

GENERAL RESEARCH

Management of the Salt Cake from Secondary Aluminum Fusion Processes

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This work describes the current situation of the production of primary and secondary aluminum. Due to the economic importance of secondary aluminum production, the process of obtaining it has been summarized, specially highlighting the generation and management of salt cake. The reassessment of this new waste is not economically viable; the best option is the minimization of its production, recovery of the metal aluminum, and disposal of the remaining fraction in controlled landfills. The process carried out at the Iberian business of light alloys (Iberica de Aleaciones Ligeras, S. L., IDALSA), a Spanish refinery, is presented. This company has implemented several new technologies in order to minimize the salt cake generation from secondary aluminum fusion processes. The incorporated treatments have helped IDALSA to decrease the salt cake generated per recycled ton of byproduct to less than half its previous value. The remaining waste is disposed of in a controlled landfill.

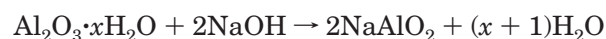
1. Introduction

Aluminum is the second most used metal after iron; it is used in a large number of applications by itself and is used in a wide range of alloys. The most important properties of aluminum have led to its use in many types of sectors, and they are the basis of the most important applications. Some of these properties are the following: clear and easy-to-color surface, low density (2.70 g/cm^3), light, malleable, low melting point (933 K), corrosion resistant, nonmagnetic, water and odor proof, large reducing power, easy to alloy with other metals (Mg, Si, Cu, Zn, and Mn), and easily recyclable.¹ Currently, this is the most widely used nonferrous metal in the world, being present in sectors as diverse as transportation, packaging, construction, electricity, and medicine, thanks to its properties, which make it essential in its multiple applications.

For a long time, aluminum was only obtained at a laboratory level, and due to its properties, it was considered to be a precious metal.² In 1886, Charles Martin Hall and Paul L. T. Héroult came up with a new industrial electrolytic process (the Hall–Héroult process), which is now the basis of aluminum production from aluminum oxide. In this process, the alumina is dissolved in an electrolytic bath of molten sodium aluminum fluorite and cryolite, using graphite electrodes. A low voltage, high intensity electric supply (of usually 150 000 Amp) goes through the electrolyte. In the hot furnace, the molten aluminum tends to accumulate at the surface and is periodically siphoned. In this process, 15.7 kW of electricity is used to produce a kilogram of aluminum from alumina. The process

requires a large amount of energy, which is why producers and smelters are located in areas with abundant energy sources (hydroelectric, natural gas, coal, or nuclear), preferably using renewable hydroelectric energy.¹

Years after the invention of the Hall–Héroult process, K. J. Bayer invented the Bayer process for the mass production of aluminum oxide from bauxite. This process allowed producers to obtain aluminum from a natural compound. The production of aluminum from bauxite is a very costly process, which is carried out in two stages. In the first one (Bayer process), by means of various treatments of grinding, absorption, solution, filtering, cooling, precipitation, and drying, alumina is extracted from bauxite. In the second stage (Hall–Héroult process), the alumina is used to obtain aluminum electrochemically. The first stage consists of the transformation of the bauxite into alumina. For this purpose, the bauxite is heated with caustic soda at a high pressure ($30.4 \times 10^5 \text{ Pa}$) and temperature (between 373 and 593 K), giving sodium aluminates.



At the same time that the bauxite is dissolved as soluble aluminate, the insoluble iron oxides, titanium oxides, and silicic acid are separated from the liquor using settling tanks, forming the so-called *red mud*. Then, the aluminate obtained is hydrolyzed, precipitates from the liquor, and is converted to alumina by calcination at a high temperature (1273 K).

In the second stage, by means of an electrolytic process, the aluminum oxide is converted into aluminum metal. In this operation, sodium aluminum fluoride is used to decrease the melting point of alumina, allowing the reduction to proceed in the molten phase. By means

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Table 1. Estimation of Aluminum Production Costs³

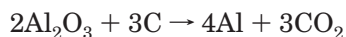
process	cost ^a (euro)
extraction of bauxite	160
refining of alumina	600
reduction	1280

^a Costs per ton of produced aluminum.

Table 2. Comparison of the Primary and Secondary Aluminum Production Processes

	primary process	secondary process
consumption of primary energy (GJ/t _{Al} produced)	174	10
atmospheric emissions (kg/t _{Al} produced)	204	12
solid waste (kg/t _{Al} produced)	2100–3650	400
consumption of water (kg/t _{Al} produced)	57	1.6

of a continuous electricity supply, the alumina is broken down into metal aluminum and molecular oxygen. The latter migrates to the anode, composed of graphite, and reacts with it, while the aluminum is concentrated on the cathode. The process can be described as



An estimation of the costs of the global process has been included in Table 1.³ We should highlight that over the past few years the consumption of energy for aluminum generation from bauxite has largely decreased thanks to technological advances, and most producers use clean technologies and renewable hydroelectric energy. Despite this, the high demand for energy in the process is one of the reasons for the importance of recycling aluminum; the metal thus obtained is called *secondary aluminum* (see Table 2).⁴

From these processes, the production of aluminum largely increased, exceeding those of other metals such as Cu, Pb, Sn, and Zn² over the last 100 years, from a production of two tons in the whole world to almost thirty million tons of primary aluminum. The production in various regions of the world has been included in Table 3. The considerable growth of China's production over the past few years should be highlighted (6589 tons in the year 2004);² this has enabled it to become one of the leading producers, leaving a large number of producers behind.

The recycling of aluminum is of great importance as it can be carried out without losing quality in the final product. Additionally, compared with the production of primary aluminum, this recycling process uses only 5–20% of the energy necessary for the primary production¹ process, and the amount of generated waste is much less (see Table 2). The production corresponding to 1997 is included in Table 4, as well as the producing countries.

Despite the great importance of aluminum due to the properties previously mentioned and the fact that it can be recycled with no loss of quality or properties, the production process provokes a substantial environmental impact. The waste and pollutants generated should be minimized and treated. In this respect, the European Union policy regarding the environment is centered on three reference points.⁵ First, all the processes involving a decrease in waste generation should be promoted; that is, waste production may be minimized. The decrease

Table 3. Production of Primary Aluminum in the World in 2004²

	production (thousands of metric tons)
Africa	1 711
Cameroon, Egypt, Ghana, Mozambique, Nigeria, and South Africa	
North America	5 110
Canada and the USA	
Latin America	2 356
Argentina, Brazil, Mexico, and Venezuela	
Asia	9 324
China, Japan, North Korea, ^a South Korea, ^a Tadjikistan, Azerbaijan, ^a Bahrain, India, Indonesia, Iran, ^a Turkey, and the United Arab Emirates	
Western Europe	4 295
France, Germany, Greece, Iceland, Italy, Holland, Norway, Spain, Sweden, Switzerland, and the United Kingdom	
Central and Eastern Europe	4 138
Bosnia-Herzegovina, ^a Croatia, ^a Hungary, Poland, ^a Romania, ^a Russia, Serbia-Montenegro, Slovakia, Slovenia, and the Ukraine	
Oceania	2 246
Australia and New Zealand	
total	29 180

^a Information on the production of these countries is not available.

Table 4. Countries with the Highest Production of Secondary Aluminum (1997)

country	production (thousands of metric tons)
USA	3543.3
Japan	1278
Italy	442.9
Germany	432.9
France	241.7
United Kingdom	236.6
Brazil	163
Spain	153.8
Holland	150.4
Mexico	123
Austria	116.5
Norway	58.6
Australia	57
Finland	38.2

can be achieved using clean technologies, also called better available technologies.⁶ Once the waste is generated, its assessment should be attempted by means of recovery, recycling, and reuse. As a last resort, the toxicity of the waste should be reduced for its final destination of controlled disposal. These three aspects will be considered in the present paper regarding aluminum production, in general, and secondary aluminum processes, specifically. As an example, the management of salt cake carried out by the Iberian business of light alloys (Iberica de Aleaciones Ligeras, S. L., IDALSA) with the advice of the author of this article is presented.

2. Types of Wastes Generated

2.1. Aluminum Production. One of the most important wastes generated during the production of primary aluminum is the *red mud* generated during the process of obtaining alumina from bauxite. The amount of generated waste, as well as its physical–chemical properties, per ton of alumina produced depends very

Table 5. Typical Composition of Red Mud

compound	chemical analysis (wt %)
Fe ₂ O ₃	25–45
Al ₂ O ₃	15–28
SiO ₂	6–16
TiO ₂	8–24
Na ₂ O (total)	4–9
Na ₂ O (soluble)	0.5–0.7
CaO/MgO	0.5–4
losses by ignition	7–12

much on the type of bauxite used. This usually varies from 0.3 to 2.5 tons. The major components are iron, silicon, and titanium oxides; it also contains zinc, phosphorus, nickel, and vanadium oxides. In general, these are acidic oxides, substances that are not dissolved under the bauxite reaction conditions. The typical breakdown of this type of waste has been included in Table 5.²

Waste management of red mud is usually carried out by means of controlled landfill disposal. Economically viable applications or uses for this waste have not been reported.

2.2. Production of Secondary Aluminum. Generation of Salt Cake. Recycled aluminum currently makes up a third of the total aluminum used in the world. Recycling is an essential part of the aluminum industry, given that this process makes economic, technological, and ecological sense. The aluminum destined for recycling can be divided in two categories: byproducts of the transformation of the aluminum and scrap of already used old parts that are transformed into ingots and plates for later commercialization (see Figure 1). The byproducts have their origin in the manufacturing process of aluminum material (shavings, off-cuts, molded parts, etc.). Usually, their quality and composition is known. They can, therefore, be melted down without having to carry out any previous treatment. The scrap is aluminum material from already produced aluminum goods, which have been used and discarded at the end of their useful life (cables, pots, radiators, etc.). This type of aluminum scrap reaches the recyclers

after a considerable number of separation processes. As it is usually found with other materials, previous treatment and separation is necessary.

The main features of secondary aluminum production are the diversity of the raw materials and the variety of furnaces that can be used. The type of raw material and its pretreatment determine the selection of the type of furnace. The most used furnace in the aluminum industry is the rotary type, as it is the one that can recycle the largest diversity of material. Thus, for example, first and second fusion dross, skimmings, and creams can be recycled. In this type of furnace, the aluminum raw material is melted under a layer of brine (salt flux), consisting, generally and specifically in the IDALSA procedure, of a mixture of approximately 30% KCl and 70% NaCl. The selection of the types of salt fluxes to be used depends on the type of raw material and on the furnace; these salt fluxes have multiple functions:⁷(a) They allow the heat transfer to the metal and contribute to the isolation of the metal from the atmosphere. For this, the furnace needs to reach a temperature high enough to melt the brine, which then floats over the metal. (b) They have the mission of mechanically dispersing the oxides and metal substances or solid nonmetal substances present in the furnace. (c) Some salt fluxes can react chemically with the aluminum oxides, dissolving them.

The amount of salt flux used in the melting process depends on the characteristics (impurities) of the raw material and the type of furnace used. First, the brine is melted in the rotary furnace, and then, the raw material is placed in the brine bath. Once melted, the metal and dross or mixture of metal and nonmetal substances is extracted. The conditions and cooling experienced during the extraction determine the most immediate appearance of the material (blocks, large parts, or powder). Dross tends to be localized (a) on the surface, floating (these will be salt fluxes that are less dense than aluminum and light metals and noncrystalline and porous oxides that tend to float, due to the amount of dissolved gases), (b) at the bottom of the

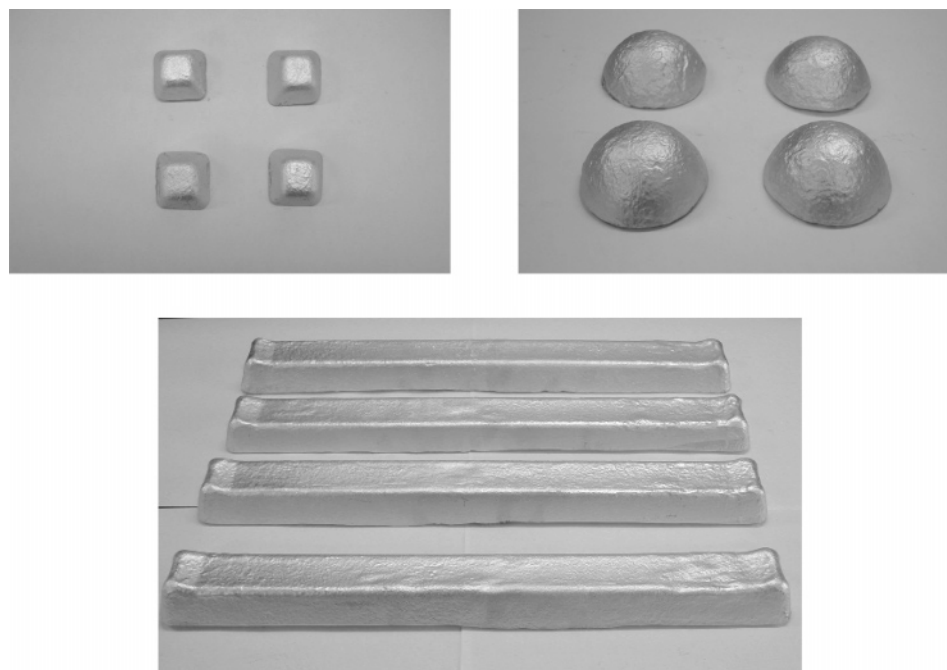
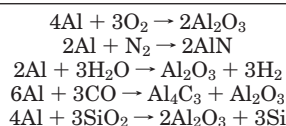
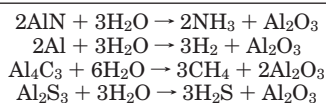


Figure 1. Various formats for the commercialization of recycled aluminum (pyramid for deoxidation, half balls, and ingots).

Table 6. Formation Reactions of Aluminum Metal Compounds under Melting Conditions**Table 7. Formation Reactions of Compounds That Can Be Emitted from the Aluminum Metal Compounds When They Are in Contact with Water****Table 8. Types of Waste Generated in Secondary Aluminum Production**

waste	origin
grinding filter powder	aluminum dross pretreatment
furnace gas filter powder	melting furnace
skimming	furnaces not using brine
salt cake	melting in rotary furnace

Table 9. Families and Compounds Present in Salt Cake

metals	Al, Fe, Si, Cu, etc.
metal oxides	Al_2O_3 , Na_2O , K_2O , SiO_2 , MgO
metal compounds	NaI, Al_4C_3 , Al_2S_3 , Si_3P_4
fluxes	NaCl, KCl, MgCl_2 , NaF, AlCl_3 , CaCl_2 , CuCl_2 , ZnCl_2
other brines	Na_2SO_4 , Na_2S , cryolite
other elements	C
foreign substances	normally included once the dross has left the furnace

furnace, decanted (these will be molten metals more dense than aluminum or oxides with high particle size or nucleating compounds with a high fusion point), and (c) next to the furnace walls, creating crusts.

During the high temperature melting process, aluminum can react with various gases creating various metal compounds (see Table 6). These compounds, in contact with water, can, at the same time, generate gas emissions (see Table 7) that can be important in the management of waste disposal in controlled landfills.

2.2.1. Wastes from Aluminum Secondary Production. During the aluminum second fusion process, various types of waste can be generated (see Table 8). Only from the point of view of the amount, the salt cakes are the more important waste. Salt cake is generated when brines are used as salt flux to cover the melted metal, prevent oxidation, and increase performance and thermal efficiency. Depending on the mixture of raw material and the type of furnace used, the amount of salt cake produced per ton of secondary aluminum varies a little, depending on the pureness of the raw material and the amount of salt flux brines needed. In the European Union, this waste is considered to be hazardous waste⁸ and its management is necessary.

3. Management of Salt Cake

Before detailing the possible ways to manage salt cakes that are available, it is necessary to clearly know what components and compounds are present in them. In this respect, the various families and compounds usually found in the dross have been included in Table 9. In the assessment process of salt cakes, three byproducts can be considered: metal aluminum (6%), flux brines (28%), and oxides (nonmetal products (NMP) 66%). The average composition of the nonmetal products

Table 10. Average Composition of the NMP Fraction

compound	chemical analysis (wt %)
$\alpha\text{-Al}_2\text{O}_3$	40–80
MgAl_2O_4	<40
MgO	<10
$\text{Al}(\text{OH})_3$	<5
Al	<8
impurities (SiO_2 , M_xSiO_y , CaF_2 , AlN, etc.)	<10

is summarized in Table 10. These oxides that have been described can be marketed in various industries (cement, ceramic, and building industries) although there are also reports that show that, due to their final characteristics, they are not of a sufficient quality for their marketing to be economically viable; the final destination of this product is the controlled landfill.

In the United States of America, at the beginning of the 1990s, through Argonne National Laboratories, the Department of Energy, and various companies (Alumitech Inc., Virginia Tech, and Alcoa), many people became aware of the serious environmental problem caused by the accumulation of salt cake generated in aluminum secondary fusion processes. After numerous studies,^{9–15} even at the pilot plant level, the final conclusion was that the recovery of the salt cake was not economically viable. The best solution was to maximize the recovery of aluminum and dispose of the waste in controlled landfills. The studies carried out by these laboratories concluded that, for the assessment process of salt cake to be economically viable, it is necessary to obtain a liquid effluent with a high content of salt, in order to reduce the costs of the water evaporation and the later crystallization, and a fraction of NMP relatively free from brines and impurities (less than 2%). The economical nonviability of the process is due to the fact that both situations cannot be achieved simultaneously and also due to the significant economic investment required, the considerable consumption of water and energy, and the low added value of the recovered salts and nonmetal products. It should be highlighted that the composition of the NMP can be very variable, depending on the recycled material, making it difficult to find solutions for general recoveries.

In some European Union member countries, the treatment of the salt cake generated by aluminum secondary fusion is carried out for possible waste valorization,^{16,17} mainly because disposal in conventional landfills is not permitted (e.g., Italy and Germany). In the Spanish refineries mainly using rotary fixed shaft furnaces, the generated salt cake is attempted to be reassessed by means of a treatment similar to the HANSE process.⁴ In this process, the saline fraction is separated from that of the oxides. The saline fraction would be treated initially to concentrate it by means of, for example, electro dialysis to subsequently obtain the salt by evaporation. The separation of the oxides would be a means of obtaining free salt. It does not seem that the various parts that are obtained, with the exception of the metal aluminum, have a real market making the valuation process economically viable.

IDALSA¹⁸ is a medium Spanish company that has the best available fusion technologies⁶ for the recycling of aluminum byproducts and their transformation into ingots of various shapes and chemical compositions. This company is located in Zaragoza, in the municipality of Pradilla de Ebro, 42.5 km off the highway from Tudela

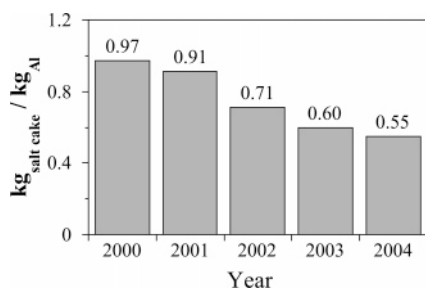


Figure 2. Evolution of the salt cake generated with respect to the aluminum recovery obtained.

to Alagon. It has more than 20 years of experience in the production of special alloys of aluminum from the recycling of byproducts of aluminum. It recycles 3500 t of scrap and byproducts of aluminum monthly, offering its clients formats such as ingots, half balls, and pyramids for deoxidation (see Figure 1).

The model of management followed by IDALSA is one that matches the policies of the European Union in the matter of wastes.⁵ The first of these is to promote the processes that support the reduction of the generation of wastes, that is, to minimize its production. The reduction can manage to employ clean technologies, also called better available technologies.⁶ When the waste has been produced, producers should try to reassess it by means of recovery, recycling, and reuse processes that should be economically viable. As a last resort, they should treat the waste by controlled landfill disposal. With the purpose of minimizing the production of salt cake, IDALSA has used the following technological measures in its production processes: oxy-combustion technology; pretreatment of raw materials; use of a tilting rotary furnace with a capacity of 18 t (with this oven the consumption of fondants is reduced and the quantity of salt cake generated is also minimized); and processing of the salt cake (the metals in the salt cake generated are separated by means of electromagnetic and mechanical processing of the saline fraction and of the nonmetallic one).

One must emphasize that these clean technologies have permitted IDALSA to reduce the quantity of waste generated by each ton of aluminum recycled to less than half its previous value in the last five years (see Figure 2), results in accordance with the main objectives

marked by the European Union in the matter of the environment, that are to reduce the consumption of materials and energy as well as to reduce the waste amount generated.⁵ The implementation of new melting technologies, such as the tilting rotary furnaces, makes the recycling of generated salt cake much less economical. There are various reasons for this. After these implementations, the amount of generated salt cake is greatly minimized. The amount of aluminum and, above all, saline waste present in this dross is much lower than that obtained in the salt cake generated in traditional rotary furnaces with fixed shafts (see Table 11).

For the waste finally generated whose management is not viable economically,¹¹ IDALSA manages it by means of controlled landfill disposal. To this end, the business has built on its lands an authorized landfill¹⁹ in which it can accumulate some of its wastes. The capacity of this landfill is approximately 100 000 m³.

4. Summary and Conclusions

The present work has shown the current situation of the production of primary and secondary aluminum, providing a summarized vision of each process. The production process of secondary aluminum is of great importance as it is the recycling of aluminum waste, which complies with the European Union policy on the environment regarding waste management, given that its assessment is economically, technically, and ecologically viable. The production process generates salt cake as waste that should be managed in compliance with the current legislation. Therefore, salt cake generation should be minimized, and the waste should be assessed in groups or in parts and, if any fraction remains, disposed of in authorized landfills.

The minimization processes are clear. The consumption of salt fluxes and the energy used in the fusion process should be reduced, as well as the amount of waste generated at the origin. All this involves an improvement of the technology that currently exists in the aluminum-recycling sector.

Even though assessment processes of this type of waste have been developed in some European countries, the studies carried out in the USA by Argonne National Laboratories clearly indicate that these are not eco-

Table 11. Composition of the Generated Salt Cake Depending on the Type of Rotary Furnace^a

component	generated amount (kg)	average percentage (wt %)
Fixed Shaft Rotary Furnace ^b		
Al concentrates	90	8
soluble parts in water (soluble parts = 1,1 kg _{salt flux} /kg _{aluminum oxide})	550	48
parts not soluble in water (metal oxides, nonrecovered metal, nonsoluble brines)	500	44
others	5 ng/kg	
total generated waste	1140 kg	
Tilting Rotary Furnace ^c		
Al concentrates	38	6
soluble parts in water (soluble parts = 120 kg _{salt flux} /t _{melted dross})	120	18
parts not soluble in water (metal oxides, nonrecovered metal, nonsoluble brines)	500	76
others	5 ng/kg	
total generated waste	658 kg	

^a For example, recycling of 1 000 kg of aluminum dross with a metal content of 50%. Data was taken from the IDALSA Company.

^b Typical composition of the salt cake generated from fixed shaft rotary furnaces. Addition of 1.1 kg of salt flux (70% of NaCl and 30% of KCl) for 1 kg of oxide. ^c Typical composition of the salt cake generated from tilting rotary furnaces. Addition of 12 wt % of salt flux (70% of NaCl and 30% of KCl) of the total scrap to recycle.

nomically viable, as there is not a real market for the byproducts generated. The best alternative for the salt cake is to maximize the recovery of the aluminum present in the waste, disposing of the remaining material, brines and nonmetal fractions, in an authorized landfill.

Therefore, as a final conclusion, the only environmentally and economically viable alternative for this type of waste is the recovery of the aluminum present and the management of the remaining fraction by means of controlled landfill disposal, as carried out in Spain by the IDALSA company.

Literature Cited

- (1) Kammer, C. *Aluminum Handbook. Fundamentals and Materials*; Aluminium-Verlag Marketing & Kommunikation GmbH: Düsseldorf, 1999; Vol. 1.
- (2) <http://www.world-aluminium.org>.
- (3) Nemererow, N. L.; Dasgupta, A. *Industrial and Hazardous Waste Treatment*; Van Nostrand Reinhold: New York, 1991.
- (4) Drossel, G.; Friedrich, S.; Huppertz, W.; Kammer, C.; Lehnert, W.; Liesenberg, O.; Paul, M.; Schemme, K. *Aluminium Handbook. Forming, Casting, Surface Treatment, Recycling and Ecology*; Aluminium-Verlag Marketing & Kommunikation GmbH: Düsseldorf, 2003; Vol. 2.
- (5) Directive 96/61/CE of the Council, 24th of September 1996 regarding the prevention and control integrated of the contamination. Law 16/2002 1st of July, BOE 157/2002 2nd of July 2002.
- (6) Farrell, F. *The impact of best available techniques (BAT) on the competitiveness of the european nonferrous metals industry. Nonferrous metals final report*; Joint Research Centre, European Commission, Institute for Prospective Technological Studies: Seville, 2001.
- (7) Soares Tenorio, J. A.; Romano Espinosa, D. C. Effect of salt/oxide interaction on the process of aluminum recycling. *J. Light Met. Weld. Const.* **2002**, *2*, 89.
- (8) Order MMA/304/2002, 8th of february 2002, about the recovery processes, waste treatments and european wastes list. BOE 43/2002, 19th of february 2002.
- (9) Jody, B. J.; Daniels, E. J.; Bonsignore, P. V.; Karvelas, D. E. Recycling of aluminum salt cake. *J. Resour. Manage. Technol.* **1992**, *20*, 38.
- (10) Hryn, J. N.; Daniels, E. J.; Gurganus, T. B.; Tomaswick, K. M. Products from salt cake residue-oxide. In *Third International*

Symposium on Recycling of Metals and Engineering Materials; Queneau, P. B., Peterson, R. D., Eds.; The Minerals, Metals and Materials Society: Warrendale, PA, 1995; p 905.

- (11) Graziano, D.; Hryn, J. N.; Daniels, E. J. The economics of salt cake recycling. In *Light Metals*; Hale, W., Ed.; The Minerals, Metals & Materials Society: Warrendale, PA, 1996; p 1255.
- (12) Sreenivasarao, K.; Patsiogiannis, F.; Hryn, J. N. Concentration and precipitation of NaCl and KCl from salt cake leach solutions by electro dialysis. In *Light Metals*; Huglen, R., Ed.; The Minerals, Metals & Materials Society: Warrendale, PA, 1997; p 1153.
- (13) Xiao, Y.; Reuter, M.; Vonk, P.; Vonken, J. Experimental study on aluminum scrap recycling. In *Recycling of Metals and Engineering Materials*; Stewart, D. L., Stephens, R., Daley, J. C., Eds.; The Minerals, Metals & Materials Society: Warrendale, PA, 2000; p 1075.
- (14) Pickens, J. W. Assuring the benefits of aluminum recycling: engineering economical environmental solutions to the issues of black dross & saltcake In *Recycling of Metals and Engineering Materials*; Stewart, D. L., Stephens, R., Daley, J. C., Eds.; The Minerals, Metals & Materials Society: Warrendale, PA, 2000; p 1195.
- (15) Krumdick, G. K.; Graziano, D. J.; Hryn, J. N. Electro dialysis technology for salt recovery from aluminum salt cake waste brines. In *Recycling of Metals and Engineering Materials*; Stewart, D. L., Stephens, R., Daley, J. C., Eds.; The Minerals, Metals & Materials Society: Warrendale, PA, 2000; p 1159.
- (16) Reynolds, R. M.; Olper, M. The Engitec System for Treatment of Salt Slag from Secondary Aluminum Smelters. In *Second International Symposium-Recycling of Metals and Engineering Materials*; van Linden, J. H. L., Stewart, D. L., Jr., Sahai, Y., Eds.; The Minerals, Metals & Materials Society: Warrendale, PA, 1990; p 439.
- (17) Unger, T. W.; Beckmann, M. Salt Slag Processing for Recycling. In *Light Metals*; Cutshall, E. R., Ed.; The Minerals, Metals & Materials Society: Warrendale, PA, 1991; p 1159.
- (18) <http://www.idalsa.com>.
- (19) Royal Decree 1481/2001, 27th of December, by which the elimination of waste by means of disposal in tips is regulated. BOE 25/2002, 29th of January 2002.

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