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Original research article

OPTIMIZING METAL RECOVERY FROM EAF DUST: A COMPREHENSIVE APPROACH BEYOND THE WAELZ KILN PROCESS

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ABSTRACT – The Electric Arc Furnace (EAF) process is predominantly used for recycling steel scrap, generating EAF dust at approximately 10-20 kg per ton of steel. This dust is rich in valuable metals like iron and zinc, in addition to metal oxides such as lead, manganese, nickel, and chromium. The DustRec project endeavours to recover all these elements, offering a comprehensive alternative to the traditional Waelz kiln process, which primarily focuses on zinc recovery. The project employs magnetic separation to initially divide dust samples into magnetic and non-magnetic fractions, followed by gravity separation to further refine these into heavy and light fractions. This detailed classification enables targeted processing of each stream through tailored pyrometallurgical and hydrometallurgical methods, according to their specific compositions. Throughout the project, numerous EAF and cupola furnace (CF) dust samples were collected from various sources, with the most suitable samples selected for advanced reprocessing. Separation based on particle size yielded diverse outcomes. The subsequent hydrometallurgical and pyrometallurgical treatments of these fractions resulted in significant metal recoveries.

Keywords: EAF Dust, Magnetic Separation, Gravity Separation, Extraction, Recycling.

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INTRODUCTION

The Electric Arc Furnace (EAF) process is the most widely used method for recycling steel scrap, primarily due to its ability to smelt 100% of the solid charge [1]. In contrast, the Basic Oxygen Furnace (BOF) typically handles only 20% of the total charge weight as cold metallic burden [2]. During the melting, EAF dust accumulates at a rate of 10-20 kg per tonne of liquid steel [3]. This dust contains valuable metal oxides, including iron (Fe), zinc (Zn), lead (Pb), manganese (Mn), nickel (Ni), and chromium (Cr), alongside some halides [4]. The composition of EAF dust varies significantly based on the input materials, particularly the proportion of galvanized steel (for Zn) or high-alloy/stainless steel (for Cr and Ni), leading to fluctuations in chemical content from day to day and even between heats within the same steel shop [5]. During the smelting operation, zinc vaporizes and escapes the metal bath as gaseous Zn, which subsequently oxidizes to ZnO during transport with the off-gas, along with other metal oxides [6]. EAF dust is typically collected in bag filters from the off-gas treatment system. If not managed properly, the disposal of this dust can harm the environment due to the mobilization of hazardous metals like Zn, Cd, Cr, Ni, and Pb, while also imposing financial burdens on the metallurgical industry [7]. In 2022, approximately 0.6 to 1.2 million tons of EAF dust were produced, which brings the global total to about 5.5 to 11 million tons [8]. Projections estimate that this figure could reach at least 18 million tons by 2050. Notably, the combined presence of Fe and Zn in EAF dust is particularly remarkable, accounting for 50 to 60% of its weight. The extraction of Zn is the primary focus due to its higher market value (approximately $2,950 per ton) compared to iron, which is valued at around $368 per ton [9]. Consequently, current reprocessing efforts primarily target Zn recovery, as technologies for extracting other valuable metals remain underdeveloped.

Most existing EAF dust treatment technologies employ pyrometallurgical techniques for zinc extraction, with the Waelz kiln process leading the market by capturing over 85% of it. Alternative pyrometallurgical processes have emerged that convert Zn into ZnO for later use in processes like sulphate electrolysis or the Imperial Smelting Process (ISP) [10]. One example is the Rotary Hearth Furnace (RHF) method, which is coal-based and effectively processes EAF dust containing significant quantities of iron, carbon, zinc, lead, and alkalis, yielding high-quality zinc products and Direct Reduced Iron (DRI) instead of slag [11]. However, this process is best for EAF dust with low zinc levels, and technological advancements are needed to manage challenges like zinc oxide blockage. Moreover, the high start-up costs for this technology require improvements in its economic feasibility [12]. Conversely, the Primus® process [12] employs a multiple-hearth furnace technology designed to reduce metal oxides efficiently and quickly using low-cost, unprepared feed at lower operating temperatures. Although it produces high-quality outputs, it faces issues like rapid wear and the evaporation of alkaline compounds, coupled with size restrictions that limit its production capacity. Another pyro-metallurgical method called the INDUTEC® process [13] aims to enrich EAF dust in an induction furnace, recovering Zn and Pb as Crud Zinc Oxide (CZO) through flue gas filtration and obtaining reducible oxides as molten pig iron. The technology developed through the EIT 2sDR project focuses on enhancing the recycling process by recovering both iron (Fe) and zinc (Zn). It currently does not separate and recycle lead (Pb) and copper (Cu), which are commonly present in the material stream. This process is in the prototype phase and is being analysed to assess its compliance with existing and future environmental regulations. Processes are frequently inefficient, expensive, and can present environmental issues [14]. Hydrometallurgical approaches, such as the Zincex® [15] and Ezinex® [16] processes, have also been developed. Zincex® utilizes atmospheric leaching, solvent extraction, and traditional electrowinning to produce high-purity zinc ingots (99.99%). Ezinex® employs chloride leaching to extract oxidized zinc but is currently limited to pilot-scale operations, making it less reliable for large-scale EAF dust processing.

Current processes primarily focus on zinc extraction due to its financial viability, with other metals often discarded as toxic waste. Our approach aims to improve this by employing a variety of mineral beneficiation techniques combined with hydrometallurgical and pyrometallurgical processes. This strategy seeks to maximize the separation and extraction of all valuable metals, while repurposing the residual waste for use in the construction industry, ultimately working towards achieving near-zero waste manufacturing.

EXPERIMENTAL

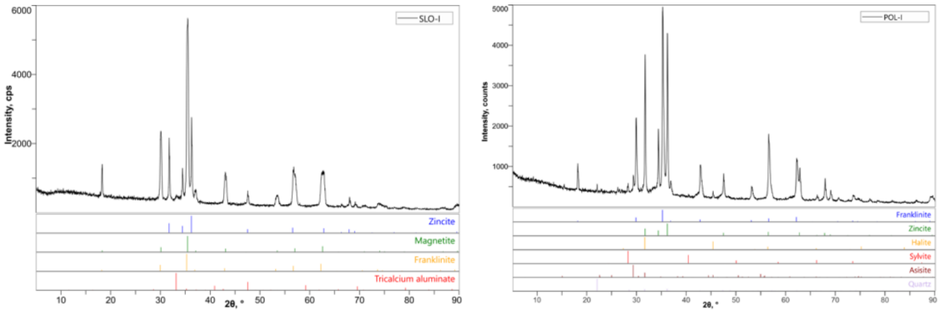
In this study, two different EAF dusts were analyzed: one from Metal Ravne, SI, and the other from Boleslaw, PL. These samples were selected from a variety of options based on their composition (Table 1). Their composition was determined through ICP-OES (refer to Table 1), XRPD (see Figure 1), and SEM microscopy. XRPD analysis revealed that zinc is present in the forms of franklinite and zincite. In the case of Metal Ravne, SI, these zinc forms, along with magnetite, constitute the majority of the sample. Additionally, Metal Ravne, SI dust contains significant quantities of chromium, whereas the Boleslaw, PL, dust is notable for its chlorides and lead content. Due to these compositional differences, these samples are particularly suitable for further testing.

Magnetic and gravity beneficiation techniques were applied to the sample to increase the concentration of ferrous metals in one fraction and nonferrous metals in another. Magnetic separation was conducted using a "Dings" wet magnetic separator equipped with a permanent magnet and a magnetic induction of B = 0.1 T. To improve separation, the sample (-0.025 + 0.00 mm) was additionally ground. For gravity separation, a Multi-Gravity Separator (MGS) was employed, leveraging advanced technology that harnesses both gravitational and centrifugal forces to effectively separate materials based on density.

The ferrous fraction, consisting of the magnetic fraction from magnetic separation and concentrate from gravity separation, was further processed using pyrometallurgical methods with various reducing agents (graphite, biochar and carbon rich CF dust) to produce an iron alloy suitable for direct use in the Electric Arc Furnace as a substitute for scrap metal or for feeding into the Ladle Furnace. Conversely, the non-ferrous fraction, comprising of the non-magnetic fraction obtained by magnetic separation and tailings from gravity separation, was evaluated for the hydrometallurgical extraction of zinc, lead, and copper.

Table 1 Elemental composition of both samples made by ICP-OES

	w (µg/g)									
Sample	**Ca**	**Cr**	**Cu**	**Fe**	**Mg**	**Mn**	**Ni**	**Pb**	**Zn**	**Si**
Metal Ravne, SI	27144	34610	1089	298897	18330	14948	1026	1903	260707	12454
Boleslaw, PL	38465	2331	2112	229300	16755	16763	< LOD	24581	295027	23477



Metal Ravne, SI   Boleslaw, PL

Figure 1 XRPD of both samples

Table 2 Mineral composition of both samples

	Franklinite	Zincite	Magnetite	Chlorides	Quartz
Metal Ravne, SI	20.6	19.0	56.6		
Boleslaw, PL	60.2	31.7		5.30	2.00

RESULTS AND DISCUSSION

Interestingly, rather than being complementary, both beneficiation techniques excelled in one sample while underperforming in another. Magnetic separation proved more effective for Boleslaw, PL (refer to Table 3), whereas gravity separation achieved a significant enhancement for Metal Ravne, SI (refer to Table 4).

Table 3 Recovery and upgrade of Boleslaw, PL through magnetic separation methods

	Zn		Fe		Pb	
	Recovery [%]	**Upgrade**	**Recovery [%]**	**Upgrade**	**Recovery [%]**	**Upgrade**
magnetic	48.3	1,09	55.7	0.95	48.3	0.95
Non magnetic	51.7	0,90	44.3	1.06	51.7	1.06

Table 4 Recovery and upgrade of Metal Ravne, SI through gravity separation methods

	Zn		Fe		Pb	
	Recovery [%]	**Upgrade**	**Recovery [%]**	**Upgrade**	**Recovery [%]**	**Upgrade**
conc	1.8	0.23	13.2	1.72	9.9	0.23
tail	91.7	1.15	74.7	0.94	84.4	1.15
left	3.9	0.89	4.4	0.99	5.7	0.89

Optimization of the pyrometallurgical treatment of ferrous fractions revealed the necessity of reducing material at 1500 °C using cupola furnace dust as both a reductant and flux to ensure complete separation of slag and metal. The test results indicated that the reduction yield of Electric Arc Furnace Dust (EAFD) concentrate exceeded 40% (expressed as the metal-to-charge ratio), while the slag constituted between 10% and 22% of the initial briquette mass. Notably, the use of biochar demonstrated less effectiveness in this process. The pyrometallurgical treatment successfully recovered three primary metals: Fe, Mn, and Cr, with recovery yields ranging from 0.88 to 0.97 for Fe, 0.00 to 0.66 for Mn, and 0.64 to 0.97 for Cr.

Hydrometallurgical extraction of Zn by the utilization of sulfuric acid showed optimal results at conditions in Table 5.

Table 5 Optimal experimental conditions for leaching of Zn and copper

	T (°C)	t (min)	% Zn leached	% Fe leached	% Cu leached
Boleslaw, PL	40	60	80	15	65
Metal Ravne, SI	25	80	81	12	31

Lead was extracted from the sulphate leaching residue with triethylenetetramine. It was determined that lead recovery from the non-magnetic fraction of EAF dust is feasible (residue non-mag. Boleslaw, PL), achieving extraction efficiencies of up to 90%. The proposed process optimization includes ideal conditions for leaching EAF dust at room temperature with a solid-to-liquid (s/l) ratio of 100 g/dm³ over a duration of 1 to 2 hours. The optimal concentration of TETA required for effective lead extraction under these conditions was established to be 4%. The tested precipitation resulted in lead 97.7% carbonate.

CONCLUSION

The application of beneficiation methods, followed by hydrometallurgical or pyrometallurgical processes, demonstrated significant improvements in the treatment of Electric Arc Furnace (EAF) dust. This approach led to the concentration of essential metals in the separated fractions, achieving an upgrade of 1.15 and a recovery rate of 91.7%. These results indicate that such methods can be effectively applied to secondary raw materials, in addition to primary ores. Further research and development in this area are necessary to address smaller particles, commonly found in process wastes, transforming them into valuable secondary raw materials. The obtained fractions underwent appropriate pyrometallurgical or hydrometallurgical treatments, resulting in reduced material volumes and consequently lower processing costs. The pyrometallurgical treatment effectively recovered three key metals: iron, manganese, and chromium. Furthermore, the extraction of zinc, followed by iron precipitation and copper cementation, achieved a remarkable 95% purity with a recovery rate of 78.9%. Lead extraction also performed impressively, yielding 90% with $PbCO_3$ of sufficient purity for smelter applications. These results underscore the feasibility and effectiveness of maximizing metal recovery from waste materials.

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