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Editorial

Feature Papers in Extractive Metallurgy

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1. Introduction

Unit metallurgical operation processes are usually separated into three categories: (1) hydrometallurgy (leaching, mixing, neutralization, precipitation, cementation, and crystallization) [1], (2) pyrometallurgy (roasting and smelting) [2], and (3) electrometallurgy (aqueous electrolysis and molten salt electrolysis) [3]. In hydrometallurgy, the target metal is first transferred from ores and concentrates to a solution using selective dissolution (leaching; dry digestion) under an atmospheric pressure below 100 °C, a high pressure (40–50 bar), and high temperature (below 270 °C) in an autoclave and tube reactor. The purification of the obtained solution is performed using neutralization agents such as sodium hydroxide and calcium carbonate, or more selective precipitation agents such as sodium carbonate and oxalic acid. The separation of metals is possible using liquids/liquid processes (solvent extraction in a mixer-settler) and solid–liquid (filtration in filter-press under high pressure) methods. Crystallization is the process by which a metallic compound is converted from a liquid into a solid crystalline state via a supersaturated solution. The final step is metal production using electrochemical methods (aqueous electrolysis for basic metals such as copper, zinc, and silver and molten salt electrolysis for rare earth elements and aluminum). Advanced processes for metal production, such as ultrasonic spray pyrolysis and microwave-assisted leaching, can be combined with reduction processes.

2. Results and Discussion

China's crude steel production has reached 1.019 billion tons, and the energy consumption of China's steel industry has reached 561 million tons of coal. China's steel industry, with its dominant reliance on coal for energy and the primary use of blast furnaces and converters in production processes, as well as its massive output, has become the main field for achieving China's "carbon peaking" and "carbon neutrality" goals. Firstly, this article summarizes the current production status of the steel industry and its situation regarding carbon emissions. Secondly, it discusses the dual carbon policies based on the national and steel industry levels and outlines the future directions for China's steel industry [Contribution 1]. Subsequently, it analyzes the current state of research and application of mature and emerging low-carbon technologies in the industry and details the low-carbon plans of China's steel companies using the low-carbon technology roadmaps of two representative steel companies as examples. Finally, the article gives policy suggestions for further carbon reduction in the industry. The purpose of this paper is to show the efforts and contributions of China's steel industry to the early realization of its "carbon peaking" and "carbon neutrality" goals.

There is a long process for transforming bauxite, a critical raw material, into a substance with the required properties of cast aluminum alloys for use in electro automotive parts. Thanks to its unique properties, aluminum has become the material of choice for

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clean technology manufacturers in applications such as use in the automotive industry, renewable energy, batteries, electrical systems, resource-saving packaging, energy-efficient buildings, and clean mobility [4]. The restructuring of the economy, the oil crisis, air pollution, and global warming are some of the factors that have moved the automotive industry towards electrification since the beginning of the 21st century. This paper aims to highlight the required properties of cast aluminum alloys applied to the production of electro automotive parts, such as their mechanical and thermophysical properties, dimensional stability, corrosion resistance, electromagnetic compatibility, and crashworthiness. Furthermore, this paper discusses which of the cast aluminum–silicon alloys, as well as heat treatments and casting processes, are most suitable.

This paper considers the impact of copper mining-influenced water and metallurgical wastewater on the surface water in the Bor area, Serbia. Sampling, realized through four campaigns (2020–2021), confirmed that both types of water, discharged without appropriate treatment into the Bor River, had a signific impact on the concentration of metal ions, pH, and electrical conductivity on the watercourse in the Bor area [Contribution 2]. The highest concentrations of the following metal ions, Cu—271 mg/L, As—25,991 µg/L, Ni—13,856 µg/L, Cd—2627 µg/L, and Pb—2855 µg/L, were registered in the metallurgical wastewater samples. After changes occurred in the copper production process by stopping the discharge of untreated wastewater into the Bor River, the concentrations of monitored elements drastically decreased. In the period 2022–2024, the concentration values for Cu, As, and Pb ions were below the maximum allowable value, and the concentration values of Ni and Cd ions had also decreased. The values for pH and electrical conductivity were in the maximum allowable range. The return of wastewater to the copper production process would lead to both a reduction in the primary water consumption and a reduction in the negative impact on the environment [5].

In modern times, more and more different materials (including alloys) are in direct contact with human electrolytes (sweat, saliva, lymph, blood, etc.). One of the most important properties for the use of these materials is therefore their chemical inertness or resistance to corrosion when they are in contact with human electrolytes. Consequently, during the development of such new materials, it is necessary to study and understand their basic electrochemical behaviour in a given environment [Contribution 3]. The purpose of this research was to monitor the electrochemical behaviour of the new Au-Ge alloy in artificial sweat and saliva solutions, depending on the electrolyte composition and exposure time. This new alloy represents a potential material for use in dentistry or for jewellery [6,7]. The obtained results of the study show that the immersion time and the pH value have a significantly greater influence on the corrosion resistance of the new Au-Ge alloy than on the composition of the electrolyte solution. The results of the SEM/EDX analysis additionally confirm the main results of the electrochemical measurements.

Copper smelting slag is a significant potential resource for cobalt and copper. The recovery of copper and cobalt from copper slag could significantly augment the supply of these metals, which are essential in facilitating the transition to green energy while simultaneously addressing environmental concerns regarding slag disposal [Contribution 4]. However, the complex mineral composition of copper slag poses an enormous challenge. This study investigated the mineralogical and chemical characteristics of copper slag, which are vital for devising the most effective processing techniques. XRD and FESEM-EDS were employed to examine the morphologies of copper slag before and after the reduction process. The effects of borax and charcoal (carbocatalytic) reduction on phase transformation were evaluated. The XRD analysis revealed that the primary phases in the copper slag were Fe_2SiO_4 and Fe_3O_4. The FESEM-EDS analysis verified the presence of these phases and yielded supplementary details regarding metal embedment in the Fe_2SiO_4, Fe_3O_4, and

Cu phases [8]. The carbocatalytic reduction process expedited the transformation of copper slag microstructures from crystalline dendritic into amorphous and metallic phases. Finally, leaching experiments demonstrated the potential benefits of carbocatalytic reduction by yielding high extractions of Cu, Co, and Fe.

In the pre-reduction cyclone of the HIsarna process, both thermal decomposition and gas reduction in the injected iron ores occur simultaneously at gas temperatures of 1723–1773 K. In this study, the kinetics of the thermal decomposition of three iron ores (namely OreA, OreB, and OreC) for HIsarna ironmaking were analyzed as an isolated process with a symmetrical thermogravimetric analyser (TGA) under an inert atmosphere [Contribution 5]. Using various methods, the chemical and mineralogical composition, particle size distribution, morphology, and phase distribution of the ores were analyzed [Contribution 6]. The ores differ in their mineralogy and morphology, where OreA only contains hematite as the iron-bearing phase and OreB and OreC include goethite and hematite. To obtain the kinetic parameters in non-isothermal conditions, the Coats–Redfern Integral Method was applied for heating rates of 1, 2, and 5 K/min and a maximum temperature of 1773 K. The TGA results indicate that goethite and hematite decomposition occur as a two-stage process in an inert atmosphere of Ar. The proposed reaction mechanism for the first stage of goethite decomposition is chemical reaction with an activation energy ranging from 46.55 to 60.38 kJ/mol for OreB and from 69.90 to 134.47 kJ/mol for OreC. The proposed reaction mechanism for the second stage of goethite decomposition is diffusion, showing an activation energy ranging between 24.43 and 44.76 kJ/mol for OreB and between 3.32 and 23.29 kJ/mol for OreC. In terms of hematite decomposition, only the first stage was analyzed. The proposed reaction mechanism is chemical reaction control. OreA shows an activation energy of 545.47 to 670.50 kJ/mol, OreB of 587.68 to 831.54 kJ/mol, and OreC of 424.31 to 592.32 kJ/mol.

The electrochemical performances of an oxygen-evolving anode produced by the reactivation of waste Ti substrate by a typical IrO_2-Ta_2O_5 coating are correlated to the textural (non)uniformities of the coating and its exhaustion state [Contribution 7]. Coating degradation is considered operational loss of the activity in a metal electrowinning process. It was found that (pseudo)capacitive performances can vary over the coating surface by 20–30% and depend on the type of dynamics of the input perturbation: constant through cyclic voltammetry (CV) or discontinuous time-dependent through electrochemical impedance spectroscopy (EIS). CV-EIS data correlation enabled profiling of the capacitive properties through the depth of a coating and over its surface. The correlation was confirmed by the findings for the analysis of coating activity for an oxygen evolution reaction, finally resulting in the reliable proposition of a mechanism for the operational loss of the anode. It was found that the less compact and thicker coating parts performed better and operated more efficiently, especially at lower operational current densities.

SmCo magnets are a common material utilized in advanced technological applications. These magnets contain elevated concentrations of Sm and Co within their structural compositions. Given that both Sm and Co are classified as critical metals, the recycling of these magnets after their operational lifespan is of significant economic and environmental importance [9]. Hydrometallurgical recycling processes represent an effective method for the recycling of these magnets. In this study [Contribution 8], a pH-controlled selective precipitation method was developed using two HNO_3 solutions with distinct oxidizing properties for the recovery of Sm and Co from end-of-life (EoL) SmCo magnets. In the initial stage of the process, the magnets were leached in a low-oxidizing 2M HNO_3 solution, with a 1:30 (w/v) solid-to-liquid ratio at 20 °C. This step was undertaken to ensure the dissolution of Fe, thereby creating an environment conducive to its removal from the solution. The leaching experiments resulted in dissolution efficiencies of 95%, 96%, and 96%

for Sm, Co, and Fe, respectively. In the second stage, a leaching experiment was performed using 3M HNO_3 with a 1:10 solid-to-liquid ratio at 60 °C. Under these conditions, Sm and Co achieved dissolution efficiencies of 99%, while Fe remained undissolved in the solid phase due to hydrolysis at the high temperature, thus increasing the solution purity. In the precipitation process, the pH of both leachates was initially adjusted to 4 to precipitate impurities such as Fe ions. As a result of precipitation at pH 4 in the 2M HNO_3 leachate, Fe ions were almost completely removed. This was followed by selective Sm precipitation in the pH range of 5–6.5 using NH_4HCO_3. The highest purity of Sm precipitation was achieved when the pH reached 6.5. An increase in Sm precipitation efficiency was observed with increasing pH, with an efficiency of 12.75% at pH 5, which rose to 82.37% at pH 6.5. Furthermore, although the precipitation efficiency of Co increased from 6.25% to 10% within this pH range, no significant difference in the extent of this increase was observed. In the case of the 3M HNO_3 leachate, the Sm precipitation efficiency at pH 5 was 44.28%, while at pH 6.5, nearly all of the Sm ions were precipitated. The co-precipitation efficiency at pH 5 was 1.89%, increasing to 36.43% at pH 6.5. This increase in co-precipitation was attributed to the system's Eh value, which reflects the enhanced oxidizing properties of the 3M HNO_3 leach solution. The results of the study indicate that as the oxidizing strength of the solution increased, the co-precipitation rate also increased with rising pH.

The efficient extraction of zinc from polymetallic concentrates is crucial for the metallurgical industry. Traditional leaching techniques often rely on strong oxidizing agents, which can be wasteful and environmentally harmful [10]. While cyclic oxidation systems like the Fe^{3+}/Fe^{2+} pair are known, they often fail to achieve high leaching rates, especially when the raw material contains multiple sulphide minerals. In this study, we developed a novel oxidation system using manganese dioxide (MnO_2) as the primary oxidizing agent and potassium iodide (KI) as a supporting material to create an I_2/I^- oxidation cycle in a sulphuric acid medium, at an atmospheric pressure between 40 °C and 80 °C. Leaching experiments were conducted under varying temperatures and KI doses [Contribution 9]. The results demonstrated that for the MnO_2-KI system, a zinc leaching degree of 89.78% was achieved after 3 h of leaching at 80 °C, and kinetic studies indicated that the leaching process is diffusion controlled (through the thin film), with an activation energy of 27.65 kJ mol^{-1}. Moreover, this system offers an improved method for separating iodine from the leachate upon completion, enhancing the overall process efficiency. It also opens up opportunities to test other primary oxidizing agents in combination with iodide salts. These findings suggest that the MnO_2-KI oxidation system offers a promising approach for improving zinc recovery from sphalerite concentrates.

With the growing demand for metals driven by technological advancements and population growth, recycling lithium-ion batteries has become vital for protecting the environment and recovering valuable materials [11]. Developing sustainable recycling technologies is now more essential than ever [12]. This paper focuses on using electrodialysis to process a leach solution of $LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$ (NMC 111) cathode materials leached with citric acid. This study demonstrates that the complexing properties of citrate anions contribute to the efficient separation of Li from Ni, Co, and Mn via electrodialysis [11]. This is achieved by promoting the formation of anionic species for Ni, Co, and Mn while maintaining Li in its cationic form. The leach solution was produced under the following optimal experimental conditions to reach a final pH of 5 and high leaching efficiency: a citric acid concentration of 1 mol L^{-1}, a leaching temperature of 45 °C, a leaching time of 5 h, a liquid/solid ratio of 100 g/L, and 8 vol.% H_2O_2. These conditions resulted in leaching efficiencies of 89.3% for Ni, 95.1% for Co, 77.1% for Mn, and 92.9% for Li. This solution led to the formation of a lithium-rich supernatant and a precipitate [Contribution 10]. The supernatant was then used as the feed solution for electrodialysis. Pure lithium was successfully separated with a faradic efficiency of 71.4% with a commercial cation-exchange membrane. This strategy enables selective lithium recovery while minimizing membrane fouling during the process.

3. Conclusions

Unit metallurgical operation processes are usually separated into three categories and are explained in detail in this paper. Advances in the understanding of different technologies in the extractive metallurgy of non-ferrous metals and iron and steel were studied in this work.

Conflicts of Interest: The author declares no conflicts of interest.

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