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THE ROLE OF ADDITIVE MANUFACTURING IN MINERAL AND METAL EXTRACTION

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ABSTRACT – Mineral and metal production has been increasing annually, driven by the growing demands of advancing industries and green technologies. To meet this demand sustainably, mineral and metal extraction and processing must adopt environmentally conscious innovations. Among key innovations impacting these processes, Additive Manufacturing (AM, commonly known as 3D printing), alongside artificial intelligence and big data analytics, has significantly impacted these processes by enhancing productivity, increasing profit margins, and reducing operating costs. An AM technology offers numerous advantages, including enhanced customization and the capability to produce tailored components that meet specific requirements. Since its groundbreaking development in the 1980s, AM has contributed substantially across a wide range of industries. Numerous reviews document the integration of this manufacturing technology in industrial applications, for example, in wastewater treatment, to enhance separation efficiency for oil, heavy metals, and other pollutants. In recent years, AM has entered the domain of mineral and metal production; however, its scale remains largely unquantified. This paper presents the applications of AM in mineral and metal extraction and explores the advantages of implementing additive manufacturing in separation processes.

Keywords: Mineral and Metal Extraction, Additive Manufacturing, Applications.

INTRODUCTION

Extractive metallurgy is a broad field that encompasses various raw materials and numerous separation techniques. It is generally divided into two main branches: mineral processing and metallurgy [1].

The primary objective of extractive separation methods is to process materials to obtain a metal concentrate in its purest possible form [2]. Mineral processing involves separating valuable minerals from the gangue within the ore and concentrating them, while metallurgy extracts metals from their compounds and purifies them through chemical reactions [3]. The advantage of mineral processing lies in its reliance on physical concentration methods [2] and involves several different stages: 1) size reduction with 2) size separation (classification), 3) separation (beneficiation), and 4) dewatering [1]. In

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contrast, metallurgical processes, which occur either in aqueous solutions or at high temperatures, can be classified into: pyro-, hydro-, biohydro-, and electrometallurgy.

The demand for mineral and metal production has been rising annually, driven by the needs of advancing industries and green technologies [4]. To meet this demand sustainably, the extraction industry must integrate environmentally conscious innovations [5]. One such innovation contributing to industry sustainability is additive manufacturing (AM, also known as 3D printing). AM enhances sustainability in four key areas: 1) product and process redesign, 2) material input processing, 3) make-to-order component, and 4) product manufacturing [6]. These advantages translate into several environmental benefits, including eco-friendly design, reduced overproduction, minimized material waste, lower energy consumption, enhanced material recycling, decreased tooling requirements, and a more sustainable supply chain [7].

The initial approach to fabricating a 3D object through computer-aided design (CAD), known as rapid prototyping, emerged in the 1980s to manufacture models and prototype parts. The primary benefit of AM lies in its capability to construct nearly any conceivable shape, facilitated by its layer-by-layer production method [8]. The American Society for Testing and Materials has developed a set of standards that divides the range of AM processes into seven broad categories: vat photopolymerization (VP), powder bed fusion (PBF), material extrusion (ME), material jetting (MJ), binder jetting (BJ), sheet lamination (SL), and directed energy deposition (DED) [9].

Since its groundbreaking development, AM has contributed substantially across a wide range of industries. Numerous studies document its integration into industrial applications, including wastewater treatment [10], analytical chemistry [11], and medicine [12]. More recently, AM has begun to enter the domain of mineral and metal production; however, its adoption on a large scale remains unquantified. This paper presents the applications of AM in mineral and metal extraction and explores its potential advantages in separation processes.

APPLICATION OF AM IN MINERAL AND METAL EXTRACTION PROCESSES

Additively manufactured devices and components are utilized in two key stages of mineral processing: classification and upgrading. This includes a range of printed devices such as classifiers and gravity spiral separators, as well as critical components like classifier modules, dissolved air flotation (DAF) system elements, flotation impellers, and magnetic filters. In metallurgy, AM devices and components are primarily applied in hydrometallurgical processes, including solvent extraction and solid-phase extraction, where they serve as reaction vessels or adsorptive mesh structures. The following sections below present a more detailed discussion of AM application in extractive metallurgy.

Additively manufactured devices

Design modifications of hydrocyclones due to material costs and manufacturing time are usually limited to final design scaled metal model tests, where traditional manufacturing methods are commonly used. However, AM has the potential to enhance research in hydrocyclone designing and testing. Tina et al. [13] explored the use of fused deposition modeling (FDM- sub-category of ME AM) to fabricate hydrocyclones. Their study demonstrated that manufacturing time for a traditional hydrocyclone prototype can be reduced from 12–26 weeks to just 2 weeks, while costs can be reduced by 2.5 to 25 times. Moreover, AM combined with computational simulations enables even more precise experimental validation, as demonstrated elsewhere [14, 15]. A strategy based on integrating computational fluid dynamics (CFD) modeling with AM, was applied to address the limitations of hydrocyclone design. This approach facilitated the manufacturing and testing of hydrocyclones with varied crucial design parameters, such as vortex finder and spigot diameters or different arc inlet designs and cone angles. Xu et al. [15] observed that the proposed innovative arc inlet introduced a pre-classification effect, minimizing the misplacement of fine (<5 µm) and coarse (>10 µm) particles, a feature absent in traditional inlets. The simulation data were proved by the experimental comparison of the classification of ultrafine MnO_2 particles using the novel 3D-printed hydrocyclone and the conventional one. The results showed that the 3D-printed hydrocyclone significantly outperformed the conventional design, achieving a notable increase in fine particle removal efficiency from 72% to 93%. A similar approach, combining CFD methods with AM, was applied to another centrifugal classifier for gas-solid separation [16]. A series of cyclones with elliptical bodies were designed and manufactured by stereolithography (SLA- sub-category for VP AM), experimentally demonstrating 2% improvement in separation efficiency reaching 97% and 43% reduction in pressure drop.

AM has also been suggested as a viable method to design and manufacture new classification devices. Sun et al. [17] fabricated a conical centrifugal particle separator for valuable mineral separation directly on the lunar surface, serving as an alternative to conventional heavy auxiliary equipment or fluidic separation systems. The separation trials used a mineral mixture containing quartz, barite, and calcite, categorized into three particle size fractions: fine (<180 µm), medium (180–300 µm), and coarse (300–500 µm). During fine particle separation, the system achieved peak fine particle concentration, experimental recovery, and theoretical recovery values of 74%, 54%, and 46%, respectively. Another new design, the closed spiral classifier, inspired by spiral concentrators, was fabricated using FDM 3D printing [18]. The device achieved the separation efficiency comparable to hydrocyclones and was tested on silica particles. The mean size of the outer outlet sample was close to 75 µm, which is three times the mean size of the inner outlet sample.

A different approach was demonstrated by Munasinghe and Paul [19], members of the research team responsible for developing a large-scale industrial 3D printer to print Gravity Separation Spirals (GSS). While traditional mold-based manufacturing is often uneconomical for customizing specific spiral profiles, the full-scale 3D printer can easily accommodate such adjustments. The designed printer is an extrusion-based machine equipped with two robotic arms and a centrally positioned rotating column. If successful, the proposed strategy will open up the possibility of manufacturing fully customized separation devices directly at the processing plant location.

In hydrometallurgical applications, AM was utilized to produce oscillatory baffled reactors for Co(II) and Ni(II) separation [20]. The device was fabricated using SLA and showed a productivity of 117 g Co^{2+}/day, notably 3–4 higher than most other studies handling the cobalt extraction using Cyanex 272. Moreover, manufactured reactors provided satisfactory mechanical and chemical performance, low production cost, and optical access to the reactor's interior.

Additively manufactured components

AM can also serve as an alternative manufacturing method for iterative testing and wearable spare parts. A notable example was presented by Carpenter et al. [21], who manufactured classifier modules mounted on a spinning centrifuge generating 55 G-force. Each module consisted of AM inclined channels, with Accura Extreme plastic used as the feed material. Similarly, Zhou and Shen [22] proposed a specialized design for 3D-printed outlets that enable the collection of up to 10 different products with a narrow particle size distribution during air classification.

AM has also contributed to beneficiation processes such as flotation and magnetic separation. Kouhestani et al. [23] tested innovative pressure-release nozzles fabricated using AM technology from polylactic acid (PLA), designed to generate microbubbles in DAF systems. These nozzles were evaluated both in laboratory settings and in a full-scale plant. Laboratory tests revealed that the nozzle geometry with a perpendicular surface after the nozzle perforation enhanced the formation of smaller bubbles and the number of generated small bubbles is primarily influenced by the saturator pressure. Similarly, Gradov et al. [40] examined an auto-aspirated sparger for DAF systems designed by Outotec Oy and additively manufactured from stainless steel. The tested sparger generated bubbles ranging from 190 to 2500 µm in water, which were evenly dispersed. Yang et al. [24] proposed 3D-printed fractal impellers to enhance fluid turbulence and generate micro-vortices. These conditions not only improved the dispersion of mineral particles but also facilitated better adsorption of collectors onto mineral surfaces. In the field of magnetic separation, Wei et al. [25] introduced AM magnetic architectures for the removal of heavy metal ions. Net-shaped structures were fabricated using a direct ink writing (DIW), the ME-based method, with NiO, ZnO, and Fe_2O_3 powders. The removal process was enhanced by polymer-coated Fe_3O_4 nanoparticles, which effectively adsorbed metal ions such as Pb(II), Ni(II), Cu(II), and Co(II). The system demonstrated high adsorption capacity, fast kinetics, and efficient nanoparticle capture (>90%) by manufactured magnetic architecture and recovery under a low magnetic field.

In hydrometallurgy, AM has been utilized to fabricate devices for solid-phase extraction for analytical purposes, and for metal ions recovery from secondary resources. A photocurable resin and the digital light processing (DLP- VP-based method) were used to create a solid-phase extraction (SPE) column for extracting metal ions (Mn, Co, Ni, Cu, Zn, Cd, and Pb) from high-salt samples while also removing the sample matrix prior to inductively coupled plasma mass spectrometry (ICP-MS) analysis [26]. For lithium recovery, Yu et al. [27] successfully fabricated a monolithic adsorbent containing 75% lithium-ion sieve from lithium titanate (Li_2TiO_3), montmorillonite, and SiO_2 using a DIW technique. Virtanen et al. [28] explored using selective laser sintering (SLS, the PBF subcategory)-manufactured nylon-12 filters with incorporated phosphonic acid groups for recovering rare earth elements (REEs) from simulated mining waste solutions.

Additionally, SLS-manufactured nylon-12-based scavengers were tested for Au(III) recovery from the printed circuit board waste and a synthetic multimetal leach solution [29]. Figure 1 provides an overview of various additively manufactured devices and components in extractive metallurgy.

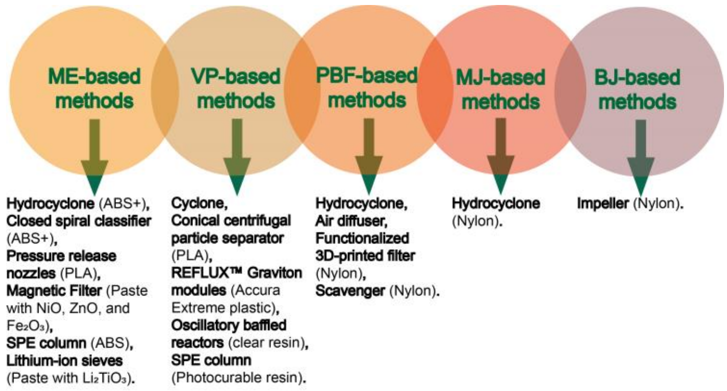

Figure 1 Additively manufactured devices and components utilized in extractive metallurgy, highlighting the applied methods and materials

CONCLUSIONS

AM applications in extractive metallurgy are expanding, offering benefits such as rapid prototyping, cost reduction, and customized designs across various processes, including classification, gravity concentration, flotation, magnetic separation, and hydrometallurgy. Integrating CFD simulations with AM enables design refinement before fabrication, directly contributing to cost savings. The geometric modifications of additively manufactured devices or components significantly impact separation efficiency and overall process performance. AM techniques such as ME, MJ, BJ, PBF, and VP have expanded the range of materials available for production, with polymers as first-choice material. The future potential of AM in mineral and metal extraction includes applications in space mining, multi-stage beneficiation, extraction from secondary resources, and enhanced fine particle separation.

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