综 述

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A review on recycling of waste aluminum alloy

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Abstract: Because of the low density, high strength, good corrosion resistance and other excellent properties, aluminum alloys have become the second widest used metal material. In recent years, more and more attention to the recycling of waste aluminum alloys has been paid, which not only effectively alleviates the global shortage of bauxite resource, but also contributes to the sustainable development of economy, environment, and energy. Due to the special working environment of aerospace industry, it has higher performance requirements for the aluminum alloy, i.e. strength, heat resistance, corrosion resistance and fatigue resistance. Therefore, the aerospace aluminum alloys contain many types of alloying elements and create higher recycling value. With decades of research and exploration, there are still problems limiting the recycling, such as unstable product quality, high burning rate, and severe oxidation. Heavy-medium separation, dual-chamber furnace smelting, and LARS metamorphic treatment technologies and equipments have been successively developed. This article summarized the types of commonly used aluminum alloys, the equipments and technologies used in the recycling process, including pretreatment, remelting regeneration and refining. The status of recycling and utilization of aerospace aluminum was highlighted. Finally, the difficulties and future trends in the aluminum recycling industry were discussed and looked ahead.

Key learning points:

(1) Summarized the classification mechanism of waste aluminum alloys.

(2) The characteristics of waste aerospace aluminum alloy and the status of recycling technology were analyzed.

(3) Overview of the global waste aluminum alloy recycling equipments and technology development.

Key words: secondary aluminum; pretreatment; refining; metal impurities; aerospace aluminum

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废旧铝合金回收利用的研究现状

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摘 要：铝合金由于其密度小、强度高、耐腐蚀等一系列优良性能，已经成为世界上第二大金属材料。随着原铝产量的严重短缺和各种铝产品相继达到报废年限，人们对各类废旧铝合金的回收利用越发关注。再生铝行业的兴起不仅可以有效缓解全球铝土矿资源日益匮乏的局面，而且对经济、环境和能源的可持续发展都有很大贡献。航空航天用铝由于工作环境特殊，对铝合金强度、耐热性、抗腐蚀性和抗疲劳性等有严格的要求，航空铝有更高的循环利用价值。通过几十年的研究探索，针对废铝回收过程产品质量不稳定、烧损率高、氧化严重等问题，相继开发了重介质分离、双室炉熔炼、LARS变质处理等技术和设备。本工作对常见废旧铝合金在预处理、重熔再生和金属熔体精炼过程中所用设备和技术进行了总结，重点归纳了航空铝的回收利用现状，对铝回收行业存在的难点问题和未来发展趋势进行了讨论和展望。

要 点：

(1) 总结了废旧铝合金分类机制。

(2) 分析了航空废旧铝合金特点及回收技术现状。

(3) 综述了全球废旧铝合金回收设备和技术现状。

关键词：再生铝；预处理；精炼；金属杂质；航空铝

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1 前 言

随着全球经济的快速发展，铝及其合金材料凭借其耐腐蚀、易加工、可循环再利用等优良特性被大规模生产和应用，成为仅次于钢铁的第二大金属材料，使用比例逐年稳步提升[1]。我国已成为全球最大的铝生产国[2]，2017年全球铝产量为6200多万吨，其中我国总产量为3630万吨[3]，占比为58.5%。我国已探明的矿产储量中，铝土矿可供开采时间已不足 30 年[4]，我国每年有30%~50%的氧化铝依赖进口，原铝总产量不足已严重影响了我国国民经济的发展[5]。

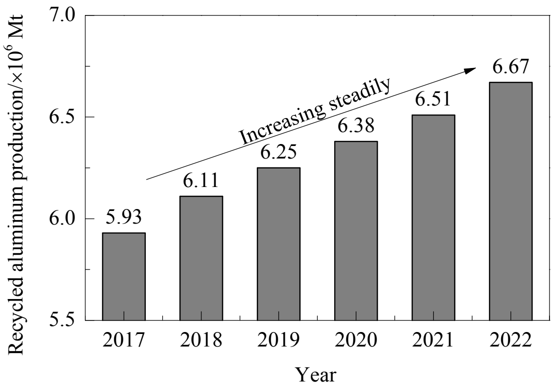

图1 中国再生铝产量预测[8]

Fig.1 Prediction of aluminum production in China[8]

铝土矿资源匮乏和大量废旧铝合金堆积等问题严重限制了铝合金材料的生产和利用。对废旧铝合金的循环利用显得尤为重要，再生铝对缓解资源压力和节能环保都有很大贡献[7]。2015 年，全球再生铝合金产量为2531 万吨，预计到 2020 年会突破 3000 万吨，我国的总产量也将达到638万吨，我国再生铝产量预测见图1[8]。

世界上主要发达国家已经形成了一套相对成熟的废旧铝合金回收再生生产线，再生铝的年产量超过了铝总产量的一半，基本保持在 70%左右，日本再生铝产量更是达到了铝总量的 99%以上。而我国再生铝产量占比不及 20%[9]，远远落后于全球平均水平，再生铝消费占比情况见表 1[10]。我国再生铝行业起步相对较晚，初步形成于 20 世纪 70 年代后期，再生铝企业相对分散，没有形成规模化，冶炼技术和设备相对落后，预处理分选阶段多数依靠人工操作，冶炼设备以反射炉为主，且没有配套的蓄热和除尘等辅助系统，导致冶炼过程中金属烧损严重，杂质元素和夹杂物含量较高，冶炼过程产生的废水、废气、废渣得不到有效处理，达不到资源高效循环利用的效果[11]。我国要使再生铝产业真正达到高效化、绿色化，缩小与欧美等发达国家的差距，要从“废料–重熔–精炼–再利用”整个流程出发，全方位吸收和研发先进冶炼设备和技术手段，深入研究杂质元素的物相和作用方式，有针对性地选定除杂方法[12]，将各种元素控制在国标范围内，将再生铝发展成为我国在国际上

有竞争力的一个行业。

表 1 2016 年再生铝消费情况[10]

Table 1　Consumption of recycled aluminum in 2016[10]

Country	Japan	Europe and America	Worldwide average	China
Proportion	>99%	70%	30%	<20%

目前，废旧铝合金回收预处理主要以人工和磁选等方法为主，冶炼设备以反射炉及其各种衍生炉型为主，精炼过程主要采用熔剂法和过滤法等。再生铝产品受原料、预处理、熔炼设备和精炼手段等各方面的限制，主要以铸造铝锭为主，进行降级使用[13]。只有极少量的优质废旧铝合金能实现其固有价值，如废旧饮料罐循环再生[14]、重熔再生汽车板等。本工作对废旧铝合金进行分类总结，对工业生产设备和技术现状及其优缺点进行了比较，最后总结了再生铝行业发展中存在的问题，对以后的发展趋势进行了展望。

2　废旧铝合金的分类

废旧铝合金可分为新废料和旧废料两大类[16]。新废料指在铝冶炼、熔铸、轧制、精整等深加工过程中产生的结构明确、成分单一、可直接入炉重熔成特定牌号合金的废料。对同一牌号的新废料国家有明确的分类标准。按工序、尺寸、形状和洁净度将废料分为 4 个等级，级别越高，烧损率越严重，重熔再生难度越大[17]。常见的铝合金废料见图 2。旧废料指各种铝合金产品报废后产生的废料，来源十分广泛，主要包括建筑行业废铝、废旧铝饮料罐、汽车板废铝及航空废铝等。废料牌号成分各不相同[18]，不同种类的合金元素及其含量见表 2。饮料罐用铝主要是含 Mn 和 Mg 元素的 3xxx 系列合金，汽车板用铝主要是以 Si 为合金元素的 6xxx 系列合金和以 Mg 为合金元素的 5xxx 系列合金为主，航空航天用铝主要以 2xxx 系列合金和 7xxx 系列合金为主，都含大量回收价值很高的合金元素，国内很多再生铝企业不重视对废料的分类，造成了大量优质合金浪费。

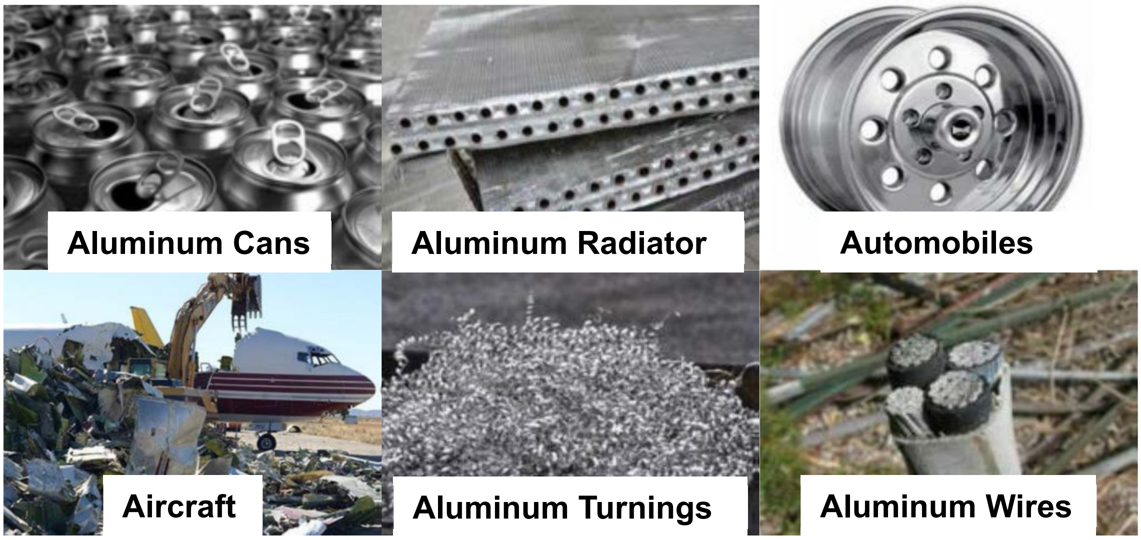

图 2　常见的铝合金废料

Fig.2　Common aluminum alloy scrap

表 2　不同种类合金的元素及其含量

Table 2　Elements and contents of different types of alloys

Alloy type	Grade	Element/wt%							
		Si	Fe	Cu	Mn	Mg	Zn	Ti	Al
Aluminum cans	3004	0.3	0.7	0.25	1.0~1.5	0.8~1.3	0.25	＜0.1	Others
	3104	0.6	0.8	0.05~0.25	0.8~1.4	0.8~1.3	0.25	＜0.1	Others
Automotive aluminum	6016	1.0~1.5	<0.5	<0.2	<0.2	0.25~0.6	＜0.2	＜0.15	Others
	5022	<0.25	<0.4	0.2~0.5	<0.1	3.5~4.9	＜0.15	＜0.15	Others
Aviation aircraft aluminum	2024	<0.5	<0.5	3.9~4.9	0.3~0.9	1.2~1.8	＜0.25	＜0.15	Others
	7075	<0.4	0.5	1.2~2.0	0.3	2.1~2.9	5.1~6.1	＜0.2	Others

航空废铝含多种有价值的合金元素，属于典型的优质废料。从 20 世纪 20 年代到 21 世纪初，飞机铝合金零部件占总质量的 75%~80%[19]，航空铝合金达 20 多种，成分非常复杂[20]。针对飞机不同部位材料的性能需求，在冶炼过程中，对不同牌号和同一牌号用于不同部位的铝合金需采用不同的热处理机制，尽可能延长合金的使

用寿命。不同铝合金的热处理状态和用途见表3[21]。飞机材料用铝的质量要求非常严格，价格比普通熔铸铝合金高十几倍甚至几十倍，如能合理高效地重熔再生[22]，重新用于飞机制造而不是降级成普通的铸造铝锭，经济效益将会显著增加[23]。

表3 不同合金的热处理条件及其用途[21]

Table 3 The heat treatment of different alloys and use[21]

Alloy	Heat treatment	Application
2024	T351, T851	Fuselage structure, wing resistance area, rigid structure
2124	T851, T351	Machined parts, bulkheads, wing skins, structural parts, etc.
7050	T7651, T7451	Frames , bulkheads of the fuselage
7150	T7751, T6151	Upper airfoil skin, stiffener, low-level stability panel
7055	T7751	Upper wing structure, horizontal stabilizer, keel beam, cargo rail
7075	T7651, T651, T7351, T73	High-strength structural parts, moderate toughness, corrosion resistance of inter- and lower-air ribs
7475	T651, T7351	Part of the fuselage, wing skin, bulkhead, spar

据预测，到2029年全球报废飞机数量约为1.2万架，我国在未来几年也会有一大批飞机淘汰，月平均数为1.5架。一架报废飞机的重量平均约为40 t，其中75%以上为铝合金材料，主要以2024和7075合金为主[24]，其具有高强度、耐热性良好和抗疲劳性优异等共同优点。如飞机用铝的再生能力按年产6万吨计算，经济效益将高达数十万美元。报废飞机拆解可直接拉动物流、自动化等行业，将为企业创造更大的综合经济效益。目前，由于航空铝中锌、钛合金掺杂和表面涂层[25]等问题，没有合理的分类机制，世界上对航空航天业报废铝合金的高效循环利用还没有给出让人满意的答案[26]，统一的做法是将可被利用的零部件进行修复流向二手市场，最终淘汰的铝合金进行表面处理[27]、破碎解体、入炉重熔成铸造铝锭进行降级使用[28]，造成了优质铝资源大量浪费。另外，飞机表面涂层主要由铬酸盐类颜料和环氧有机物组成，目前市场上酸性或碱性去漆剂尚不能满足涂层去除的要求，研发新型高效环保的去漆剂是航空铝回收预处理的首要难题。炉内冶炼工序的主要难点是极其复杂的合金成分和高达50%的烧损率，所得成品质量仅为入炉料总质量的一半。为提高产品质量，目前工业上主要采用提高热效率、缩短冶炼周期等方法；加入由KCl, NaCl和冰晶石按一定比例成的复合覆盖剂和定量的Be[29]；采用双重过滤等技术手段，同时实现防氧化、防吸气、脱氧和除杂等。现在很多研究人员青睐于将报废航空铝合金重熔冶炼7075合金[30]，可去除杂质Zn，只需进行纯铝稀释和合金化处理。所有的技术手段均为了避免航空航天铝合金“向下循环”利用。针对航空废铝量大、价值高等特点，探索一条高效合理的分类方法，在资源、环境、经济等方面会有很高的效益[31]。

3 废旧铝合金再生技术现状

全球再生铝行业高速发展的背后，仍有太多的问题需引起重视。缺乏一套完善的针对不同废料的独特预处理体系、烧损和氧化造成的金属收得率低、精炼技术和设备达不到预期产品质量目标，是全球再生铝企业均面临的难题[32]。

3.1 废旧铝合金的预处理

如将各种废料混合入炉熔炼，杂质合金成分复杂，加大了回收再生的难度。入炉前对各类合金进行预处理是必不可少的一个环节。拥有一套成熟完整的预处理工业流水线有助于再生铝企业保持竞争优势。废旧铝合金预处理流程见图3，主要包括破碎解体、水洗、除漆除水、分选归类、成分分析、称量入炉[33]。分类、分析和称量直接影响着入炉料的配比和成品质量。预处理阶段用到的主要设备有破碎机、锤磨机、挤压设备、烘干设备、机械浮选磁选设备、称量设备、成分检测仪[34]。分选归类阶段目前国际上主要采用重介质分离和抛物分选法[35]，更先进的选料技术和设备正在逐步开发应用，如空气分离[36]、涡流分离[37]、日本的神经网络分析分选器[38]、感应激光衰变光谱仪分选器[39]和海德鲁铝业应用X射线仪建立起来的废料分类和破碎生产线[40]等。我国

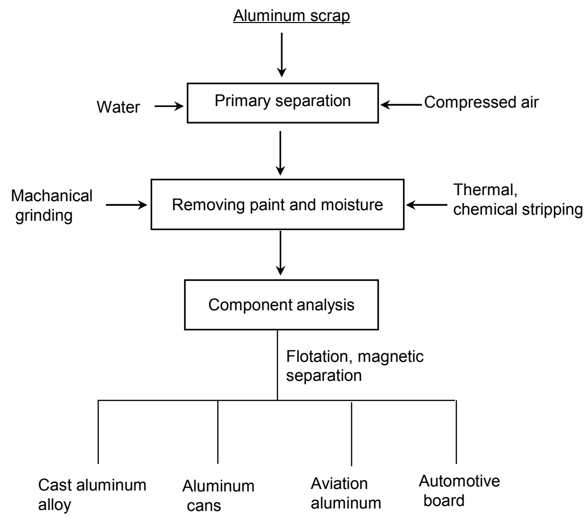

图3 废旧铝合金预处理流程

Fig.3 Flow chart of pretreatment of waste aluminum alloys

的再生铝预处理技术水平尚有很大差距[41]，除漆去涂层尚无很好的办法，分选归类方面大多数企业依靠人工操作，没有成熟的入炉配料标准，导致很多高品质废料只能被重熔轧制成低端铸造铝锭[42]。建立一条合适完整的预处理工业生产线是我国再生铝企业面临的首要难题。

3.2 废旧铝合金的重熔再生

从加料入炉到铝液出炉属于重熔再生阶段，是主要的能源消耗过程。整个工序需在高温下进行，废料熔化速率、单位时间内的产量、吨铝能耗、烧损率和各种污染物的排放量均会直接影响企业的经济效益[43]。铝合金重熔再生流程见图 4，炉内熔炼过程分为加料、加热熔化、加入辅料、适当搅拌、除渣、成分检测和在线合金化，最后得到预期的金属熔体[44]。20 世纪 90 年代，为了减小烧损率，炉型主要为高功率感应坩埚炉[45]和对流式 L 型熔铝炉。不同熔铝炉的比较见表 4。随着技术发展，现在的熔炼设备主要有回转炉、侧井炉(铝屑炉)、单炉膛火焰熔化炉[46]、感应熔铝炉[47]、竖炉[48]、双室熔炼炉[49]和反射炉[50]。反射炉被国内多数再生铝厂广泛使用，企业根据自身的实际情况，在反射炉的基础上衍生了很多炉型，如双室反射炉[51]、对流式反射炉、加料井式熔铝炉、旋转式反射炉、落差式反射炉、辐射式反射炉、携带电磁搅拌系统的反射炉等[52]。

废旧铝合金在冶炼过程中，金属液的反应和流动行为会影响金属熔体的质量，例如金属液与炉衬之间的反应、溶液上表面与产生的烟气之间的反应、金属液与冶炼渣之间的反应等。国际上有些企业在原有设备的基础上增加了热交换系统或蓄热系统[53]，通过提高热效率有效控制金属熔体中夹杂物含量和增铁行为，或增设炉外循环系统和模拟系统，有效控制铝箔型废料的烧损率和氧化再污染[54]。

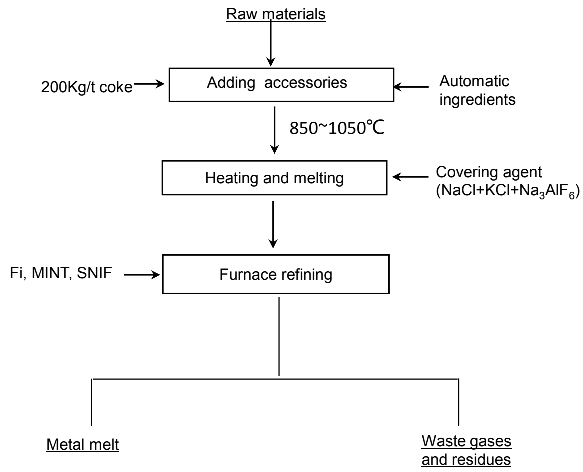

图 4　重熔再生过程流程

Fig.4　Flow chart of the remelting regeneration process of waste aluminum alloys

表 4 常见熔铝炉的类型和特点

Table 4　Common types of melting furnace and their features

Melting equipment	Scope of application	Advantage	Disadvantage
Side well furnace	Small size scrap	Effective recovery of powdered waste, low energy consumption	Serious pollution, serious burned waste
Aluminum slag rotary kiln	Hot aluminum slag	Reduce waste	High risk
Reverberatory furnace	Various pieces of waste	Operate convenient, high stability, suitable for industrial production	Serious pollution, high energy consumption, low thermal efficiency
Dual-chamber melting furnace	Bulk material, thin material, aluminum ingot	Pollutant emissions reduced, energy consumption reduced	Complex structure
Induction melting furnace	High quality scrap	Product uniformity, reduced oxidation rate, high automation	Severe lining erosion, poor power supply stability

3.3 熔体精炼

炉内冶炼受高温等一系列不可控因素的影响，很难控制每种元素含量和产品的机械性能均满足客户要求，后期金属熔体的精炼过程显得尤为重要[55]。熔体中的杂质主要分为固体夹杂和气体夹杂[56]，固体夹杂主要包括各种固体氧化物、来自耐火材料的尖晶石颗粒和一些聚集夹杂物等，气体夹杂主要是油和水产生的氢气，其中金属铁及其化合物夹杂和氢气对金属熔体的危害最大。固体夹杂物主要利用金属液与夹杂物的密度、粒度、吸附性等物理性差异去除，主要方法为熔剂法和电磁净化法；气体夹杂物最主要的去除方法为通入惰性气体促进金属液流动及对金属熔体进行真空处理，降低气体分压，常见方法为气泡浮游法和真空法[57]。

精炼方式按净化原理分为吸附和非吸附两种[58]，具体方法有熔剂法[59]、吹气法(气泡浮游法)、电熔剂法[60]、电磁净化法、过滤法、真空法和超声波法。其中熔剂法被广泛使用，但必须使用多种不同功能的熔剂，延长了冶炼周期，降低了经济效益。氟盐和氯盐[61]是最常用的精炼剂，产物 HCl 气体对人体和生产设备都有很大损害。过滤法[62]和吹气法[63]也因热损高、二次氧化严重等局限性，正在逐步被淘汰，取而代之为更先进的精炼方式如旋转喷粉法[64]、泡沫陶瓷法、稀土净化法[65]，具体有 FI

法、Heproject(移动式旋转喷射熔剂)法、MINT 法、SNIF 法、ALPUR 法等[66]。MINT 法由反应器和泡沫陶瓷过滤器两部分组成，氩气从反应器底部通入，金属液在反应器内作旋转运动并向下移动，气液两相能充分接触，有很好的除气效果。ALPUR 法的基本原理是利用高纯石墨制成的旋转喷嘴在金属液中产生微小气泡，同时增加金属液与气泡的接触面积和接触时间，提高精炼效果。20 世纪 90 年代中期美国开发的 LARS 变质处理技术[67]是国际上最先进的金属熔体精炼系统之一，基本原理是将卤素气体与惰性气体混合，通过特制的石墨转子对金属熔体进行变质处理，在熔池底部产生微小气泡，将固体杂质和废气带入熔渣，达到精炼金属熔体的目的。自 20 世纪 90 年代起，我国一些大型再生铝企业相继引进了 MINT 和 ALPUR 等先进的在线熔体净化系统，同时也开发了一些适合我国国情、拥有自主知识产权的处理工艺，尽力缩小与发达国家的差距。铝熔体主要净化方法比较见表 5.

表 5 铝熔体主要净化方法

Table 5 Main method of purification of aluminum melt

Purification method	Principle	Feature	References
Adsorption purification	Adsorption of refining agent for impurity removal and degassing	Blowing purification, chlorine salt refining agent purification	[62]
Non-absorbent purification	Under vacuum, the generated hydrogen bubbles can achieve the purpose of impurity removal	Vacuum static purification, vacuum dynamic purification	[62]
Foam ceramic filter	Filtrate with alumina and zirconia as the main material	Significant purification effect, convenient operation, suitable for continuous casting and rolling	[63]
FI method	Filtrate with alumina balls while passing nitrogen gas and covering agent	Good degassing and slag removal	[64]
SNIF method	Argon and nitrogen are blown into the rotating nozzle	Well purification effect, but the nozzle is easy to burn	[65,66]
ALPUR method	Argon gas is injected into the melt from the rotating nozzle to form bubbles	Improve efficiency, better purification	[67]

表 6 金属杂质的去除方法和基本原理

Table 6 Metal impurities removal methods and basic principles of waste aluminum alloys

Removal method	Suitable element	Principle	Reference
Nitriding method	Na, Li, Ti	Generate stable nitrides and be removed	[68]
Oxidation	Zn, Ca, Mg, Zr	Selective oxidation	[69,70]
Chlorination	Mg	Magnesium has stronger affinity for chlorine than aluminum	[70]
Precipitation	Fe, Zn	Difference in density	[71]
Flux method	Mg, Fe	Add flux to form a stable phase and remove from the metal	[71,72]
Segregation crystallization	Fe, Na, Ca	Difference in solubility, vacuum distillation	[72]

3.4 废料中不同杂质元素的脱除技术

再生铝行业的主要原料来源非常广泛，且入炉前没有完善的预处理过程，重熔过程中的物理化学反应和耐火材料的侵蚀等使再生铝产品的元素种类和含量很难有效控制[68]。据检测，熔炼过程中除 Al 之外金属液中存在的其它元素有 Cu, Mn, Si, Zn, Cr, Fe, Co 和 Ni 等近 20 种，复杂的成分严重影响了再生铝产品的质量。经济环保地去除杂质元素[69]，使合金元素含量满足国标要求是限制企业发展的关键环节。

不同的杂质元素都有其特有的物理化学性质，氧化性、挥发性、溶解度、电磁性、吸附性等存在一定差异，所以不同的杂质元素有各自独特的去除方法。目前再生铝企业在生产过程中采用的去除杂质元素的方法主要包括选择性氧化法[70]、氮化法、氯化法[71]、稀释法、冰晶石熔剂精炼[72]、蒸馏法等，通过控制温度、真空度、时间等条件，力求将各种元素都控制在标准范围之内，使产品的各种性能均满足目标合金要求。金属杂质的去除方法和基本原理见表 6。

铝制饮料罐和交通运输行业废铝的回收都受回收流程和元素物理化学特性的影响，Fe, Mg, Zn 均为重点去除杂质元素[73]。废旧铝重熔再生过程技术现状见表 7。

稀释法和重力沉降法是控制铁元素含量最基本的方法，由于温降太大，只有一些小企业还在使用。此外还有向熔体中加入氯化锰或硼砂等的熔剂法、以密度差异为原理的离心去除法、利用富铁相与金属液电磁性差异的电磁分离法和先加入合金元素形成特定相再使用泡沫陶瓷过滤器的复合除铁法。

适当含量的 Mg 能很好提升合金的强度，但一旦过量会加速合金的腐蚀和开裂，直接影响产品的使用周期。工业上去除 Mg 的方法很多[74]，例如利用镁铝与氧的亲和力不同进行氧化除 Mg、利用能生成更稳定的氮化物除 Mg、利用镁元素易挥发的特性蒸馏除 Mg、外加 SiO_2 等添加剂除 Mg 和用吸附性差异用特定装置吸附除 Mg 等。

表 7 废旧铝重熔再生过程技术现状

Table 7 Technical status of recycling process of waste aluminum remelting

Process	Technical method	Fundamental	Advantage	Disadvantage
Pretreatment	Wind selection	High-pressure air is introduced to separate waste paper, plastic, sand, etc.	Simple process, efficient removal of light waste	Environmental pollution
	Magnetiic separation	Remove magnetic waste according to magnetic differences	Low investment, simple equipment	Not suitable for larger wastes, incomplete sorting
	Flotation	According to the difference of density, remove impurities with water or dry sand as medium	The medium can be reused, simple implement	High investment, not suitable for the hollow material
	Heavy medium separation	Remove heavy non-ferrous metal impurities according to the density of aluminum is smaller than others	Remove heavy non-ferrous metals	Process complicated
	Parabolic sorting	The same volume of objects are thrown out of by different forces	Be evenly separated from other impurities	High investment
	Eddy current	The differences in conductivity and density	Separate non-metallic and other non-ferrous metal impurities	High investment in equipment, not suitable for particulate impuritie
	Spectral analysis	Determine the type of waste by XRD	Accurate classification of alloy grades	Complex processes, high investment
Metal smelting	Side well furnace	Consisting of heating furnace, feed well and aluminum water electromagnetic pump	High utilization rate, high thermal efficiency	Strict requirements for raw materials
	Dual-chamber furnace smelting	Be divided into feeding chamber and melting chamber	Continuous feeding, increase metal yield	Complex equipment
	Reverberatory furnace	Heat source reflection and radiation	Operate convenient	High energy consumption, low thermal efficiency
Melt refining	Flux method	According to different physical properties add salt flux	Wide application, simple process	Serious secondary oxidation, poor separation of slag aluminum
	Filter method	Filtrate with alumina and zirconia as the main material removes impurities	Operate convenient, low investment	Labor intensity, serious heat loss
	Rotary blowing	Argon gas and nitrogen gas are injected into the rotating nozzle	High efficiency	Reduced thermal efficiency
	Rotary blowing flux	Fine particle solids injected from rotating nozzle	Uniform contact, high efficiency	Expensive equipment, reduced thermal efficiency
	LARS modification	Mixing halogen and inert gas through graphite rotor	Clean, uniform	Complex process, high cost

Zn 对合金的焊接性能有很大影响，除 Zn 的方法有搅拌法、沉淀静置法和真空蒸馏法，其中搅拌法不仅会造成合金大量烧损，还会引入气体夹杂，一般不会采用。

不同企业根据自身的生产条件选用不同的方法去除各种杂质元素。不论是操作、经济性，还是环保、安全性，每种除杂技术都有一定局限性，所以探索更加经济高效的去除杂质元素的方法很有必要。

4 结语与展望

通过对目前全球范围再生铝行业发展的总结，对行业发展中存在的问题进行了分析。

再生铝是解决我国铝土矿资源短缺极为有效的方法，充分利用了铝的可循环再生特性，具备流程短、能耗低等特点，可提高能量和资源的利用率。再生铝工业作为一个充满活力的朝阳产业，将生产、消费、回收、再利用组成一个循环流程，展现出了越来越高的环境效益、经济效益和社会效益，废旧铝合金的高效循环利用是必然趋势。

废旧铝合金有明确的分类标准，各类铝合金所含合金元素种类和含量不同。航空废铝的数量和质量均决定了其具有较高的回收价值，但目前尚无完善的飞机涂层处理和冶炼工序，针对航空废铝的高效回收及航空材料的再生，应加大研发新技术和新设备的投入。

近年来我国废铝回收生产线积极引进国外的先进设备和技术，但预处理、炉内冶炼和炉外精炼等工序依旧存在很大差距。目前，我国再生铝行业自动化程度低、金属收得率较低、精炼技术相对单一，无法实现资源高效利用。要使再生铝行业高效可持续发展，在发展分类技术和冶炼技术的同时，也要注重规范化和法制化的发展。

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