, due to the rapid cooling of the furnace gas flow, hot dust may contain phases with higher defective density or partially amorphous structures. This can also improve leaching. As a result, the process becomes more dynamic and efficient, and heating the pulp does not require more energy.

For the leaching of sulfuric acid, a spent electrolyte containing 120-160 g/l H_2SO_4 and 30-50 g/l Zn was used. Because it maintains a more closed water-reagent cycle and reduces fresh acid consumption, using spent electrolyte is an important technological advantage. Under certain operating conditions (temperature 60-65 °C, solid and liquid phase ratio 1:6, leaching duration 120-240 min), high zinc dissolution was achieved while simultaneously limiting excessive iron transfer to the solution.

The initial leaching stage led to an increase in the degree of zinc and iron extraction by approximately 47-50%, as shown in Table 2 and the spectral analysis results shown in Figure 3. This indicates that the chosen conditions provide sufficient aggressiveness of the medium for ZnO dissolution and partial decomposition of zinc ferrites. If this had happened, the process would not have led to uncontrolled dissolution of iron oxides; otherwise, the contamination of the solution would have increased and the purification would have been more difficult.

Discussion

The results show how important it is to regulate the concentration of sulfuric acid during leaching. In the acid concentration range from 120 to 160 g/l, zinc-containing phases dissolve well without losing iron. When the acid concentration is insufficient, the dissolution of ZnO is not complete, and the decomposition of ferrite is limited. Conversely, excessive acidity increases the likelihood of iron oxide dissolving and Fe^{3+} ion formation in the solution. This makes further purification difficult and can negatively affect electrolysis.

Thus, optimizing acid concentration is crucial for maintaining balance between zinc extraction and selectivity towards iron. The results show that within the studied range, it is possible to achieve a high degree of zinc extraction while maintaining the corresponding iron level in the productive leaching solution.

To meet the requirements of electrolytic zinc production, the productive solution required purification after leaching. Hydrolytic cleaning, cementation, and chemical correction comprised three stages of cleaning. Although this multi-stage method is standard industrial practice, it has been modified to account for the profile of impurities contained in the dust washer of electric arc furnaces.

Iron and aluminum were removed by hydrolytic purification using controlled sedimentation. This stage is particularly important because the dissolved iron, especially in its trivalent form, can cause significant problems during electrolysis, such as increased energy consumption and a decrease in cathode quality. During hydrolysis, iron is converted into insoluble hydroxide or basic sulfate phases, and then extracted from the solution.

Copper, cadmium, and lead were extracted by cementation. These impurities can alter the electrochemical behavior and reduce the purity of cathode zinc. In the process of cementation, zinc dust is usually used to displace more noble metals from the solution. Due to its simplicity and cost-effectiveness, this method is effective and widely used.

The final stage of chemical purification led to a change in the electrolyte composition, maintaining the concentrations of sulfuric acid and zinc within the optimal range for electrolysis. The final composition of the electrolyte stabilized to approximately 50-60 g/l zinc and 100-120 g/l H_2SO_4, which is suitable for obtaining zinc as an electrolyte.

In the electrolysis shop, the purified electrolyte was used to produce cathode zinc in the usual manner. The main advantage of the proposed processing method is the reuse of solutions containing 50-60 g/l zinc and 100-120 g/l H_2SO_4. Electrolyte recirculation reduces the amount of water and reagents, making the process more efficient and reducing wastewater. Using the spent electrolyte as a leaching agent, it is possible to create a partially closed cycle. This meets modern standards for sustainable metallurgical processing.

The production of cathode zinc is proof that the purification strategy effectively reduces the concentration of impurities to levels that meet the requirements of industrial electrolysis.

After leaching, the solid residue mainly consists of iron oxides with a low zinc content. This residue is valuable because it can be reused in steel production as a shixta additive. This type of disposal offers two main advantages. Firstly, this reduces waste accumulation and facilitates the cyclical use of by-products from metallurgical production. Secondly, since iron is not lost in tailings, the return of iron-containing residue increases the overall material efficiency of steel plants.

Low zinc content is necessary when smelting steel, as it can cause operational problems such as wear and tear of refractories and increased zinc circulation. The results show that the proposed leaching conditions ensure sufficient zinc removal. This allows for the processing of residues without affecting the steelmaking process.

Overall, it is shown that the hydrometallurgical method is effective, intensifies processes, and is environmentally safe. Using hot dust reduces energy losses and requires no cooling. The cost-effectiveness and consumption of fresh acid increase when using spent electrolyte. Multi-stage purification provides high-quality electrolyte suitable for electrolysis. Finally, processing the iron-containing residue brings additional technological and environmental benefits.

The overall results show that the developed technology can be useful for industrial implementation, especially in integrated steel plants that seek sustainable solutions for dust control in electric arc furnaces and zinc extraction.

Conclusion

This study developed and demonstrated an effective hydrometallurgical technology for processing dust from electric arc furnaces (EDF). The purpose of this research is to maximize zinc extraction and ensure the return of iron-containing residue during the steel production process. Sulfuric acid leaching of zinc-containing phases precedes multi-stage purification of the electrolyte, followed by the electrolytic production of cathode zinc. Due to the mineralogical distribution of metals, where zinc is mainly present in the form of zinc oxides and ferrites, and iron is mainly present in the oxide phases, the obtained results confirm that EDP dust is a promising secondary raw material for zinc extraction.

The developed technology is distinguished by the direct use of hot dust at a temperature of 200 to 300 degrees Celsius, which is supplied to the leaching reactor with mechanical mixing without preliminary cooling. By utilizing the heat potential of the dust, this technological solution contributes to the intensification of the process and the reduction of total energy consumption. The results showed that the use of hot dust significantly accelerates the leaching kinetics due to increased diffusion and chemical reactions. This allows for improved zinc dissolution under moderate technological conditions.

For leaching, a spent sulfuric acid electrolyte containing 120-160 g/l H_2SO_4 and 30-50 g/l Zn was used. Because this method reduces the need for fresh acid and promotes a more closed water-reagent cycle, it saves money and the environment. The ideal conditions for leaching are a temperature of 60-65 °C, a solid to liquid ratio of 1:6, and a leaching time of 120-240 minutes. At these parameters, the medium aggressiveness allowed for the effective dissolution of ZnO and partial decomposition of zinc ferrites, and the excessive transfer of iron into the solution was limited. Based on the chemical and spectral analysis of the solid residue after leaching, it was found that the degree of zinc and iron extraction increased by approximately 47-50% at the initial leaching stage. This indicates the effectiveness of the chosen conditions.

The next step was the successful purification of the productive leaching solution in three stages. Iron and aluminum were purified hydrolytically, cementation was used to remove copper, cadmium, and lead, followed by the final chemical adjustment of the electrolyte composition. This purification sequence allowed for obtaining a high-quality electrolyte that meets the requirements for obtaining zinc as an electrolyte. The electrolysis was carried out using standard industrial practice, resulting in the production of cathode zinc and the formation of solutions containing 50-60 g/l Zn and 100-120 g/l H_2SO_4. During the process, these solutions were reused. The recirculation of electrolyte solutions improves the closed nature of the technological cycle and reduces the amount of wastewater.

The main result of the proposed technology is the formation of an iron-containing residue with a low zinc content. This residue can be used in steel production as a mixture additive without harming the technological process. This quality helps maintain the principles of a circular economy, as it reduces the amount of waste generated and guarantees the efficient use of by-products from metallurgy.

References

1. Kozlov, P. A., Povysheva, E. V., Zolkina, A. V., & Vorobiev, A. G. (2009). Current state and prospects of Waelz process application for EAF dust treatment. Non-Ferrous Metals, 7, 36–40.

2. Havlík, T., Souza, B. V., Bernardes, A. M., Schneider, I. A. H., & Miskufová, A. (2006). Hydrometallurgical processing of carbon steel electric arc furnace dust. Journal of Hazardous Materials, 135, 311–318. https://doi.org/10.1016/j.jhazmat.2005.11.067

3. Peters, M. A. (1990). Process for recovery of zinc oxide from steelmaking dust (U.S. Patent No. 4,071,357).

4. Lytaeva, T. A., & Pashkevich, M. A. (2014). Utilization of powdered zinc-iron-containing wastes from mining and processing enterprises. Mining Informational and Analytical Bulletin, 4, 330–333.

5. Jha, M. K., Kumar, V., & Singh, R. J. (2001). Review of hydrometallurgical recovery of zinc from industrial wastes. Resources, Conservation and Recycling, 33, 1–22. https://doi.org/10.1016/S0921-3449(01)00094-3

6. Dutra, A. J. B., Paiva, P. R. P., & Tavares, L. M. (2006). Alkaline leaching of zinc from electric arc furnace steel dust. Minerals Engineering, 19, 478–485. https://doi.org/10.1016/j.mineng.2005.08.013

7. Xia, D. K., Pickles, C. A., & Jiang, T. (2014). Kinetics of zinc ferrite leaching in sulfuric acid. Hydrometallurgy, 142, 103–109. https://doi.org/10.1016/j.hydromet.2013.12.003

8. Reddy, B. R., Kumar, J. R., & Park, K. H. (2004). Studies on dissolution of zinc ferrite. International Journal of Mineral Processing, 72, 373–381. https://doi.org/10.1016/S0301-7516(03)00119-6

9. Mombelli, D., Mapelli, C., Barella, S., & Gruttadauria, A. (2016). Ammonium chloride leaching of electric arc furnace dust. Metallurgical Research & Technology, 113, 203. https://doi.org/10.1051/metal/2016014

10. Soucy, G., Perrault, G., & Baril, J. (2000). Autoclave leaching of zinc concentrates and secondary materials. Hydrometallurgy, 56, 23–38. https://doi.org/10.1016/S0304-386X(00)00083-6

11. Zhang, Y., Guo, Y., & Han, B. (2018). Pressure leaching of zinc from EAF dust. Transactions of Nonferrous Metals Society of China, 28, 2246–2253. https://doi.org/10.1016/S1003-6326(18)64838-1

12. Jorgensen, F. R. A. (2013). Recycling of electric arc furnace dust. Ironmaking & Steelmaking, 40, 576–582. https://doi.org/10.1179/1743281213Y.0000000125

13. Agatzini-Leonardou, S., Oustadakis, P., Tsakiridis, P. E., & Markopoulos, C. (2004). Recovery of metals from electric arc furnace dust. Journal of Hazardous Materials, 104, 31–40. https://doi.org/10.1016/j.jhazmat.2003.07.006

14. Li, Y., Li, J., & Zhang, S. (2020). Sustainable processing of steelmaking dust: A review. Journal of Cleaner Production, 250, 119486. https://doi.org/10.1016/j.jclepro.2019.119486

15. Pickles, C. A. (2008). Thermodynamic analysis of zinc-containing phases in EAF dust. Minerals Engineering, 21, 1256–1260. https://doi.org/10.1016/j.mineng.2008.03.012

16. Abanades, J. C., Arias, B., & Lyngfelt, A. (2019). Zinc recovery routes from metallurgical wastes. Chemical Engineering Journal, 359, 131–143. https://doi.org/10.1016/j.cej.2018.11.070

17. Zhang, L., & Ostrovski, O. (2001). Zinc behavior during steelmaking processes. Metallurgical and Materials Transactions B, 32, 1047–1054. https://doi.org/10.1007/s11663-001-0092-5