

Application of synergistic system of nitrogenous heterocyclic compounds and organic acids in extraction and separation of nickel and cobalt

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Abstract: In recent years, synergistic systems of various nitrogenous heterocyclic compounds and organic acid extractants have been developed, which have significantly improved the extraction performance of nickel and cobalt, and enhanced the separation effectiveness from impurities. These synergistic systems have great potential in practical applications. These kinds of synergistic extraction systems consisting of some typical nitrogenous heterocyclic compounds and organic acid extractants were reviewed in this work. The synergistic effect for nickel and cobalt extraction and the separation of commonly co-existed impurities were discussed. The possible practical applications of the synergistic extraction systems were also discussed. The extraction of nickel and cobalt and the separation of impurity elements were mainly determined by the properties of acid extractants and the effects of nitrogenous heterocyclic synergists. The synergistic extraction system consisting of organic sulfonic acid, carboxylic acid, phosphonic acid and nitrogenous heterocyclic compounds showed different selectivity for the separation of metal impurities. In the production process of nickel and cobalt, they also showed different application value.

Key learning points:

- (1) The synergistic extraction system consisted of nitrogenous heterocyclic compounds and organic sulfonic acid extractants can selectively extract nickel and cobalt and separate iron and aluminium.
- (2) The synergistic extraction system composed of nitrogenous heterocyclic compounds and carboxylic acid extractants can selectively extract nickel and cobalt and separate calcium, magnesium and manganese.
- (3) The synergistic extraction system composed of nitrogenous heterocyclic compounds and organic phosphoric acid extractants can selectively extract nickel, cobalt and manganese, and separate calcium and magnesium.

Key words: nitrogenous heterocyclic compound; synergistic extraction; nickel; cobalt

收稿: 2019-07-23, 修回: 2019-08-28, 网络发表: 2019-10-08, Received: 2019-07-23, Revised: 2019-08-28, Published online: 2019-10-08
基金项目: 国家自然科学基金资助项目(编号: 51774260); 中国科学院前沿科学重点研究项目(编号: QYZDJ-SSW-JSC021)
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引用格式: 刘文森, 雷泽, 朱兆武, 等. 含氮杂环化合物与有机酸协同体系在镍、钴萃取分离中的应用. 过程工程学报, 2020, 20(4): 382-389.
Liu W S, Lei Z, Zhu Z W, et al. Application of synergistic system of nitrogenous heterocyclic compounds and organic acids in extraction and separation of nickel and cobalt (in Chinese). Chin. J. Process Eng., 2020, 20(4): 382-389, DOI: 10.12034/j.issn.1009-606X.219266.

含氮杂环化合物与有机酸协同体系在镍、钴萃取分离中的应用

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摘要:近年来开发了多种含氮杂环化合物与有机酸类萃取剂的协同体系,明显提高了镍、钴的萃取性能,同时增强了对杂质元素的分离效果,具有较大的实际应用价值。本工作综述了一些具有代表性的含氮杂环化合物与有机酸类萃取剂组成的协同萃取体系,探讨了萃取体系对镍、钴的协同萃取效果及与常见杂质元素的分离,并讨论了协同萃取体系潜在的工业应用。协同体系对镍、钴的萃取及对杂质元素的分离主要是由酸性萃取剂本身性质和含氮杂环协萃剂的影响共同决定,有机磺酸、羧酸、膦酸等萃取剂与含氮杂环化合物组成的协同萃取体系在萃取镍、钴的过程中对金属杂质元素分离的选择性不同,在镍、钴的提取及生产过程中也展现出不同的应用价值。

要 点:

- (1) 含氮杂环化合物与有机磺酸类萃取剂组成的协同萃取体系能选择性萃取镍和钴,分离铁和铝。
- (2) 含氮杂环化合物与有机羧酸类萃取剂组成的协同萃取体系能选择性萃取镍和钴,分离钙、镁和锰。
- (3) 含氮杂环化合物与有机膦酸类萃取剂组成的协同萃取体系能选择性萃取镍、钴、锰,分离钙和镁。

关键词:含氮杂环化合物;协同萃取;镍;钴

中图分类号:TF804.2

文献标识码:A

文章编号:1009-606X(2020)04-0382-08

1 前言

镍和钴是支持国民经济发展的的重要有色金属,在不锈钢、合金、航空航天、能源、电子等领域应用十分广泛。镍钴伴生资源主要有硫化镍矿(39.4%)和红土镍矿(60.6%)^[1]。近年来,高品位硫化镍矿开采量大,逐渐趋近枯竭,低品位红土镍矿将成为镍和钴的主要来源,其冶炼分火法工艺和湿法工艺^[2-5],前者直接在高温还原条件下生产镍铁,用于不锈钢的生产;后者针对红土镍矿原料来源及组成变化常采用不同的工艺提取镍和钴。

溶剂萃取技术是湿法工艺提取分离镍、钴的主要手段,具有选择性高、流程简单、连续性强和工业设计简单等优点。硫酸体系中萃取分离镍、钴广泛应用的萃取剂主要有酸性膦类萃取剂,如P204[二(2-乙基己基)磷酸酯]、P507(2-乙基己基磷酸单2-乙基己基酯)和Cyanex272[二(2,4,4-三甲基戊基)次膦酸]等,羧酸类萃取剂,如Versatic10(2-甲基-2-乙基庚酸)、环烷酸等^[6-8]。尽管这些萃取剂基本上满足了工业生产需要,但现有萃取体系还存在较大局限性:红土镍矿常压浸出所得浸液含大量铁和铝,传统沉淀除铁、铝的方法会造成大量镍、钴等有价值金属损失,溶剂萃取直接提取镍和钴具有较大优越性,但还不能实现镍、钴和大量铁、铝的分离;红

土镍矿高压浸出液常含大量镁和锰,常用的酸性膦类萃取剂及羧酸类萃取剂对镍、钴和镁、锰的分离困难,传统硫化物沉淀及氟化物沉淀工艺复杂、环境污染大^[1,2,7]。为简化工艺,降低生产成本,减轻环境污染,急需开发新的溶剂萃取体系,提高镍、钴萃取分离效率。

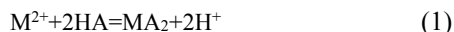
Grinstead等^[9,10]报道了含氮杂环化合物与二壬基萘磺酸(DNNSA)协同体系,研究发现该协同萃取体系能在较低pH范围内优先萃取镍和钴,而铁和铝几乎不被萃取。之后,研究人员开发了大量不同的含氮杂环化合物和有机酸组成的协同萃取体系,萃取分离镍钴的工业应用价值非常大。目前,关于含氮杂环化合物协同体系萃取纯化镍钴的研究已有报道^[8,11],但并未涵盖近期有关新型协同萃取体系的报道。因此本工作结合相关报道,更全面系统地综述了含氮杂环化合物协同体系萃取纯化镍和钴的研究进展,重点讨论了镍、钴萃取分离机制、萃取特点及潜在的工业应用等。

2 含氮杂环化合物与有机酸协同体系萃取分离机制

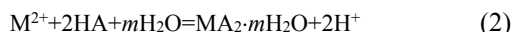
含氮杂环化合物易进行结构修饰,可方便地引入各种功能基团,能与过渡金属离子(如镍、钴、铜等)形成稳定的配合物,且通常毒性较低,在金属配位、医药、

催化材料等领域应用非常广泛^[12,13]。当含氮杂环化合物分子中具有庞大的疏水基团时,较适合作为萃取剂应用于冶金分离。

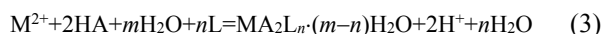
酸性萃取剂是湿法冶金分离中常用的萃取剂,在镍、钴提取与分离中得到广泛应用,特别是酸性膦类萃取剂和羧酸类萃取剂。酸性萃取剂萃取金属离子为阳离子交换反应,以HA代表萃取剂,以萃取二价金属离子 M^{2+} 为例,萃取反应如下:



研究表明,金属离子萃取时与酸性萃取剂配位,当萃取剂配体无法完全满足金属离子的配位需求时,萃合物中往往有水分子参与配位^[11,14,15],如式(2)中二价离子与酸性萃取剂形成萃合物的反应。P507 与镍形成的萃合物分子式为 $NiA_2 \cdot 2H_2O$ ^[16],有机磺酸、羧酸等萃取剂与镍形成的萃合物也被证实有水分子参与配位^[15,17]。



当含氮杂环化合物加入有机酸萃取体系时,化合物(L)中的氮为强的电子给予体,在空间位阻允许时代替水分子参与金属离子配位,如式(3)所示。含氮杂环化合物参与配位后形成更稳定的萃合物,提高金属离子的被萃取能力,使金属离子的萃取向低pH移动,这在镍钴萃取中表现非常突出。而对于某些金属离子,可能由于外层电子轨道结构不允许或空间位阻太大,含氮杂环化合物不能参与金属离子配位或配位能力很弱,无协同萃取效果或协同萃取效果很弱。甚至某些金属离子与含氮杂环化合物形成配位后,由于空间位阻太大,阻碍酸性萃取剂对金属离子的萃取,产生反协同作用,金属离子萃取性能降低,如1,5-萘二磺酸(H_2DNS)与镍形成配位化合物的结构为 $[Ni(H_2O)_6]NDS$,加入吡啶酯类化合物(L)后,L参加配位,形成 $[Ni(H_2O)_4L_2]NDS$ 萃合物,大大增强了镍的萃取性能,而三价金属离子,如Fe(III)和Al(III)与L配位后可能阻碍酸性萃取剂与其结合,从而萃取能力变弱,增大了镍与铁、铝的萃取分离^[17]。



3 含氮杂环化合物与不同有机酸协同萃取体系

不同类型酸性萃取剂对金属离子的萃取不同,与含氮杂环化合物形成的协同萃取体系对镍、钴及杂质元素的协同萃取和分离效果差别也较大。根据不同酸性萃取剂类型和含氮杂环化合物结构组成的萃取体系,讨论镍、钴及与常见杂质元素的分离,并探讨萃取体系潜在的应用。

3.1 含氮杂环化合物与有机磺酸协同萃取体系

有机磺酸含磺酸基团,一般水溶性大,不适于有机萃取体系。工业上常用的水中溶解度低的有机磺酸主要有二壬基萘磺酸(DNNSA)和二壬基萘二磺酸(H_2DNNS)。有机磺酸酸度大,对金属离子萃取能力强,但选择性差,因此这类试剂未在湿法冶金萃取分离中得到应用,目前研究较多的是用DNNSA与一些试剂的协同萃取体系,如在DNNSA体系中引入吡啶羧酸酯,可明显增强铜、镍、钴的萃取,减弱铁(III)、铝、锰、镁、钙等的萃取,不同pH下该体系对金属离子的萃取如图1所示^[18]。该协同萃取体系可用于含铁、铝等的溶液中萃取分离铜、镍、钴。

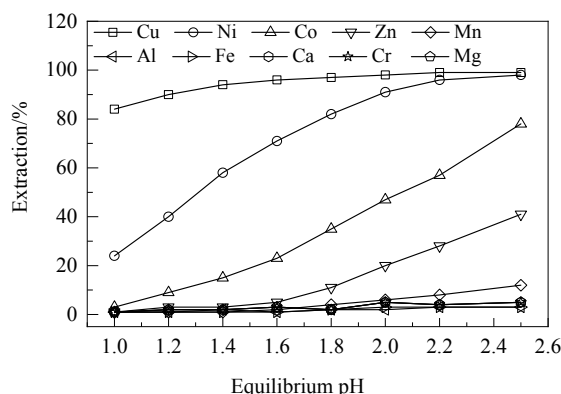


图1 不同pH下DNNSA与吡啶酯类化合物协同萃取体系对一些金属离子的萃取^[18]

Fig.1 Extraction of some metal ions by synergistic extraction system of DNNSA and pyridyl ester under different pH^[18]

从上世纪80年代开始,许多学者对含氮杂环化合物与DNNSA组成的协同萃取体系进行了大量研究,相继开发了多种含氮杂环化合物,表1为典型含氮杂环化合物与DNNSA组成的协同萃取体系对金属萃取分离的特性。可见含氮杂环化合物与DNNSA协同体系一般应用于硫酸体系或低浓度($<0.1 \text{ mol/L}$)氯化物体系,协同萃取体系仍为阳离子交换机理[式(3)]。尽管水相中的阴离子不参与配位,对金属离子的萃取性能影响不大^[17,33],但 Cl^- 或 ClO_4^- 浓度很高($>4 \text{ mol/L}$)时,一些含氮杂环化合物以阴离子交换方式萃取金属离子,导致金属离子的萃取与分离复杂化^[34-36]。因此,此类萃取体系较适用于硫酸体系或较低浓度的 Cl^- 和 ClO_4^- 体系。协同萃取体系对镍和钴的选择性很好,而对铁(III)、铁(II)和铝离子选择性差,这可能是由于含氮杂环化合物与铁、铝离子配位后阻碍了磺酸萃取剂与该离子的结合,形成反协同效果,使协同萃取体系对镍、钴与铁、铝的分离效果很好。由于含氮杂环化合物的结构不同,具体的体系对镍、钴萃取和铁、铝及其它杂质元素的分离效果也不相同。

表 1 含氮杂环化合物与 DNNSA 协同萃取体系萃取金属的特性

Table 1 Characteristics of extraction of metals by synergistic extraction system of nitrogenous heterocyclic compounds and DNNSA

Compound	Chemical structure	Performance	Problem	Aqueous medium	Reference
Alkyl bipyridine amine		Cu was strongly extracted, Ni and Co were extracted at pH<2, Fe(III) and Al were slight extracted at pH<2, <i>R</i> significantly affected the metal extractions.	Phase separation was poor and water solubility was high if inappropriate <i>R</i> was selected; synthesis was expensive.	Sulfate system	[9], [10], [19]
Pyridine carboxylate		Cu, Ni were strongly extracted at pH<2, good Co extraction at pH>3, all Fe(III), Al, Mn, Ca and Mg were slightly extracted.	Co extraction was poor, system was not very stable, phase separation was poor.	Sulfate system	[20–27]
Pyridine imidazole		Good Ni extraction was at pH=1~2, Fe(II), Fe(III) and Zn were slightly extracted at this pH range.	Co extraction was very poor, synthesis was difficult.	Sulfate or dilute chloride systems	[28]
Pyrazole derivatives		Ni and Co extraction were much stronger than that of Fe(III), Al, Mg at pH<0.5.	Stripping of Ni and Co was very difficult, molecular structure was complex and difficult for synthesis.	Sulfate system	[29]
Benzimidazole sulfide		The extraction of copper, nickel, zinc and cobalt was very high at pH=3~4.	Ni and Co separation from impurities, such as Mn, Mg and Cu was poor.	Sulfate system	[30]
Benzimidazole amine		Co was preferentially extracted at pH=0~2.6, iron was not extracted at this pH range.	Ni extraction was poor and its separation from impurities of Mn, Mg was also very poor.	Sulfate system	[31]
Alkyl benzotriazole		Cu, Ni and Co were selectively extracted at pH=1~2, Fe and Zn were slightly extracted.	Stripping of Ni and Co was difficult.	Sulfate system	[32]

吡啉酯类化合物由于具有相对简单的分子结构、合成难度低、原料易得、预测合成成本较低，且协同萃取镍、钴分离铁、铝的效果较好，因此其协同萃取体系的工业应用前景较好，如红土镍矿常压浸出液中往往含大量铁和铝，传统沉淀除铁铝工艺镍钴损失量大，难以实现镍钴回收，采用此类协同萃取体系可在浸液中直接萃取回收镍和钴；一些含镍废催化剂、含镍电镀废液等往往含大量铁和(或)铝，可采用协同萃取体系高效回收镍。

Zeng 等^[18]采用吡啉酯类化合物与 DNNSA 组成的协同萃取体系对高镁红土镍矿硫酸浸液进行了直接萃取分离镍、钴的中试实验，采用多级混合澄清槽，工艺流程如图 2 所示。浸液组成(g/L)为 Ni 3.750, Co 0.183, Zn 0.016, Al 0.930, Fe²⁺ 1.350, Fe³⁺ 2.920, Mn 0.310, Mg 42.300, Ca 0.470, Cu 0.005, Cr 0.096，料液初始 pH=1.99~2.19, 用 45vol%协同萃取剂的磺化煤油体系在相比(有机相与水相比, O:A)为 1:1 及室温下，铜、镍和钴的萃取率分别达 98.24%, 89%和 42%，其它杂质的去除率达 99%。用 0.5 mol/L 的硫酸溶液反萃，镍、钴的反萃率大于 98%，反萃液中 Ni 的平均浓度为 39 g/L。协同萃取体系对镍选择性较高，对电镀污泥中提取镍、从高浓度硫酸钴溶液中除去少量镍的效果均很好^[23,25]。

Huang 等^[26]研究了吡啉酯类化合物与 HDNNSA(同 DNNSA)组成的协同体系在萃取过程中的相分离速率，

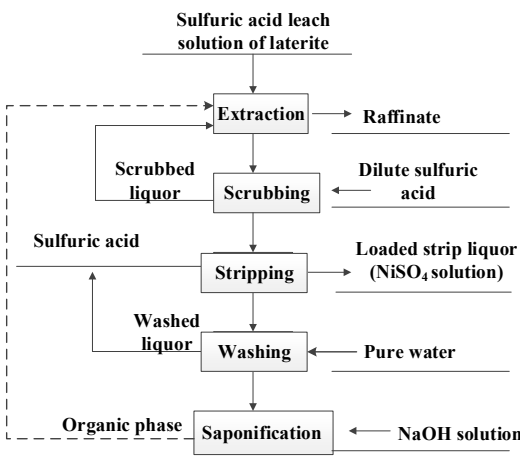


图 2 DNNSA 协同萃取体系从高镁红土镍矿硫酸浸出液中提取镍和钴的工艺流程^[18]

Fig.2 Technology process for extracting nickel and cobalt by DNNSA synergistic extraction system from sulfuric acid leaching solution of laterite ore with high magnesium content^[18]

考察了负载有机相的物理化学性质对相分离的影响。发现随萃取剂浓度增加，负载有机相黏度增大，有机相含水量也增大，在有机相中易形成反相微乳液，分相速率减慢，因此协同萃取体系需要控制合适的有机相浓度。

目前萃取体系尚未广泛的工业应用，含氮杂环化合物不同的碳链结构对萃取分离及分相效果影响较大，优化的协同萃取体系的稳定性、水中溶解性、反萃液的特

性等均需更深入的研究,针对具体提取镍、钴的料液还需系统的工艺评价。这类萃取体系对钴的萃取率普遍较低,只有少数体系萃取能力强,但会造成钴的毒化,难反萃,因此含氮杂环化合物协萃剂仍需进一步改进。

3.2 含氮杂环化合物与有机羧酸协同萃取体系

目前报道的有机羧酸萃取剂主要有 Versatic10、环烷酸、烷基水杨酸、烷基苯氧羧酸等。含氮杂环化合物与有机羧酸萃取剂同样对镍钴萃取的协同效果较强。

有机羧酸类萃取剂萃取镍钴的 $\text{pH} \approx 6.5$, 可用于萃取富集镍和钴^[37-39]。澳大利亚 Bulong 公司采用 2 个萃取循环从红土镍矿硫酸高压浸出料液中提取镍和钴^[40], 第一个循环中用 Cyanex272 萃取分离钴, 第二个循环中用 Versatic10 提取萃余液中的镍。但镍萃取工段 pH 较高 ($\text{pH} = 6.5$), 导致 Versatic10 溶解度大, 萃取剂损失严重, 分相效果差。另外, Versatic10 对镍和钙的分离效果差, 易造成钙的积累, 在萃取过程中会形成固体硫酸钙沉淀, 影响萃取过程的进行。

Preston 等^[41-43]对 Versatic10 与吡啶酯/烷基吡啶类化合物组成的协同萃取体系进行了大量研究, 发现在 Versatic10 体系中加入吡啶酯/烷基吡啶类化合物, 镍、钴及铁(III)、铜、锰等金属离子萃取的 pH_{50} (金属萃取率达 50% 的 pH 值) 向低 pH 方向移动, 而钙、镁萃取的 pH_{50} 几乎不变, 因此增强了镍、钴与钙、镁的分离效果。协同萃取体系对金属离子的萃取顺序为 $\text{Fe} > \text{Cu} > \text{Ni} > \text{Co} \approx \text{Zn} > \text{Mn} > \text{Ca} > \text{Mg}$ 。Preston 等^[44]还研究了烷基水杨酸与吡啶酯组成的协同体系, 发现对镍、钴的萃取性能与 Versatic10 组成的协同萃取体系相似, 金属萃取顺序也相同。Cheng 等^[45,46]对此类协同体系的研究也得到了类似的结果, 且协同体系的稳定性及分相效果良好, 组成的协同体系对金属离子的萃取见图 3, 可知该体系中镍

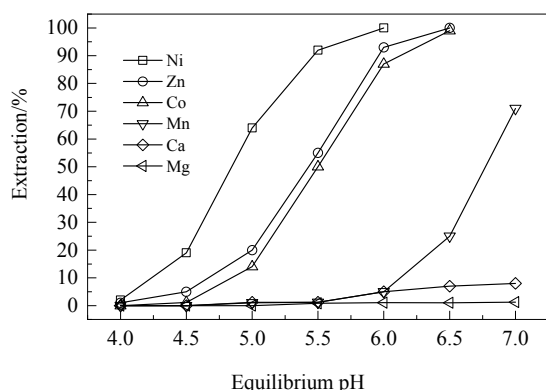


图3 不同 pH 下 Versatic10 与吡啶酯类化合物协同萃取体系对一些金属离子的萃取^[45]

Fig.3 Extraction of some metal ions by synergistic extraction system of Versatic10 and pyridyl ester under different pH ^[45]

钴与钙、镁、锰等金属杂质的分离效果较好。

针对红土镍矿硫酸高压浸出溶液, 现有工艺多采用镍钴沉淀后二次浸出提取镍和钴, 如果采用萃取工艺从高压浸出溶液中直接萃取镍和钴, 可大幅度简化流程、降低成本。为提高镍、钴萃取能力, 增大与钙和镁的分离效果, Cheng 等^[47]用 Versatic10 与酯类含氮杂环化合物组成的协同萃取体系, 设计了镍、钴全萃取提取工艺 (图 4), 避免了沉淀后二次浸出的复杂步骤、工艺流程短, 特别是协同体系萃取的少量锰离子可通过低浓度硫酸洗涤去除, 避免了消耗大量的高价碱试剂。另外, 该协同萃取体系稳定性好, 可适用于具有氧化性的硝酸体系, 在 $\text{pH} \approx 5$ 时, 协同萃取体系中钴与锰的分离系数达 53.4, 比单一 Versatic10 体系 (约 2.74) 有明显提高^[48]。

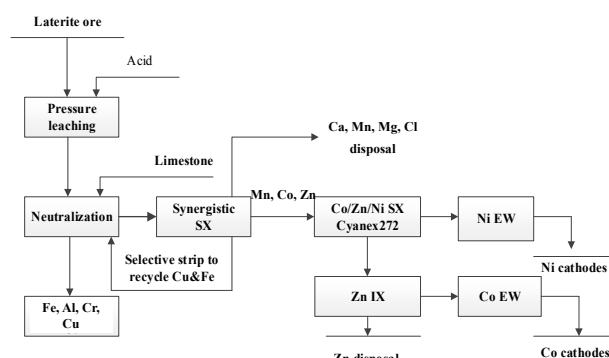


图4 Versatic10 协同萃取体系从红土镍矿高压酸浸液中提取镍钴流程^[47]

Fig.4 Extraction process of nickel and cobalt from high pressure acid leaching solution of laterite ore by Versatic10 synergistic extraction system^[47]

包福毅等^[49]用环烷酸与一种对位取代吡啶酯 (PE206) 组成的协同萃取体系研究了盐酸介质 (Cl^- 浓度约 2 mol/L) 中铜、镍、钴的萃取, 发现该体系对 3 种金属离子的协同萃取效应明显, 萃取体系中环烷酸和 PE206 的浓度均为 $15 \text{ vol}\%$ 时镍、钴萃取效果最佳。利用该协同萃取体系对金川镍业公司提供的一种钴电解液进行纯化, 钴电解液组成 (g/L) 为 $\text{Ni } 0.4 \sim 1.2$, $\text{Co } 98 \sim 123$, $\text{Cu } 0.03 \sim 0.57$, $\text{Fe } 0.08 \sim 0.26$, 用多级环隙式离心萃取器, 经 P204 萃取除铁, 协同萃取体系除铜和镍, 纯化后的电解液满足电解工艺要求, 钴总收率大于 99% ^[50]。

烷基苯氧羧酸萃取剂比 Versatic10 和环烷酸的酸性更强, 与含氮杂环化合物组成的协同体系可在更低的 pH 下萃取镍钴, 且能提高镍、钴与杂质金属离子锰、镁、钙等的分离效果。Oshima 等^[51]研究了对叔辛基苯氧乙酸 ($\text{tOP-OCH}_2\text{COOH}$) 与含氮杂环化合物 (吡啶、2,2'-联吡啶、1,10-菲罗啉) 组成的协同体系, 结果表明, 在低酸 (盐酸) 条件下, 该体系对镍钴萃取有很强的协同作

用,相比与 Versatic10 组成的协萃体系,可在更低的 pH 下萃取镍和钴,对杂质离子的分离系数更大。

这类协同协萃体系能很好地萃取镍、钴,分离锰、镁、钙等杂质元素,尽管镍的萃取优于钴的萃取,但两者的分离系数不大,难以分离。如需单一的高纯镍和高纯钴产品,需另外的萃取循环进行分离,可用传统的 Cyanex272 或 P507 萃取剂萃取钴,在萃余液中回收纯镍产品^[7]。镍和钴溶液中的微量杂质元素,如锌、铜等可采用特殊性能的树脂吸附,去除纯化^[52]。

3.3 含氮杂环化合物与有机膦酸协同萃取体系

有机膦酸类萃取剂在湿法冶金中已得到广泛应用,常用的萃取剂有 P204, P507 及 Cyanex272,与含氮杂环化合物对镍、钴也具有较强的协同萃取效果。

P204 与吡啶酯组成的协同萃取体系萃取镍、钴的 pH₅₀ 明显向低 pH 方向移动,而钙、镁由于配位能力较弱,萃取 pH₅₀ 几乎不变,从而增大了镍、钴与钙、镁的分离效果^[53]。协同萃取体系在硫酸盐体系中对金属的萃取顺序为 Cu>Ni>Zn>Co>Ca>Mg,萃取体系对镍、钴与镁的分离效果较好。

曾理等^[54]用 P204 与吡啶羧酸酯组成的协同体系从硫酸盐溶液中萃取镍,并分离杂质锰、钙、镁,考察了有机相配比、平衡 pH、平衡时间等因素对萃取分离的影响。结果表明,用 0.25 mol/L P204+1.25 mol/L 4PC 组成有机相,水相中的离子浓度(g/L)分别为 Ni 2.9, Co 2.9, Mn 2.75, Ca 0.4, 萃取平衡时间为 10 min,平衡 pH=2.0,有机相皂化率为 40%,镍与锰、钙、镁的分离系数分别为 $\beta(\text{Ni/Mn})=9.67$, $\beta(\text{Ni/Mg})=108.3$, $\beta(\text{Ni/Ca})=81.79$ 。孙振等^[55]研究了该体系选择性萃取镍的反应热力学,发现该过程为吸热反应,焓变和熵变分别为 29.52 J/mol, -6.35 kJ/(mol·K),升高温度有利于该体系萃取镍。

Wang 等^[56]在硫酸盐溶液中用此类协同萃取体系萃取锰,并与钙、镁分离,制备了高纯的锰产品,所得结果也较好。Gallacher 等^[32]研究了 D₂EHPA 与烷基苯并三氮唑组成的协同萃取体系,结果表明,在 D₂EHPA 中加入苯并三氮唑显著提高了铜、镍的萃取能力。

有机膦酸萃取剂与含氮杂环化合物组成的协同体系往往能选择性萃取镍、钴和锰,对钙、镁离子具有很好的分离效果。实际工艺中,可考虑用该类协同萃取体系共同萃取镍、钴、锰,分离钙、镁等杂质。如在镍、钴、锰三元电池材料回收中,可将镍、钴、锰有效成分一同萃取,分离其它元素,大大简化了电池材料回收流程。但由于该体系萃取镍、钴,分离锰的效果较差,实际生产的应用领域需进一步拓宽。

4 结语与展望

综上所述,含氮杂环化合物与有机酸类萃取剂组成的协同体系对镍、钴的萃取具有显著的协同作用,同时增强了镍钴与常见杂质元素的分离效果,在镍、钴的提取及生产过程中具有重大的潜在应用价值。但目前开发的大多数含氮杂环化合物协同萃取体系并不完善,在实际应用中存在一定局限性。已有的 DNNSA 协同萃取体系对钴的萃取率偏低,需对协萃剂含氮杂环化合物进一步优选改进;有机羧酸协同萃取体系对镍、钴的分离效果差,需进一步萃取循环才能实现二者分离并获得单一镍、钴等产品。因此现存体系还需进一步研究和完善。

开发新型萃取体系以满足镍、钴的生产要求是当前该领域重要的研究方向,其中含氮杂环协萃剂的选择十分关键。但含氮杂环化合物种类繁多,不同种类对萃取体系性能的影响规律还不明确,高性能协同萃取体系的开发面临着一定挑战。因此,在新型萃取体系开发过程中应加强理论基础及分子微观结构的研究,为将来开发更高效的协同萃取体系提供坚实的理论支撑。

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