XVI International Mineral Processing and Recycling Conference
28-30 May 2025, Belgrade, Serbia

DOI: 10.5937/IMPRC25375S
Original research article

EXPLORING ELECTROHYDRAULIC FRAGMENTATION FOR PROCESSING ELECTRIC ARC FURNACE SLAGS

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ABSTRACT – Electric arc furnace slags (EAFS) are steelmaking by-products rich in valuable metals such as Fe, Mn and Cr. As the steel industry moves towards decarbonization and increases the use of electric arc furnaces, the generation of EAFS is expected to rise, highlighting the need for efficient metal recovery to support waste reduction and circular economy goals. Conventional mechanical processing methods often cannot effectively separate metals from other slag components. This study conducted geochemical, mineralogical, and structural characterization of EAFS to assess the suitability of electrohydraulic fragmentation (EHF) for processing. Mineral Liberation Analysis (MLA) results showed that EAFS comprises finely intergrown magnetic, Fe-rich oxide phases and non-magnetic, Ca-rich oxide and silicate phases with mean grain sizes of <60 µm. EHF was applied to enhance the liberation of metal phases, followed by sieving and magnetic separation. EHF effectively liberated granular metal components in coarse grain fractions (>1 mm), while chemical analysis found no significant enrichment of Fe in magnetic fractions for smaller grain sizes. The findings indicate that combining EHF with sieving and magnetic separation may effectively enhance metal recovery from EAFS. This integrated approach offers a promising method for recycling slag waste and contributes to sustainable practices in the steel industry.

Keywords: Electrohydraulic Fragmentation, Electric Arc Furnace Slags, Metal Inclusions, Mineral Liberation Analysis, Magnetic Separation.

INTRODUCTION

Electric arc furnace slags (EAFS) are the most significant by-products generated during steelmaking in electric arc furnaces, which primarily recycle metal scrap to produce steel. In 2018, approximately 103 million tonnes of EAFS were produced globally [1]. This number is expected to rise in the future as the steel industry transforms towards low-carbon processes by increasing the use of electric arc furnace technology to meet international climate and environmental goals. Currently, EAFS are mainly reused in the construction industry, serving as aggregates in bituminous mixtures for road construction and as additives in cement and concrete [2,3]. While these applications provide a

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sustainable outlet for EAFS, their potential may not be fully exploited, especially regarding the recovery of valuable resources. Conventional crushing and magnetic separation techniques often cannot fully separate metal and slag materials. As a result, while the chemical compositions of EAF slag can vary widely, they often contain high amounts of valuable metals, such as Fe (10-50 wt.% FeO) and Mn (3-8 wt.% MnO) as well as significant concentrations of Cr_2O_3 and V [4,5]. These metals are usually incorporated in oxides and silicates; however, elemental iron may also be present [6]. Consequently, exploring reprocessing techniques to recover these metals may offer economic benefits, reduce the demand for primary raw materials, improve recycling rates, and promote a circular economy, aligning with the EU's Circular Economy Action Plan on waste reduction and resource efficiency.

Here, one potential alternative processing method in electrohydraulic fragmentation (EHF) is explored, which utilizes high-voltage electrical discharges in a fluid medium to generate mechanical shockwaves that preferentially fragment materials along mechanical weak points, such as interfaces of materials with different acoustic properties, e.g., grain boundaries, allowing for high material selectivity [7]. This process can enhance the liberation of individual grains, establishing a basis for magnetic- or gravity-based separation methods. EHF has been successfully applied to selectively comminute various composite materials and recover valuable components from electronic waste, such as photovoltaic panels, as well as for the fragmentation of rocks [7,8]. To optimize the application of EHF for EAFS processing, comprehensive characterization of the slags regarding phase composition and distribution, grain sizes, and overall microstructural information is essential for adjusting EHF process parameters, such as energy input and pulse frequency, and therefore to enhance the efficiency and selectivity of the fragmentation process. By effectively liberating metal-rich phases from the slag matrix, the EHF process may improve metal recovery rates, offering a more sustainable and economically viable method for processing EAFS.

EXPERIMENTAL

Materials

Approximately 500 kg of EAFS representing the 0/32 mm fraction (charge ID: FG02) were collected from a German slag processing facility. The bulk material was thoroughly homogenized to obtain representative subsamples suitable for analytical procedures and EHF processing.

Mineral Liberation Analyses

Automated SEM analysis was performed using Mineral Liberation Analysis (MLA) on a polished, carbon coated, epoxy-embedded block (measurement area: 22.5 x 22.5 mm) of EAFS sample FG02/1 at ERZLABOR Advanced Solutions GmbH, Freiberg, Germany. The Grain X-ray Mapping (GXMAP) measurement mode was used, which combines X-ray mapping with grey-level analysis from backscattered electron (BSE) imaging to enhance slag phase discrimination for phases with similar BSE contrasts, allowing for phase distribution mapping. The analysis was conducted using appropriate measurement parameters as shown in Table 1.

Table 1 Summary of MLA measurement parameters

Voltage	Emission current	BSE image calibration	Working distance	MLA single image size	BSE single image size	BSE image resolution
25 kv	10 nA	Cu 249	12 mm	500 x 500 px	1.5 x 1.5 mm	3 µm/px

Electrohydraulic Fragmentation

The EAFS samples were subjected to EHF to enhance the liberation of metal inclusions and improve subsequent separation efficiency. The treatment was carried out using a laboratory-scale IMPULSTEC EHF lab unit at ImpulsTec GmbH, Radebeul, Germany. For the batch tests, high-voltage electrical discharges were generated in a water-filled vessel to comminute approximately 1.4 kg of EAFS sample type FG02. The samples were exposed to electrical pulses with high pulse energy. Following EHF treatment, the fragmented slag samples underwent mechanical screening, using integrated sieves, separating them into five size fractions: >1 mm, 0.8-1 mm, 0.5-0.8 mm, 0.25-0.5 mm, and <0.25 mm. Subsequently, the samples were dried, and each grain size fraction was subjected to magnetic separation using a ferrite (F1) hand magnet to separate strongly magnetic grains, followed by two neodymium hand magnets (N1, N2) to capture weakly magnetic grains.

Chemical Analysis

To gain approximate information about the chemical composition of the EHF fractions, chemical analyses were performed using an Olympus Vanta C-series portable XRF (pXRF) instrument equipped with a 50 kV Ar target X-ray tube. Analyses were conducted in "GeoChem" measurement mode with a measurement time of 60 s per sample. Each measurement was repeated three times to obtain a reliable dataset.

RESULTS AND DISCUSSION

MLA of EAFS sample FG02/1 identified Fe-rich oxides that, based on their modal composition, resemble magnetite, magnesiowustite and chromite – phases that often occur in these slags [4] – as well as Ca-rich oxides and silicates as the most prevalent phases. In addition, phases of mixed composition were observed, labeled as Fe-ox (an FeCaAlMgSiMnO-mix phase) and Ca-ox (a CaAlFeSiMgMnO-mix phase), as depicted in Figure 1. These mixed phases occur when the interaction volume of the electron beam exceeds the size of the individual grains. As a result, the beam overlaps multiple phases at grain boundaries, producing mixed EDX spectra that reflect compositions of both adjacent minerals. The high modal abundance of the mixed phases (ca. 30%) likely results from the overall small median grain sizes (P_{50}) of <60 µm for most phases (Figure 1a). The modal phase composition suggests that approximately 70% of the slag components are magnetic, with the metals of interest (Fe: 88%, Mn: 86%, Cr: 100%) largely present in these phases, assuming that Fe-ox is predominantly a Fe-oxide phase with magnetic behavior, while Ca-ox is non-magnetic (Figure 1b). Phase association analysis (Table 2) indicates that the magnetic phases are often intergrown with non-magnetic phases (M:NM = 0.59), whereas the non-magnetic phases are rarely associated with other non-magnetic phases (M:NM = 2.96).

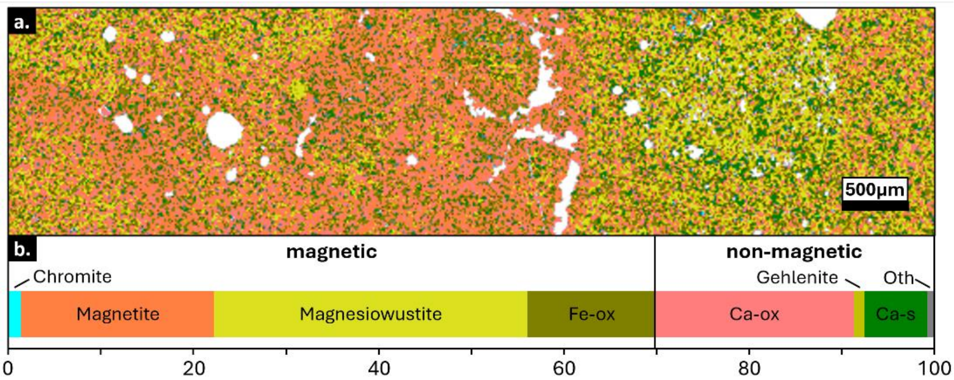

Figure 1 (a.) False-color MLA mineral map of sample FG02/1. **(b.)** Corresponding modal phase composition, categorized into magnetic and non-magnetic fractions. Fe-ox = FeCaAlMgSiMnO-mix, Ca-ox = CaAlFeSiMgMnO-mix, Ca-s = Ca-silicate, Oth = Others.

Table 2 Proportional magnetic and non-magnetic phase association in sample FG02/1 as shown by MLA analysis. M:NM represents the ratio of magnetic to non-magnetic phase associations

	Magnetic Association (M)	Non-Magnetic Association (NM)	M:NM
Magnetic phases	24.9 %	42.5%	0.59
Non-Magnetic phases	21.4%	7.2%	2.96

EHF tests demonstrate that, across all grain size fractions, most grains exhibit at least weakly magnetic behavior, with the total proportion of processed material summing up to 73.0%, which aligns closely with the 70% of magnetic phases estimated from MLA observations (Figure 2).

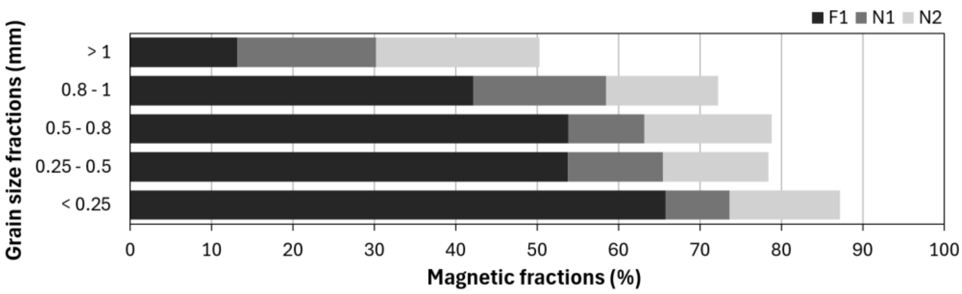

Figure 2 Grain size fractions and their magnetic proportions (F1: ferrite magnet, N1/N2: Nd magnets) within EAFS sample FG02 after EHF processing

The most significant increase in the proportion of magnetic material occurs between the >1 mm fraction and the 0.8-1 mm fraction, beyond which differences in magnetic content among finer fractions become less pronounced. The expected intergrowth of magnetic and non-magnetic phases in larger grains may reduce their overall magnetizability, hindering their recovery during magnetic separation and explaining the lower proportion of magnetic material in the >1 mm fraction. However, in fractions with smaller grain sizes, the opposite effect may occur, where non-magnetic grains may be drawn into magnetic fractions due to agglomeration effects, leading to a significant portion of Ca-oxides and silicates in the magnetic fractions. This is supported by the results from pXRF analysis that found that the Fe content for the magnetic fraction of >0.25 mm is 35.0 wt.%, while for the same grain size in the non-magnetic fraction the Fe content is 33.3 wt.%, only marginally lower. Thus, due to the high association of magnetic phases with non-magnetic phases and the small median grain sizes of the investigated phases, efficient separation may only be achieved at much smaller particle sizes than those investigated in this study.

While granular metal particles are not visible in smaller fractions, in the >1 mm fraction they can be clearly distinguished from the dark matrix material that rarely shows residual metal components attached to it (Figure 3a, b). This observation indicates that EHF effectively liberates metal components from other phases, consistent with expectations that fragmentation of the slags preferentially occurs at grain boundaries. It also suggests that metal inclusions may have a minimum size threshold for their formation and are not further fragmented during EHF treatment. Thus, while EHF successfully separates metal particles from the slag matrix, the larger metal inclusions remain intact, potentially facilitating their recovery. However, due to the total weight of only 16 g (equals ca. 1% of sample weight) for the hand-sorted metallic fraction (Figure 3a), extracting significant amounts of metal solely from this fraction may not be sufficient and therefore, additional recovery from finer fractions is necessary.

Figure 3 Grain fractions in EAFS sample FG02 after EHF processing. Liberated and hand-sorted grains from the >1 mm magnetic fraction showing the effectiveness of phase separation by EHF processing of metallic components **(a.)** from the slag-matrix **(b.)**. No visual differences between the magnetic **(c.)** and non-magnetic fraction **(d.)** for smaller grain sizes (< 250 µm) could be identified.

CONCLUSION

This study investigated the potential of EHF to enhance the liberation and recovery of valuable metals from EAFS. MLA of a representative EAFS sample revealed that Fe-rich oxides and Ca-rich oxides and silicates are the most prevalent phases, with significant fine-grained intergrowth between magnetic and non-magnetic phases. This microcrystalline intergrowth poses challenges for efficient separation using conventional methods. EHF processing tests showed that granular metal components could be effectively liberated from surrounding slag material, aligning with expectations that material is preferentially fragmented at grain boundaries. The occurrence of metal particles only in the coarse grain fractions (>1 mm) suggests that these are not further fragmented during EHF treatment. However, the effectiveness of magnetic separation and liberation for specific grain sizes and magnetic fractions requires further investigation. The median grain sizes of the liberated phases of <60 µm, the high rate of Fe-rich magnetic intergrown with Ca-rich non-magnetic phases and the similar Fe concentrations between magnetic and non-magnetic fractions suggest that efficient separation may only be achievable for much smaller particles sizes than investigated in this study. Thus, EHF parameters need to be adapted to enhance fragmentation and liberation at finer grain sizes. Additionally, future studies should focus on developing improved separation techniques to maximize metal recovery from EAFS, especially for small grain size fractions. This may include exploring more advanced magnetic separation methods, gravity concentration, or flotation. By addressing these challenges, the EHF process could offer a more sustainable and economically viable method for processing EAFS, contributing to waste reduction and resource efficiency in the steel industry.

ACKNOWLEDGEMENT

The research was funded by the Germany Ministry of Education, Science, Research and Technology (BMBF) under 033RK109A.

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