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Hydrome-metallurgical waste management: Turning metal-enriched waste into valuable resources

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Abstract

The convergence of hydrometallurgical waste management and the principles of the circular economy holds immense potential for addressing the challenges posed by metal-enriched waste. By turning waste into valuable resources through efficient metal extraction, this approach not only aligns with sustainable development goals but also contributes to the conservation of resources, reduction of waste, and the promotion of economic and environmental well-being. This article deals with the further possibilities of processing metal-bearing wastes in the form of steel drifts via hydrometallurgy. The main part of this research focuses on the development of suitable technology for the leaching of steel flakes to obtain selected non-ferrous metals, mainly zinc and lead, for economic and environmental reasons. Laboratory experiments are carried out to verify a suitable leaching agent in the form of high-temperature acid leaching, neutralizing leaching, and magnetic separation verified in lead seals. From the results of the experiments, a suitable technology for processing steel fumes is proposed.

Introduction

In the contemporary landscape of industrial processes, the imperative of sustainable resource management has underscored the need for innovative waste management strategies (Scorţar, Vereş Vincenţiu & Anamaria, 2010). This necessity becomes particularly pronounced when considering the intricate realm of hydrometallurgical waste, distinguished by its inherent enrichment of valuable metals (Radzyminska-Lenarcik, Ulewicz & Ulewicz, 2018). This article is devoted to the adept conversion of waste replete with essential metals into resources of discernible value. Through meticulous optimization of operational methodologies and a conscientious embrace of the circular economy paradigm, the objective is to engineer efficacious value streams. The latter are envisioned not merely to alleviate the ecological footprint associated with waste but, crucially, also to beget newfound economic prospects (Gucma, Deja & Szymonowicz, 2023).

The relentless advancement of technology, coupled with a burgeoning global population and its escalating requisites, has precipitated an escalating exploitation of the natural milieu. Concomitantly, human activities have inadvertently engendered a disconcerting augmentation of environmental pollution. In light of these pressing concerns, previous research (Tomsana, Itoba-Tombo & Human, 2020; Lazar, Klimecka-Tatar & Obrecht, 2021) advocated a concerted commitment to safeguarding the global environment. They contend that such preservation is not only vital for facilitating sustained economic and societal progress but also for bequeathing the fruits of development to posterity (Czajkowska & Ingaldi, 2023). In response to this imperative, the scientific community is fervently engrossed in the cultivation of innovative technologies engineered towards efficiency while addressing ecological ramifications (Szataniak, Novy & Ulewicz, 2014). This burgeoning consciousness towards environmental equilibrium is palpable even within the realm of logistics process optimization. Beyond the conventional focus on process optimization's intrinsic excellence, contemporary perspectives are attuned to the imperative of curtailing the environmental footprint associated with logistical operations (Nowicka-Skowron & Ulewicz, 2015).

An additional pivotal aspect revolves around fostering diverse forms of innovation within environmental preservation and sustainable development strategies (Grebski & Mazur, 2022; Hlushchenko et al., 2022; Wachnik, 2022). Recent shifts in global climate patterns, coupled with a rapid depletion of finite fossil fuel reserves, underscore the urgency of seeking remedies. The latter extend beyond efficient production methods (Ingaldi & Ulewicz, 2020) and the utilization of renewable energy sources (Ulewicz et al., 2021; Gavardashvili & Vartanov, 2023) by encompassing the imperative management of waste resulting from natural disasters (Boonmee, Legsakul & Arimura, 2023).

The contemporary global dilemma revolves around the transformation of the existing consumption model based on the production-consumption-waste cycle into a circular economy (CE) that is regenerative and grounded in production-consumption-reuse. The circular economy is founded upon the principles of 3Rs (i.e., reduce, reuse, and recycle), which have subsequently been expanded into the 10Rs (i.e., refuse, rethink, reduce, reuse, repair, renew, remanufacture, repurpose, recycle, and recover) (Zhidebekkyzy, Temerbulatova & Bilan, 2022).

Hydrometallurgical waste management represents a pivotal approach in addressing the challenges posed by metal-enriched waste, transforming what was once considered a disposal problem into a valuable resource opportunity. This process involves the application of hydrometallurgical techniques to extract and recover metals from various waste streams, such as electronic waste, mining tailings, and industrial byproducts.

The conventional linear economy model, which follows the "take-make-dispose" paradigm, has led to the accumulation of significant amounts of metal-containing waste that often ends up in landfills or poses environmental hazards. However, the principles of the circular economy, particularly the tenets of the 10Rs, offer an alternative and sustainable path forward.

Hydrometallurgical waste management effectively aligns with the circular economy's philosophy by focusing on several key aspects. First, it aims to recover valuable metals from waste materials through processes such as leaching, solvent extraction, and precipitation. These extracted metals can then be reintroduced into the production cycle, reducing the need for virgin raw materials and mitigating the environmental impact of mining.

Moreover, this approach contributes to waste reduction by effectively extracting metals from waste streams. As a result, the amount of waste destined for landfills is significantly reduced, aligning with the "reduce" and "recycle" principles of the circular economy and contributing to a more sustainable waste management approach. Economically, the process of recovering metals from waste offers certain benefits beyond environmental considerations. Valuable metals like gold, silver, copper, and rare earth elements can be reclaimed and sold, creating economic incentives for the adoption of hydrometallurgical waste management.

Furthermore, the environmental benefits of hydrometallurgical waste management are noteworthy. Traditional metal extraction methods are often energy-intensive and environmentally harmful. In contrast, when properly executed, hydrometallurgy can be more environmentally friendly due to it consuming less energy and producing fewer greenhouse gas emissions.

The implementation of hydrometallurgical techniques for waste management drives innovation in both metallurgy and environmental science. Researchers are continuously exploring new methods to optimize metal recovery processes and minimize their environmental footprint. Effective hydrometallurgical waste management necessitates collaboration among industries, governments, and research institutions. Regulations and standards need to be established to ensure safe and responsible waste treatment and resource recovery.

The dust from steel furnaces (i.e., steel drift) was experimentally processed by the process of melt reduction. The aim of these works was to assess the effect of self-reducing briquettes (prepared from steel drift) on the cupola furnace charges and, above all, to verify the degree of reduction of iron oxides. Simultaneously, the behavior of zinc in these processes and the efficiency of its removal were monitored (Majerčák, 1986).

While some authors (Kursa et al., 1999; Baran et al., 2003) propose to recycle drift and sludge in the technological cycle of pig iron and steel production, it should be noted that such solutions are not promising in terms of environmental protection and ever more stringent permissible emission standards. During the recycling of contaminated drift and sludge, the zinc and lead accumulate, and their contents increase, especially in the blast furnace charge. This means that part of the enriched and trapped drift that is non-recyclable must be landfilled appropriately. Previous works, e.g., Imriš, Klenovčanová & Imriš (1998), and the average composition of steel sludge produced in tandem furnaces (Klein, 1998) showed that drift and sludge are a fine pulverulent substance generated in the production of pig iron and steel. The concentrations of iron, zinc, lead, cadmium, copper, manganese, chromium, carbon, sulfur, Al_2O_3, CaO, MgO, and K_2O vary in a relatively narrow range, depending on the type of raw materials processed. However, in terms of the zinc content of the drift and sludge, the dependence on the proportion of galvanized scrap in the charge and the phase of the technological cycle in the production of steel in an oxygen converter or tandem furnace is significant (Klein, 1998).

At present, there is an urgent need for an immediate solution aimed at reducing the amount of waste generated in the production of pig iron and steel and minimizing waste deposited in landfills. Making steel production more environmentally friendly is a fundamental trend of current industrial production, which not only benefits the more efficient use of processed raw materials but also contributes to reducing the environmental problems that arise when landfilling waste steel.

The presented experimental study examines the possibilities of processing enriched steel drift via the hydrometallurgical method. The main part of this research focuses on verifying a suitable methodology for the hydrometallurgical treatment of steel drift with the aim of obtaining non-ferrous metals of interest, especially zinc and lead. In the next part, laboratory tests are carried out, which verify the leaching of recycled steel drift in the form of high-temperature acid leaching (Džupková et al., 2011; Brožová, 2013; Brožová, Ingaldi & Šperlín, 2013; Kardas & Brožová, 2013; Bernasowski, 2014; Jonšta et al., 2016; Kardas et al., 2017).

Overview of technologies for processing steel drift and sludge

The issue of processing fine-grained metallurgical waste (i.e., FGMW) is so relevant and topical that it has been addressed by many leading companies that operate in the field of metallurgy of iron and steel. These companies focus on reprocessing these wastes in the metallurgical cycle while removing non-ferrous metals such as Zn and Pb (Bounds & Pusateri, 1990; Hara et al., 1998). In recent years, the "Waelz" process has become the most important process for processing electric arc furnace dust. In the "Waelz" process (Figure 1), sand and fine coke are deposited together with the dust pellets. At temperatures up to 1200 °C, zinc, lead, alkali, and chlorine evaporate and are trapped in electrical filters for hot gas processing. The larger, non-evaporated part of the pellets and sand forms "Wälz" slag, which must be disposed of. The minimum amount of processed material of the profitable plant is approximately 40,000 tons per year. Existing plants can process around 80,000 tons per year per unit. The BSN process was developed and tested in the laboratory of Badische Stahlwerke AG (now Südweststahl GmbH – SWS). This development is based on the evaporation of metals and metal compounds in dust pellets in indirectly heated rotary kilns. The SWS patent (PCT/EP93/00747 and P4209891.2) is based on the discovery that lead is present in electric arc furnace dust in the form of lead chloride and can be separated from zinc oxide at temperatures above 900 °C.

The Kawasaki Steel Corporation has developed a fine-grained metallurgical waste processing technology (i.e., EAF-dust) and a pickling sludge containing Cr. This technology was originally used for the production of ferrous alloys. The operation of the Chiba steel mill for commercial use began in 1994 (Brožová, 2013). The technology is based on a shaft furnace containing a coke-filled shaft with two rows of exhausts, with direct pneumatic charging of the powder material through the upper exhaust without agglomeration. Air for the furnace is enriched with oxygen to intensify heat production. The furnace gases, including the vaporized metals, are cleaned in a hot cyclone and then cooled with water in Venturi tubes. The products are metal, i.e., Fe, Ni, and Cr alloy with $C \approx 4–5\%$, $SiO_2 – CaO – Al_2O_3$ slag and scrubber condensate with $Zn \approx 60\%$. The gases are used to preheat the air.

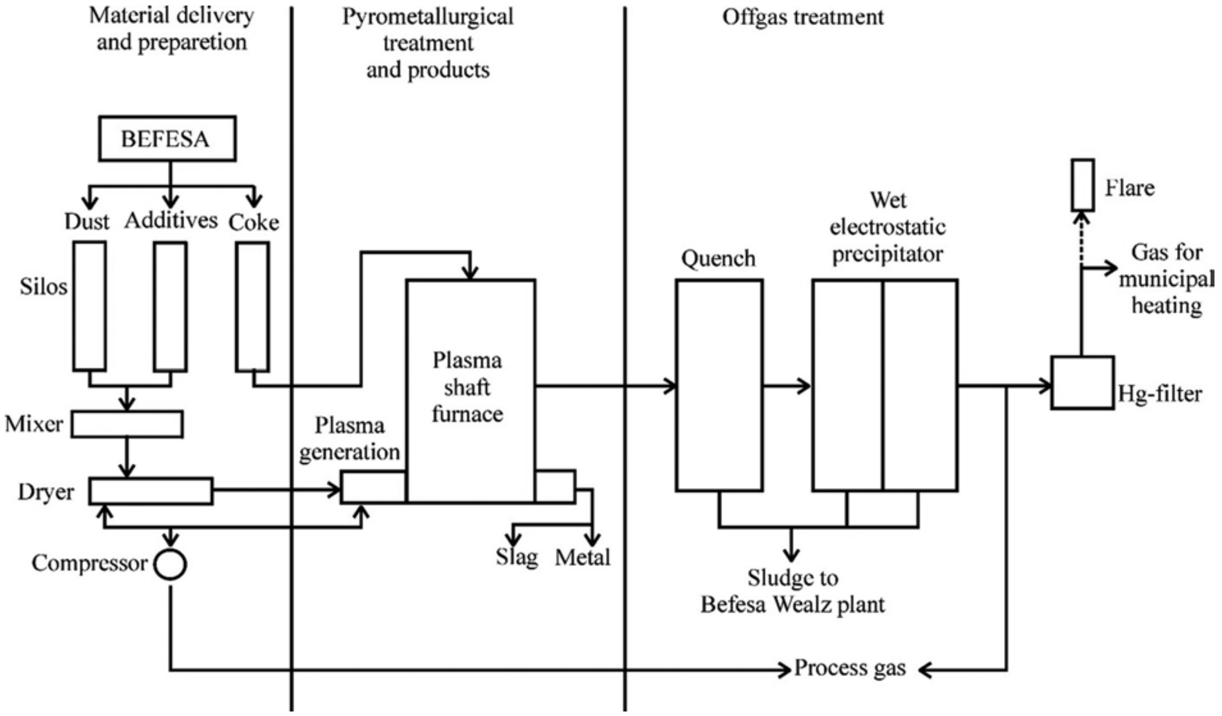

Figure 1. The SDHL Waelz process, including its processing steps (Hara et al., 1998)

The company Scandust in Lanskrona, Sweden, uses similar technology, i.e., a shaft furnace filled with coke. The heat source is a plasma burner with independent plasma flame and pneumatic charging of EAF-dust in front of the burner. Dust is sprayed with water in Venturi tubes; the products are a so-called “hot metal”, i.e., Fe, Ni, and Cr alloy with C ≈ 4–5% that is bought by the FGMW producer, slag based on $SiO_2 – CaO – Al_2O_3$, generator gas used to heat the town of Landskrona, and the zinc concentrate (Steffes, Drissen & Kuhn, 1998).

Horsehead Resource Development Co. has developed a flame reactor for processing EAF dust, in which natural gas or pulverized coal is used as the heat source and the reducing agent, and pure oxygen is employed for combustion. In this case, EAF dust is pneumatically added to the flame space; the volatile metals are evaporated and condensed as oxides in the condenser. The method of condensation is not specified; it is probably a shower of water (Heiss, Fritz & Kohl, 1998; Dvorsky et al., 2010; Oujezdsky, Sliva & Brazda, 2015).

Krupp Edelstahlprofile GmbH uses FGMW injection on the steel level below the slag in the furnace about 10 minutes after the slag has melted and a continuous foamed layer is formed. FGMW dissolves in the slag without noticeable problems. It is partially reduced, passes into steel, and the volatile metals evaporate. For each melt, a batch of 1.5 t of FGMW was added, with no appreciable effect on the course of the process (no overall furnace capacity and condensation method were given) (Sliva et al., 2003; Sliva et al., 2019).

Voest-Alpine Linz, Austria, uses recycling technology in its own steel converter in its FGMW processing technology. FGMW is added to the charge in the form of briquettes (a similar principle was used during the tests in 1985 within the New Metallurgical Plant in Ostrava, Ing. Melecký’s report) (Heiss, Fritz & Kohl, 1998; Sliva et al., 2003; Dvorsky et al., 2010; Oujezdsky, Sliva & Brazda, 2015; Sliva et al., 2019). Vaporized metals are trapped in an electrostatic precipitator. Zinc circulates in this technology until enrichment is sufficient for processing in zinc production technology. The same methods of FGMW recycling in the company’s own steel technology (i.e., electric arc furnaces) occur until sufficient enrichment (minimum 40% Zn in recycled sludge with minimum iron content) is obtained, for example, by Ugine Savoie in France. Due to the repeated cycling of the dust and, thus, the high Zn content in the dust, the recycling technologies are, with respect to work hygiene, highly dependent on the quality of operation of the separators (Legemza et al., 2019).

Laboratory experiments

Within the laboratory tests, the possibility of leaching of the enriched steel drift (ESD) was verified. High-temperature acid leaching technology was used. Three samples of ESD were also employed, which were prepared by a precisely defined amount of lead and zinc inserted into the furnace aggregate together with the ESD. The captured drift was used as the input material for the hydrometallurgical processing. Table 1 shows the chemical composition of the selected elements of interest (%) for the three laboratory samples.

Table 1. Chemical composition of the selected elements of interest (%) for the three laboratory samples

Sample no.	Fe [wgh. %]	Zn [wgh. %]	Cu [wgh. %]	Pb [wgh. %]
1	64	3	0.071	0.82
2	55	14	0.081	1.1
3	32	35	0.088	4.8

Based on Table 1, it can be observed that, by its composition, Sample 1 represents the original steel drift without enrichment. In contrast, Samples 2 and 3 are taken at various stages of the melting process.

The above-mentioned prepared samples were leached at 92–95 °C in a beaker for 2 and 4 hours. The leaching agent was a sulfuric acid solution in the range of 40, 60, and 80 $g \cdot dm^{-3}$. The leaching results are shown in Table 2. They indicate relatively rapid kinetics of the conversion of the individual metals of interest into the leachate.

Table 2. Leaching results

Sample no.	Concentration of the solution H_2SO_4	K:P	Temperature [°C]	Metal of interest	2 hours	4 hours
3	2M	5:1	92	Fe [ppm]	0.098	0.4237
				Zn [ppm]	0.1242	0.1514
3	2M	5:1	95	Fe [ppm]	1.733	1.9774
				Zn [ppm]	0.2145	0.2293
2	2M	5:1	92	Fe [ppm]	0.215	0.634
				Zn [ppm]	0.2458	0.324
2	2M	5:1	95	Fe [ppm]	0.935	1.458
				Zn [ppm]	0.125	0.148

Overall, the tests performed can be evaluated as follows:

a) The raw material shows excellent kinetics for the transfer of the metals of interest into the leachate.
b) It is difficult to change the leaching kinetics to influence the transfer of iron into the leachate with a required zinc leaching efficiency of about 95%; the transfer of iron into the leachate is typically nearly 90%.
c) Suitable leaching conditions are high-temperature acid leaching at 92–95 °C and a sulfuric acid content above 40 $g \cdot dm^{-3}$.
d) Sample 3 is suitable for hydrometallurgical treatment.

Pilot verification

Based on the results of the laboratory tests, pilot tests were performed in the metallurgical plant. Individual test materials weighing 200 kg were produced during the recycling of steel drift in the tandem furnace charge. Samples with higher contents of zinc and lead were prepared by adding zinc and lead waste to the tandem furnace charge.

Pilot verification of leaching kinetics of the ESD was carried out in a prepared apparatus with a volume of 2.5 m^3 with heating to 92–95 °C and stirring. Sulfuric acid in the range of 40, 60, and 80 $g \cdot dm^{-3}$ was used as a leaching agent.

The leaching kinetics of the ESD was monitored during the tests. Leachate samples were then taken. The results are given as follows:

a) Iron and zinc transfer kinetics are sufficiently rapid to transfer both metals into the leachate efficiently.
b) Sufficient sulfuric acid content in the leaching solution is 60 $g \cdot dm^{-3}$.
c) Pilot tests verified the laboratory experiment with the possibility of shortening the leaching time.

Conclusions

Due to the inhomogeneity of the input material, but also the effort to achieve the optimum ratio of zinc:iron (2:1) in the product of hydrometallurgical processing, the methodology with pre-treatment of the feedstock is suitable. The result of hydrometallurgical processing is a leach containing metals of interest – i.e., zinc and iron. These can then be used as secondary raw materials. Within the experiment, an approximate material and energy balance was carried out to assess the costs of obtaining metals of interest and to design a suitable processing technology.

In conclusion, the convergence of hydrometallurgical waste management and the principles of the circular economy holds immense potential for addressing the challenges posed by metal-enriched waste. By turning waste into valuable resources through efficient metal extraction, this approach not only aligns with sustainable development goals but also contributes to the conservation of resources, reduction of waste, and the promotion of economic and environmental well-being.

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