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Review

Hazardous aluminum dross characterization and recycling strategies: A critical review

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ABSTRACT

By finding appropriate recycling approaches, the volume of wastes, corresponding disposal cost, and the pollution of environment could be diminished. Also, such promising approaches can result in the conservation of natural sources and economic benefits. Aluminum dross as a hazardous solid waste in aluminum production industries has caused serious environmental and public health challenges. Various methods have been introduced for management, utilization, and recycling of the waste. The present review describes, firstly, different types of aluminum dross, their environmental and health hazards, composition, and production process and then focuses on the direct and indirect recycling approaches and recovery strategies.

1. Introduction

In general, industrial production is accompanied by issues such as generation of waste and depletion of natural resources as well. Industrial wastes accumulate over time bringing about critical environmental and public health detriments (Xiao et al., 2005). One of the most important and strategic industries producing hazardous wastes, is the aluminum production industry. Aluminum as the third most abundant element in the earth cannot be found as a free element in nature (Abdulkadir et al., 2015). Aluminum is the second most widely used metal after iron. It is a lightweight, conductive, easily paintable, malleable, corrosion resistant, non-magnetic, water/smell-proof, and easily alloyable metal with a high reducing power. It also has a low density (~2.70 g/cm^3) and low melting temperature (~933 K) (Gil, 2005; Tsakiridis et al., 2013). These characteristics have made this metal as a widely applicable material in the aerospace, building architecture and marine industries (Tsakiridis et al., 2013). In 1886, Charles Martin Hall and Paul L.T. Héroult invented industrial electrolytic process for the production of aluminum from aluminum oxide (alumina). In this process, alumina is digested in an electrolytic bath containing cryolite (chemical name: sodium hexafluoroaluminate). An electric current of about 150,000 amperes passes through the electrolyte (Tsakiridis et al., 2013). During the process, oxygen moves toward the anode and reacts with the graphite electrode. Finally, the aluminum is generated in the cathode. The overall reaction is as follows (Gil, 2005):

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2 \quad (1)$$

Compared to other materials, aluminum production is an energy-intensive industry (Abdulkadir et al., 2015) that shows the greatest difference in energy between primary and secondary production (about 174–186 MJ/kg for primary production, compared to 10–20 MJ/kg for secondary production) (Green, 2007). The reason for the much less energy consumed by the secondary Al production is that its raw feed is Al scraps and primary metallic Al (Tsakiridis et al., 2013). Therefore, today, aluminum is manufactured by means of two different pathways: the primary Al production from the alumina extracted from bauxite ore and the secondary Al production from Al scraps and used aluminum products (foils, extrusion, turnings) (Tsakiridis et al., 2013). Table 1 shows a comparison of the primary and secondary processes of aluminum production. According to the data given in Table 1, primary Al production requires much more energy and water consumption than secondary Al production. Also, primary Al production releases significant atmospheric emissions and solid wastes compared to secondary Al production.

The manufacturing process of alumina from bauxite was proposed by K.J. Bayer. In this process, bauxite, along with sodium hydroxide is heated at high pressure (~30 atm) and temperatures between 373 and 593 K resulting in sodium aluminate solution in accordance with the following reaction:

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Table 1
Comparison of the primary and secondary aluminum production processes (Car, 2016; Gil, 2005; Menzie et al., 2010; Tsakiridis et al., 2013).

Parameter	Primary process	Secondary process
Consumption of energy ($GJ/t_{Al\ produced}$)	174–186	10–20
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
Investment cost	High	Low
Emission	High level	Low level

$$Al_2O_3{\cdot}xH_2O + 2NaOH \rightarrow 2NaAlO_2 + (x+1)H_2O \quad (2)$$

At the same time, iron oxides, titanium dioxide, and silicic acid are also removed from the molten liquid and form red mud. In next step, aluminate is hydrolyzed and then precipitated in the form of aluminum hydroxide. Aluminum hydroxide is finally converted to alumina through calcination at high temperatures (about 1273 K). After the delivery of alumina to the aluminum industry, alumina is reduced to aluminum metal through an electrolytic process (Gil, 2005). In 2010, a total of about 56 million tons of aluminum metal was globally produced (approximately 18 million tons of scraps were recycled), compared to about 28 million tons in 1990 (more than 8 million tons of scraps were recycled). In the secondary aluminum industry (aluminum scrap recovery), about 200 kg of aluminum is produced per each ton of secondary aluminum (Seng et al., 2006). By 2020, annual global demand for aluminum will reach to about 97 million tons and almost 32% of which that equals to 31 million tons is expected to be supplied from scrap recycling (Tsakiridis et al., 2013).

According to Table 1, significant amounts of solid wastes are generated in both primary and secondary processes. This paper, which is based on almost all dross-related articles in the literature, for the first time, comprehensively reviews the various aspects of aluminum dross including types of it, its production process, chemical and mineralogical composition, environmental and public health impacts with an emphasis on different methods and strategies for retrieval and reuse.

2. Types of aluminum production wastes

In a general breakdown, waste materials can be classified into two broad categories: biodegradable wastes and non-biodegradable wastes. Non-biodegradable wastes remain in the environment for many years and cause serious disposal, environmental and public health problems. However, environmental effects can be reduced by adopting proper measures. Examples of such remedies include reuse, recycling, and reduction of waste (Nilmani and Makhijani, 2006). A wide variety of wastes are raised from various sectors of the aluminum production cycle, which the most notable of them are presented in Table 2. Each type of waste has its own physical and chemical properties and its value is determined by the amount of impurities and the cost of metal recovery (Hwang et al., 2006; Jirang and Lifeng, 2008).

Table 2
Various solid wastes originated from aluminum production cycle.

Waste	Process of origin	Reference
Red mud	Alumina generation from bauxite	(Liu and Naidu, 2014; Li et al., 2016)
White dross	Primary melting process	(Kim et al., 2009; Yoshimura et al., 2008)
Black dross	Secondary melting dross	(Kim et al., 2009; Yoshimura et al., 2008)
Grinding filter powder	Aluminum dross preprocessing	(Gil, 2005)
Furnace gas filter powder	Melting furnace	(Gil, 2005)
Skimming	Furnaces without brine	(Gil, 2005)
Salt cake	Melting process in rotary furnace	(Gil, 2005)

Red mud which is generated in the Bayer alumina extraction process (Gil, 2005) is considered as a hazardous solid waste due to its high alkalinity (Liu and Naidu, 2014). For each ton of produced alumina, 0.3–2.5 tons of red mud is formed (Gil, 2005). Stockpiling of the red mud in massive amounts, requires huge areas of land for the storage and also causes harmful environmental impacts. Alkaline solution and red mud slurry usually ooze into ground or underground water (Liu et al., 2009; Liu and Naidu, 2014). Red mud can be regarded as a secondary raw material for the retrieval of valuable substance (Liu and Naidu, 2014). Dross (white and black) and salt cake are produced during the melting process. For 100 kg of molten aluminum, an average of about 15–25 kg aluminum dross is generated (Liu and Chou, 2013). In general, aluminum production efficiency is diminished due to the dross formation (Yoo et al., 2011).

The amount of these types of wastes is as a function of the type and quality of the raw materials, the operating conditions, the type of technology, and the used furnace. The general chemical composition is affected by the alloying elements present in the molten aluminum in the metallurgical process (Yoshimura et al., 2008).

Dross as a mixture of elemental metal and non-metallic materials (salt and oxide) is formed when molten aluminum comes in contact with air on its outer surface (Lazzaro et al., 1994; Tsakiridis, 2012). In terms of metal content, dross is divided into two categories (Fig. 1). The dross with high metal content (more than 50 wt% of total weight of dross) is called primary dross (other common names: white dross, wet dross, or rich dross), which usually has a compact or clump form (Fig. 1a). Primary dross is mainly produced during primary Al production. It is slightly hazardous and is all valorized in secondary steel industry, or in secondary Al production. The dross with low metal content (between 5 and 20 wt% of total weight of dross) is referred to as secondary dross (also known as black dross, dry dross, or lean dross), which usually has a granular shape (Fig. 1b) (Adeosun et al., 2014; Dai, 2012; Manfredi et al., 1997; Peterson, 2002; Shinzato and Hypolito, 2005; Stewart, 1974).

The granular or secondary dross has higher salt content and gas evolution than compact or primary dross. Bulk density of the granular dross ranges from 0.80 to 1.12 g/cm^3. The greater the amount of metal in the dross, the lower the bulk density, because aluminum metal has a lower specific gravity than its oxide-form (Manfredi et al., 1997).

Grinding filter powder is produced during the dross grinding process which is performed in tertiary aluminum industry. Also there is the problem of the dust from the cyclones and the filters during the Al secondary production. This kind of waste is collected inside the filter sleeves assembled in air extraction systems (Gil, 2005; Tsakiridis et al., 2016). The European Waste Catalogue (EWC) has classified these powders as a hazardous waste (code number: 100321). The composition of these particulate wastes is similar with the corresponding of the black dross as they generally contain compounds such as corundum, quartz, calcite, iron oxide, and a few amounts of salts and other metal oxides (Galindo et al., 2015a; Tsakiridis et al., 2016). More details on salt cake are found in section 4. The possibility of reuse and recycling of wastes listed in Table 2 has been assessed by Fiore et al. (2005). According to their assessment, for most of these wastes, there is a cost-effective potential for reuse and recycling.

3. Aluminum dross

3.1. Production process

As mentioned before, there are two kinds of Al dross, including primary (white) and secondary (black) dross. The former is produced in the primary Al production and the latter is generated in the secondary smelters, where Al scraps are also recycled together with primary Al