



移动扫码阅读

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高炉冶炼粉尘湿法回收金属锌研究进展

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摘要: 高炉冶炼粉尘富含锌等有色金属, 具有较高的毒性, 其高效清洁回收利用兼具环境经济效益。湿法处理技术因其操作灵活、选择性高及能耗低, 成为锌回收领域的研究热点。系统梳理了酸法、碱法和氨法浸出体系的技术特点与研究进展。酸法浸出中锌浸出率可达 80%~95%, 但 Fe^{3+} 、 Al^{3+} 等杂质共溶导致后续净化成本高。碱法浸出对锌氧化物选择性好, 但对铁酸锌等稳定相的浸出率低, 且存在设备腐蚀问题。氨法浸出通过锌氨络合物实现高选择性, 浸出率达 85%~92%, 同时杂质元素如 Fe、Al 溶出率均小于 5%, 但氨挥发损失与再生难题限制其应用。近年来, 物理场强化技术通过调控反应动力学显著提升了锌的浸出效率。此外, 多段逆流浸出与离子液体萃取等创新工艺的耦合应用, 进一步实现了锌的高纯回收。然而, 粉尘中锌赋存形态(如铁酸锌、硅酸锌)的复杂性仍制约其浸出效率。未来研究需结合矿物相重构与绿色浸出剂设计, 闭路循环工艺, 推动湿法技术向高效、低碳和经济化方向升级, 助力冶金固废资源化的可持续发展。

关键词: 高炉粉尘; 金属锌; 湿法; 资源回收; 浸出工艺

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Research Progress on Wet Recovery of Zinc Metal from Blast Furnace Smelting Dust

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Abstract: As an important secondary resource of the iron and steel industry, blast furnace smelting dust is rich in valuable metals such as zinc and also contains potentially toxic elements. Its efficient and clean recycling is economically valuable and contributes to environmental protection. Hydrometallurgy has become a research hotspot in the field of dust recycling due to its operational flexibility, high selectivity, low energy consumption, and environmental compatibility. This paper reviews the research progress in zinc leaching technology, systematically analyzes the process characteristics and main bottlenecks of acid, alkaline, and ammonia leaching methods, discusses the innovative approaches such

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as physical field enhancement and process coupling, and anticipates future directions for technology development. The results show that the efficiency of acid leaching of zinc can reach 80% – 95%, but it has poor adaptability to highly alkaline and silica-alumina-rich materials, and is often accompanied by the co-solubilization of impurities such as Fe^{3+} and Al^{3+} , which increase the difficulty of subsequent purification. The alkali method exhibits excellent selectivity for zinc oxide. However, its leaching rate stability is system-dependent, and its capacity for amphoteric metals is limited. Additionally, equipment corrosion remains a challenge. The ammonia method achieves high selectivity through the formation of zinc-ammonia complexes, with a leaching rate of 85% – 92%, and the dissolution rate of impurity elements such as Fe and Al is below 5%. However, challenges related to ammonia evaporation loss and the complexity of its recycling and reuse limit its application prospects. In recent years, physical field enhancement technologies (e.g., ultrasonic, microwave, and electric fields) have effectively improved zinc leaching efficiency by modulating reaction kinetics and optimizing mineral phase transformations. For example, ultrasonic cavitation enhances interfacial mass transfer through mechanical vibration and cavitation effects, significantly shortening the reaction time. The magnetic field promotes the transformation of ferromagnetic mineral phases, enhancing the selective release of valuable metals. The electric field guides electron migration, enabling the preferential dissolution of specific metals. In addition, the combined use of innovative processes such as multi-stage countercurrent leaching and ionic liquid extraction has enhanced both the recovery rate and purity of zinc. However, technical challenges remain, such as the complex chemical speciation of zinc in dust (e.g., iron zincate, zinc silicate) and the need for optimizing system energy efficiency. In the future, efforts should integrate the design of mineral phase reconstruction with the development of green leaching agents. A closed-loop recycling process should be established, along with the construction of a multi-technology synergy and intelligent control system. These efforts aim to achieve high efficiency, low carbon emissions, and economic upgrading of hydrometallurgy, while promoting the resource utilization and sustainable development of metallurgical solid waste. Ultimately, this will help achieve the synergistic goals of minimization, resource recovery, and harmlessness.

Keywords: Blast furnace smelting dust; Zinc metal; Wet process; Resource recovery; Leaching process

0 引言

高炉冶炼粉尘是钢铁工业中产生的大宗危险固体废物,富含锌(以 ZnO 、铁酸锌等形式存在)、铁、碳等有价值组分,同时伴生铅、镉等重金属污染物,具有资源属性与环境风险双重特征。随着全球锌资源短缺加剧和环保法规日趋严格,开发高效清洁的高炉冶炼粉尘资源化技术已成为研究热点,这对环境保护和金属资源循环利用具有重要意义。

目前国内外对含锌高炉粉尘的处理方法主要包括返回烧结法^[1]、选冶分离利用法^[2]、固化稳定化技术^[3]、火法处理技术^[4]和湿法处理法^[4-5]等。返回烧结法通过配料回用实现铁碳回收,但存在锌、铅等重金属循环富集、设备堵塞等问题。选

冶分离利用法通过磁选、重选等技术回收高炉粉尘中的赤铁矿和磁铁矿,并通过浮选法回收碳资源,但无法有效分离和回收粉尘中的有色金属(如锌、铅等)及有害重金属组分,难以实现粉尘的全面资源化利用。固化稳定化技术通过高温烧结或水泥固化实现无害化,但无法体现高炉粉尘的资源特性,仅实现了废弃物的稳定化处理。火法处理法是目前高炉粉尘资源化利用的主要技术之一,通过高温还原将粉尘中的含锌物相转化为易挥发的单质锌或锌化合物随烟气排出,铁则被还原为低价铁或金属铁留在焙烧渣中,从而实现铁与有色金属的分离与富集^[6],但存在能耗高和二次污染等缺点^[7-8]。

湿法处理技术以选择性高、能耗低、产品纯

度高、活性大等优势成为锌回收的研究热点。该技术利用金属氧化物易溶于酸、碱等溶液的性质,采用酸浸或碱浸方式,浸提高炉瓦斯灰中的锌等有价金属组分,并结合萃取、电解等步骤实现锌的高效提取^[9]。因此,工业上一般对含锌固废进行湿法处理。按浸出剂不同,通常分为酸法、碱法、氨法(图 1)^[10-11]。酸法浸出锌回收率可达 80%~95%,但 Fe^{3+} 、 Al^{3+} 等杂质共溶增加了后续净化难度^[12];碱法浸出对锌氧化物选择性好,但对铁酸锌浸出率低^[13];氨法浸出通过络合反应($[\text{Zn}(\text{NH}_3)_4]^{2+}$)实现高选择性,却面临氨挥发与再生难题^[14]。近年来,外场强化技术(超声、微波、电场)通过加速反应动力学与优化矿物相转化,显著提升了锌浸出效率并降低了试剂消耗^[15-17]。此外,多段逆流浸出、离子液体萃取等工艺创新进一步推动了湿法工艺的绿色化与集成化发展^[18-19]。

本文系统综述湿法回收高炉冶炼粉尘中金属锌的研究进展,重点分析酸、碱、氨浸体系,探讨外场强化技术的协同作用,并展望矿物相重构、绿色浸出剂的开发及闭路循环工艺的未来方向,以期高炉冶炼粉尘的高效低碳资源化提供理论支撑与技术参考。

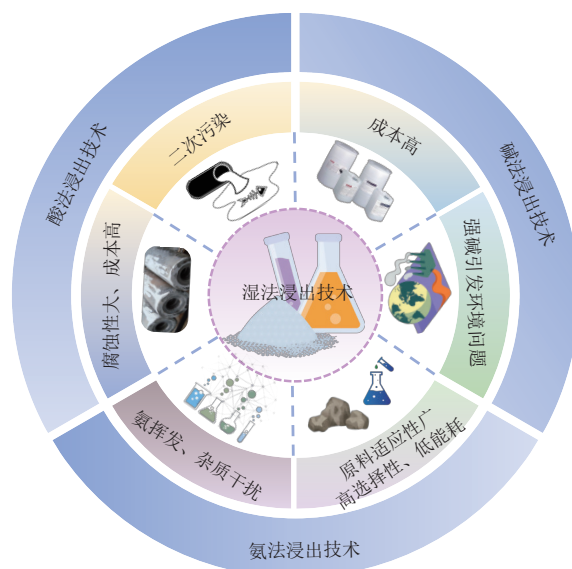


图 1 金属浸出的湿法技术

Fig. 1 Wet technology for metal leaching

1 酸法浸出

酸法浸出技术作为一种高效、经济的金属回收方法,近年来在二次资源利用领域取得了显著进展。按照浸出剂主要分为无机酸和有机酸 2 种浸出方法^[20]。典型酸法浸出技术路线如图 2 所

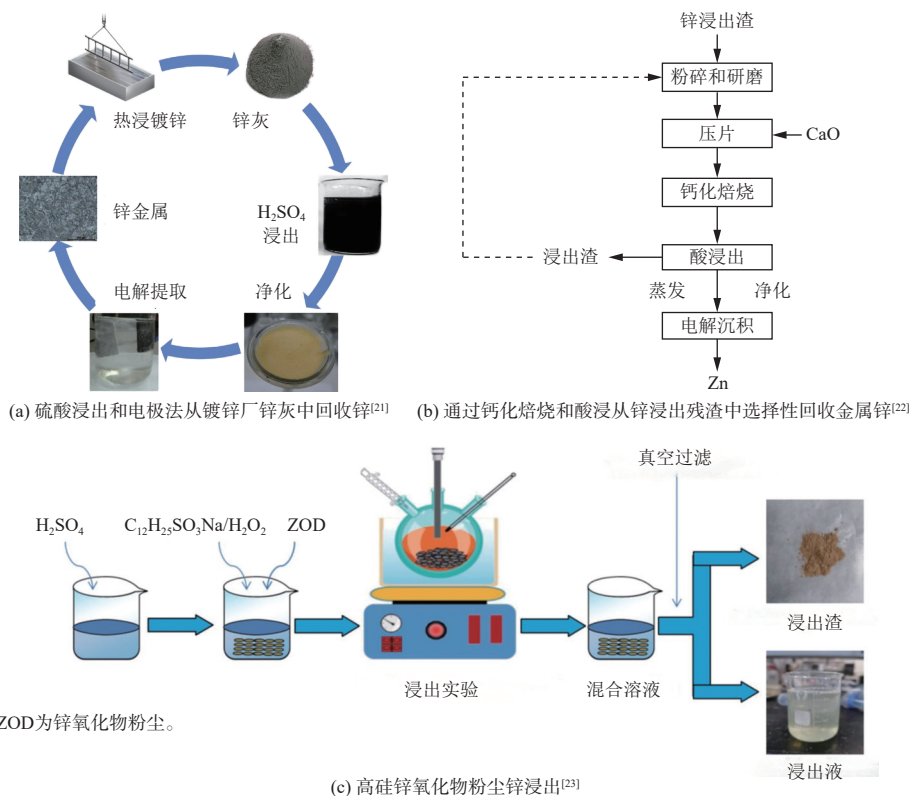


图 2 典型酸法浸出工艺技术路线图

Fig. 2 Typical acid leaching process technology route

示。无机酸体系凭借其强氧化性和成本优势,在工业应用中占据主导地位,而有机酸体系则因其环境友好性和选择性成为新兴研究方向^[24]。

1.1 无机酸体系

硫酸体系因其经济性和工艺成熟成为氧化锌浸出的首选方案,典型无机酸浸出体系特征见表1。我国研究人员为了实现次氧化锌粉尘中金属元素的回收,通过调节浸出剂浓度、温度、浸出时间等参数,实现金属元素浸出,以获得高品质的锌、铅等产品^[25]。为了提高锌的浸出率,高压酸浸技术受到较大的重视并投入实际应用,锌浸出率达到98%以上^[26]。RUDNIK等^[21]研究了固液比和硫酸浓度(20%和25%)对锌和金属杂质溶解的影响。研究发现在20% H₂SO₄中,固液比为150~

200 kg/m³的锌回收率为95%~97%,但溶液主要被Mn(Ⅱ)和Fe(Ⅱ,Ⅲ)离子污染。盐酸体系在锌浸出动力学方面展现出独特优势。研究发现,HCl在20℃、固液比为1:20条件下,可在30 min内实现锌的几乎完全浸出,特别适用于高氯含量(6%~25%)粉尘处理,通过电解沉积可直接获得金属锌,实现Cl⁻闭路循环^[27]。然而Cl⁻对设备的点蚀效应仍是工业化应用的重大挑战。相关研究发现,在常温下采用10.65 mol/dm³硝酸浸出含铜、锌硫化矿的中间产品,锌浸出率可达99.0%^[28]。相关研究发现磷酸虽能高效浸出高炉粉尘中的锌,但在电沉积过程中也会浸出Fe并腐蚀阴极,从而限制了金属锌的最终回收,限制了其在钢铁厂的应用^[29]。

表1 典型无机酸浸出体系特征比较

Table 1 Comparison of characteristics of typical inorganic acid leaching systems

方法	优点	缺点	适用类型
硫酸(H ₂ SO ₄)	成本低,易获取;腐蚀性较低,设备要求适中;反应选择性较好;适用于大规模工业应用	反应速度较慢;对某些复杂矿物(如硫化锌)需氧化剂辅助;高温下存在酸雾问题	氧化锌矿(如菱锌矿、红锌矿);焙烧后的硫化锌矿
盐酸(HCl)	反应速率快;溶解能力强,适用于高品位矿;无需氧化剂即可溶解硫化锌	强腐蚀性,设备需耐氯离子腐蚀;易挥发,产生Cl ₂ 气体(需尾气处理);难去除后续溶液中Cl ⁻ ,可能影响电解	硫化锌矿;含锌二次资源(如锌灰、锌渣)
硝酸(HNO ₃)	强氧化性,可直接溶解硫化锌;浸出效率高;副产物可回收(如硫磺)	成本高;产生NO _x 气体(需严格环保措施);对设备腐蚀性强;可能引入硝酸盐污染	难处理硫化锌矿、含杂质较多的锌原料
混合酸(如H ₂ SO ₄ +HCl、H ₂ SO ₄ +HNO ₃)	协同作用提高浸出率;减少单一酸用量,降低成本;适应复杂矿物组成	反应条件控制复杂;混合酸回收困难;可能产生多种副产物	多金属共生矿、低品位复杂锌矿

1.2 有机酸体系

研究发现有机酸对去除固体废物中重金属有一定的效果,证明了其对重金属具有络合能力,能够形成稳定的金属配合物,从而易于去除固体废物基质中的重金属^[30]。有机酸因环境友好性和选择性受到越来越多的关注,特别是在去除电子废弃物中重金属的效果较好,浸出率可达90%以上^[31]。相关研究表明,丁酸可选择性地浸出碱性氧气炼钢(BOS)粉尘中的锌(49.7%)并仅溶解2.5%的铁,酸耗仅为化学计量的70%,具有较好的工业应用前景^[32]。

1.3 外场强化技术在酸性浸出体系中的协同作用

通过优化浸出条件,如改变温度^[33]、添加氧化剂^[34]、超声波辅助^[35]、微波^[36]等,可进一步提高酸法浸出效率(图3)。LI等^[37]在复合矿石硫酸介质中添加双氧水浸出重金属,Mn提取率为95.88%,Zn提取率为99.23%,表明添加氧化剂可显著提高

难溶矿物的浸出率。XIN等^[38]超声波辅助浸出不仅可以破坏矿物的晶体结构,降低矿物的结晶度,还可以破坏矿物,打开矿物包裹体,进一步提升浸出效率。DANG等^[39]提出了一种超声增强H₂SO₄溶液浸出低品位氧化锌的新技术,最佳条件下超声强化浸出的浸出率为95.45%,比传统浸出工艺高3.61%。LANNOO等^[40]发现与常规浸出法相比,微波辅助浸出显著减少了反应时间,同时保持了金属的高浸出性能。MA等^[41]发现微波加热具有选择性加热特性,可缩短处理温度,并通过矿物间热应力差异诱导裂纹生成,增加反应界面面积,从而提升锌浸出效率。

酸法浸出仍面临诸多挑战。强酸性环境可能导致二次污染问题,如酸性废水和有害气体的产生。对于多金属共存的复杂物料,在酸浸过程中杂质Pb、Cd、Al、Mn、Fe、As、Sn、Ni等金属也会进入液相,导致后续净化和除污过程复杂,回收率

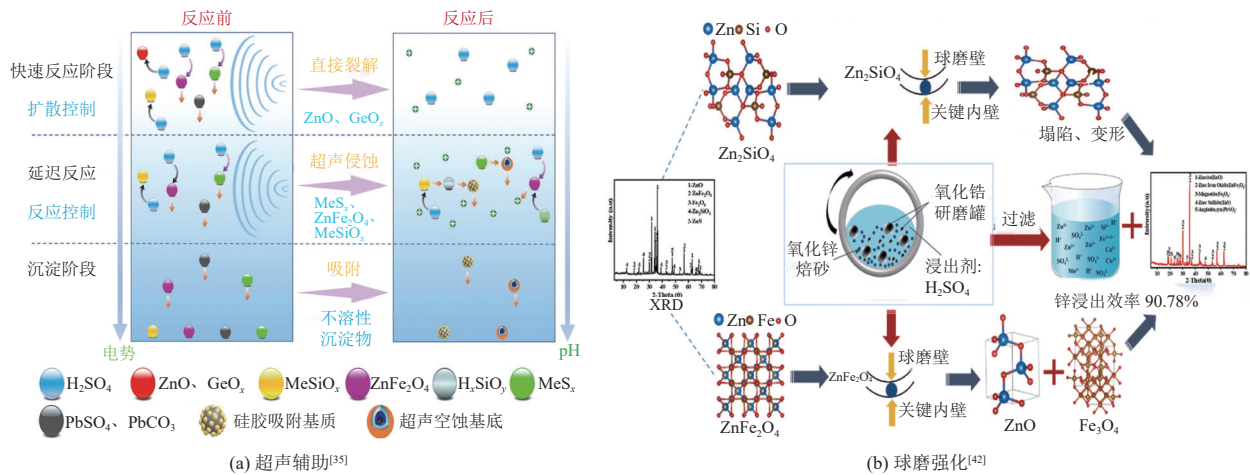


图 3 不同外场强化技术对酸法浸出金属锌性能的影响机理图

Fig. 3 Mechanism diagrams of the effects of different physical strengthening techniques on the performance of acid leaching of zinc metal

降低。此外酸法浸出还存在腐蚀性大、成本高难以避免的缺点。

2 碱法浸出

碱法浸出工艺作为湿法冶金领域的重要技术手段,在固废重金属污染治理中具有独特优势,表 2 综述了不同碱性浸出剂浸出特性。

2.1 氢氧化钠体系

该工艺主要以氢氧化钠等碱性溶液为浸出剂(图 4),通过固-液两相间的化学反应,使废料中的重金属组分转化为水溶性金属羟基配合物(如 $\text{Zn}(\text{OH})_4^{2-}$ 、 $\text{Pb}(\text{OH})_3^-$ 等),实现重金属的选择性分离^[43]。AL MAKHADMEH 等^[44]发现使用 6 mol NaOH 在 20 g/L 的固体负载量和 3 h 浸出时间下,锌的最大回收率达到 92.9%。研究发现增加浸出剂浓度或者提高温度可大大提高锌的浸出效率^[45]。电炉粉尘中锌铁氧体(ZnFe_2O_4)的存在导

致锌的回收率低,并且可能引起高能耗或铁资源浪费。ZHANG 等^[46]提出了一种在 NaOH 体系中进行水热还原的方法,选择性地从电炉粉尘中回收锌。研究发现,在最佳条件下锌的总浸出效率为 89.7%,同时产生富含 Fe(最高质量分数 39.4%)的浸出残渣。

2.2 外场强化技术在碱性浸出体系中的协同作用

为突破传统工艺的传质限制,近年来涌现出多项工艺强化技术。微波辅助浸出通过介电加热效应可使反应活化能降低 30%~40%,显著改善矿物种格结构的破坏效率^[47]、超声波空化作用产生的微射流可将固液的接触面积提升 2~3 个数量级,特别适用于致密包裹型矿物的处理^[15]。氧化剂(如 H_2O_2 、 O_3)的引入可将金属硫化物等难溶物相转化为更易反应的氧化物形态,使锌的浸出率从 52% 提升至 89%^[48]。

值得注意的是,碱性浸出技术在低品位金属

表 2 不同碱性浸出体系特征比较

Table 2 Comparison of the characteristics of different alkaline leaching systems

碱体系	优点	缺点	适用类型
氢氧化钠 (NaOH)体系	强碱性,可溶解锌的氧化物、硅酸盐及部分难溶化合物;反应条件温和,无挥发性有毒气体;对设备腐蚀性较低(需耐碱材料);适合处理高硅或含碳酸盐的锌矿	对硫化锌矿浸出效率低,需预氧化处理;高浓度碱液成本较高;杂质(如硅、铝)可能共溶,需后续净化;反应速率较慢,浸出时间长	高硅锌矿、锌工业废渣(如炼钢烟尘、镀锌废料)、含碳酸盐矿物
碳酸钠 (Na_2CO_3)体系	弱碱性,腐蚀性低;适用于含碳酸盐或氧化锌的矿物;可结合氧化剂(如 O_2 、 H_2O_2)提高效率	浸出效率低,仅适用于特定矿物;需高温高压条件;产生副产物(如碳酸盐沉淀)	低品位氧化锌矿、含锌碳酸盐矿物(如菱锌矿)
混合碱体系(如 $\text{NaOH}+\text{Na}_2\text{CO}_3$)	协同提高锌浸出率;降低单一碱用量;适应复杂矿物组成(如硅酸盐与氧化物共存)	反应条件控制复杂;碱回收困难;可能引入多种副产物(如硅酸钠)	多金属共生矿、含硅酸盐的锌矿

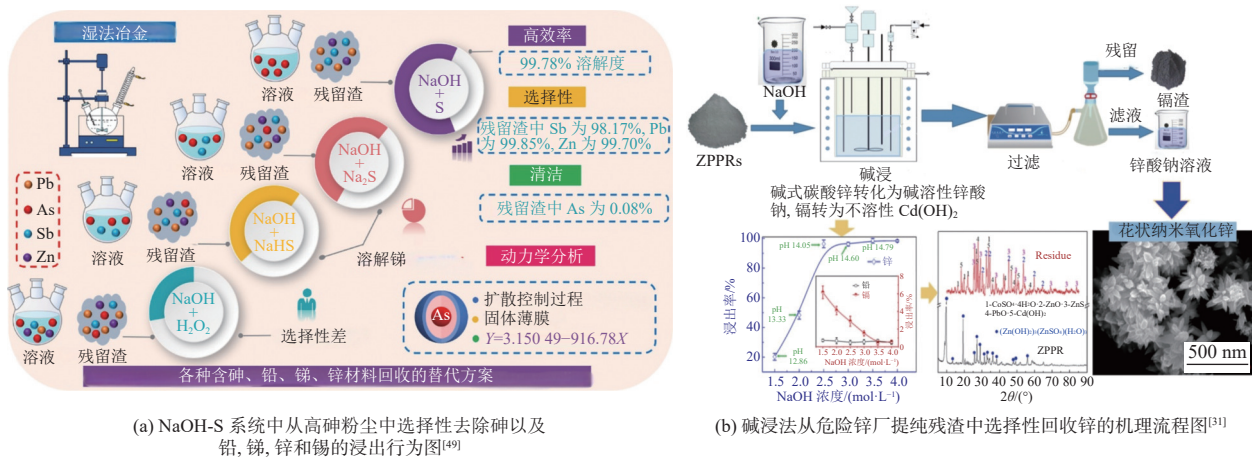


图 4 碱法浸出金属锌的机理图

Fig. 4 Mechanism diagrams of alkaline leaching of zinc meta

氧化物矿的处理中表现出显著优势。以低锌矿渣为例,其含有的 CaO 、 Al_2O_3 等碱性成分会与酸性浸出剂发生剧烈反应,导致酸的无效消耗达 40%~60%,而碱性体系则可选择性浸出目标金属,对 Pb 、 Cd 等重金属的选择性系数可达 5~8 倍^[50]。相较于酸性浸出,碱性工艺具有多重优势,如设备腐蚀速率降低,显著延长反应器使用寿命,选择性分离特性使 Fe 、 Cu 、 Ca 等杂质元素的共溶解率控制在 5% 以下,避免 H^+ 对矿物晶格的过度破坏,有利于后续浸出渣的资源化利用。然而,碱法浸出仍存在明显局限性。首先,处理低锌矿渣的药剂成本较高;其次,浸出渣中残留的强碱性物质易引发土壤盐碱化等次生环境问题;最后,对硅酸盐包裹型金属氧化物的浸出效率普遍低于 35%,需结合机械活化等预处理手段方可可提升到工业应用

水平^[51]。

3 氨法浸出

氨法浸出技术因其广泛的原料适应性,在复杂含锌物料的处理中展现出显著优势,尤其适用于高碱性矿石、高碳酸盐矿物及高铁高铝硅基质的处理。该技术不仅能有效处理低品位氧化锌矿,还可高效回收含锌粉尘、工业含锌废物和冶炼渣等二次资源。据浸出剂体系差异,氨法浸出主要分为 4 类:氨-氯化铵法、氨-碳酸铵法、氨-碳酸氢铵法和氨-硫酸铵法(表 3)。JIA 等^[12, 52]通过配位化学机理研究揭示了锌的选择性浸出机制,证实锌离子可与氨分子配位形成稳定的 $[\text{Zn}(\text{NH}_3)_n]^{2+}$ ($n=1, 2, 3, 4$) 强氨络合物,从而达到选择性浸出锌的效果(图 5)。

表 3 不同氨法浸出体系特征比较

Table 3 Comparison of the characteristics of different ammonia leaching systems

方法	优点	缺点	使用类型	典型浸出条件
氨-氯化铵法	浸出效率高(Cl^- 促进硫化锌快速溶解); 适合高硫环境; 试剂可循环利用	强腐蚀性(需耐氯设备); 含氯废水处理复杂	含硫化锌固废及矿石; 含碱性脉石的锌矿	高温(60~90 ℃), 高氨浓度(5~8 mol/L)
氨-碳酸铵法	腐蚀性低; 适合氧化锌矿; 反应温和, pH 易控制	浸出速度慢; 试剂易分解	含氧化锌固废及矿石; 低硫矿石	常温 50 ℃, pH 9~10
氨-碳酸氢铵法	成本低, 环保性好; 适合含钙镁的复杂矿; 副产物可回收	溶解度低; 反应速率低; 稳定性差	复杂氧化锌固废及矿石	低温(<40 ℃), 低氨浓度(2~4 mol/L)
氨-硫酸铵法	稳定性高, 适合连续生产; 可回收硫酸锌副产品; 腐蚀性中等	易生成硫酸钙沉淀, 干扰浸出; 硫酸盐废水处理成本高	含硫酸盐型的含锌固废及矿石; 含硫化物混合矿	中温(50~70 ℃), pH 8~9

3.1 氨-氯化铵体系

氨-氯化铵法采用高浓度氯化铵溶液实现硫化矿氧化浸出。该体系在中性条件下通过生成锌

氨络合物选择性地溶解锌, 同时将 Fe 、 Pb 、 As 等杂质稳定固相化, 获得高纯度浸出液^[53]。王瑞祥等^[54]成功构建了 $\text{NH}_3\text{-NH}_4\text{Cl-H}_2\text{O}$ 体系实现电解

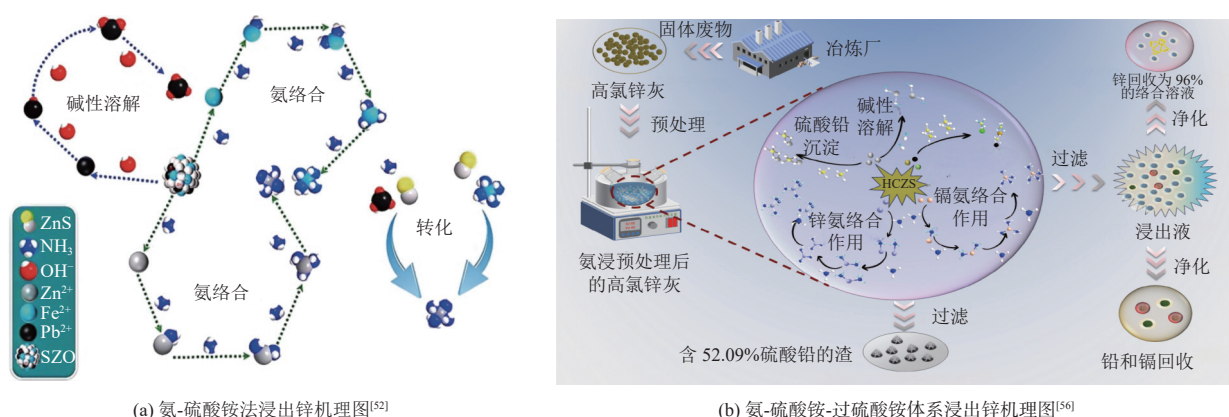


图 5 不同氨法工艺锌浸出的机理流程图

Fig. 5 Mechanistic diagrams of zinc leaching by different ammonia processes

锌的高效制备。马爱元等^[55]研究了 $\text{NH}_3\text{-NH}_4\text{Cl-H}_2\text{O}$ 体系从高炉瓦斯灰中浸出锌, 在最佳实验条件下, 锌的浸出率达 76.71%。YANG 等^[57]系统地研究了 ZnO 在该体系中的溶解行为, 经工艺优化实验验证, 搅拌速率为 200 r/min, 氨水和氯化铵浓度分别为 2.5 mol/L 和 5.0 mol/L, 反应温度为 40 °C, 液固比为 6 : 1 时, 30 min 内锌的浸出率可达 81% 以上。然而, 该方法存在浸出效率偏低、设备防腐要求严苛、能耗较高及浸出剂再生困难等技术瓶颈, 制约其工业化应用。

3.2 氨-碳酸铵/碳酸氢铵体系

基于浸出剂易再生的特点, 碳酸铵/碳酸氢铵体系在氧化锌矿处理中展现出良好应用前景^[58]。罗兴国等^[59]针对高炉瓦斯灰的锌提取难题, 通过热力学计算与配位化学分析验证了锌氨配位浸出的可行性, 优化后锌浸出率达 91%。DAI 等^[60]提出了氨水与碳酸铵协同浸出的方法, 有效解决伊萨炉尘浸锌过程中存在的锌浸出效率低的问题。氨-碳酸铵法具有较高的锌浸出效率和铁的高选择性, RODRIGUEZ 等^[51]将该体系应用于碱性氧化炉污泥处理, 通过参数优化使锌浸出率提升至 95%, 但需满足加压条件且产品品质不稳定。

3.3 氨-硫酸铵体系

唐漠堂^[61]团队在 $\text{Zn(II)-(NH}_4)_2\text{SO}_4\text{-H}_2\text{O}$ 体系研究中取得突破, 系统阐明了锌氨络合平衡规律, 并创新提出复盐结晶法处理高氟氯含锌烟尘工艺, 实现锌渣计浸出率为 85.16%。TANG 等^[62]以 $\text{Zn(II)-(NH}_4)_2\text{SO}_4\text{-H}_2\text{O}$ 溶液为研究对象, 构建 β -二酮复合萃取体系, 实现锌铜的高效分离回收。唐福利等^[63]研究 Mextral54-100(HA) 和 Mextral54-100+TRPO(HA+TRPO) 2 种萃取体系从氨-硫酸铵

溶液中萃取分离锌镉的性能, 确定锌、镉分离的最佳工艺。XUE 等^[12]通过用氨-硫酸铵系统浸提并创新引入空气氧化剂, 实现废金刚切割中铜锌协同回收。YANG 团队^[64]提出了一种以氨-硫酸铵为浸出剂, 同时加入少量柠檬酸钠来增强络合行为的低品位多相氧化锌矿浸出新体系, 锌浸出率提升至 96.91%, 其机理在于调控锌氨络合物配位形态。PINHO 等^[65]研究发现 H_2O_2 和 O_2 是最有效的氧化剂, 过量的氧化剂和氨气可实现 90% 的金属回收率。针对高氯锌渣处理难题, YANG 等^[56]利用氨-硫酸铵-过硫酸铵体系选择性高效回收锌, 过硫酸铵的引入使锌的回收率突破 96%。相较于传统氨法, 氨-硫酸铵体系在原料适应性、产品质量稳定性、设备腐蚀性和生产成本等方面具有显著优势, 有效克服了其他氨法推广的技术障碍。

3.4 外场强化技术在氨法浸出体系中的协同作用

研究者对氨法和物理方法协同浸出锌体系进行了相应研究。XIE 等^[66]提出磁化焙烧结合氨浸的协同工艺来浸出锌, 在最优条件下浸出率为 78.12%。LUO 等^[67]提出在氨浸体系中通过 CO_2 调节 pH, 使锌氨络合物转化为 Zn^{2+} , 结合溶剂萃取(如 TRPO)和蒸馏技术可高效回收锌。XIE 等^[68]通过钙焙烧重构锌铁矿物相, 结合氨浸法实现了锌铁高效分离, 在 60% CaO 配比、125 °C 焙烧条件下, 粉尘中锌铁酸锌完全转化为氧化锌, 氨浸锌回收率达 86.12%。HU 等^[69]发现氨浸过程中锌的溶解受扩散控制, 浸出效率与 NH_3 浓度呈正相关, 高温(>50 °C)可显著缩短反应时间。

氨法浸出利用氨水或铵盐选择性溶解锌氧化物, 生成可溶性锌氨络合物, 同时抑制铁、铅等杂

质金属的浸出,实现锌的高效分离。该技术具有高选择性、低能耗、环境友好等优势,适用于低品位及成分复杂的废渣。然而,氨挥发损失、高硅或有机物导致的胶体问题、残渣重金属残留及试剂成本较高等问题仍需优化。未来需通过工艺优化与设备升级,解决氨挥发与杂质干扰问题,进一步提升经济性和工业化应用潜力。

4 总结与展望

含锌高炉粉尘的资源化利用是钢铁工业实现绿色转型的关键环节,而湿法处理技术凭借其高选择性和温和反应条件成为研究焦点。本文总结了湿法浸出锌技术的研究进展,重点分析了酸法、碱法及氨法和外场强化技术发展趋势,为未来湿法工艺浸出金属的设计和冶炼粉尘资源化转化提供了参考,为后续研究方向和决策提供了一定建议。

(1)酸法虽浸出效率高,但对高碱性、高硅铝物料的适应性差,且存在杂质共溶与设备腐蚀问题;碱法在特定体系中稳定性优异,但对两性金属的选择性提取能力不足;氨法通过 $[\text{Zn}(\text{NH}_3)_n]^{2+}$ 等络合物的定向构建,实现了锌的高效选择性提取,并在杂质截留与设备兼容性方面展现出显著优势,但其浸出剂循环效率与工艺稳定性仍需优化。

(2)外场强化技术的引入为湿法回收重金属提供了新思路。超声空化通过机械振动与空化效应强化界面传质,显著缩短了浸出时间;磁场通过诱导铁磁性矿物相变以提升贵金属浸出选择性;电场则通过定向电子迁移驱动特定金属的优先溶出。通过构建“物理场-化学场”双驱动体系,可突破传统湿法回收技术的动力学限制,实现了金属回收路径的精准调控。

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