Production of aluminum (emphasis on energy and materials requirements)

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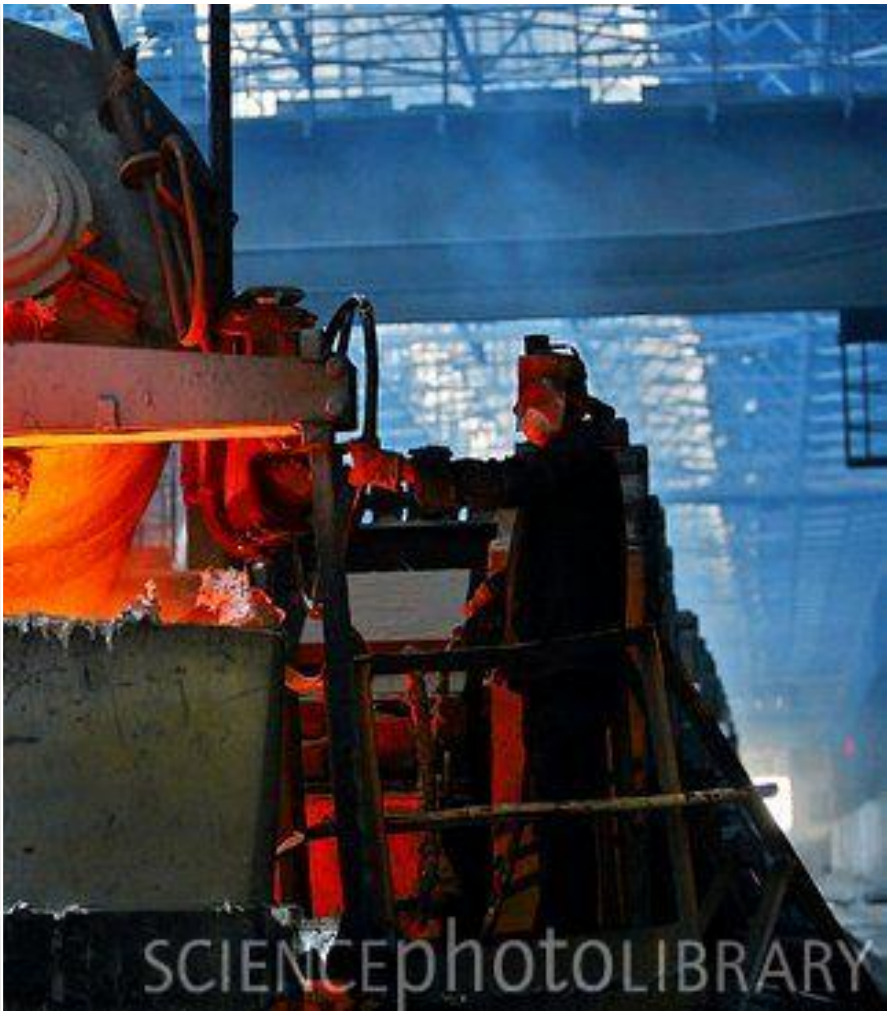

Aluminum is produced commercially using Bayer process and Hell- Héroult process. Besides scrap recycling and reuse of aluminum hydroxide contribute to total production. Bauxite is crushed, digested, precipitated, and calcined resulting in alumina. The alumina is then reduced to aluminum by electrolysis. The worldwide Al production is 41.1 million tons in 2010. The global average in energy is consumption is about 15kWh/kg of Al. The production process is energy intensive and used about 3% of global electricity production in 2010.

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Executive Summary:

This paper summarizes the production of aluminum with an emphasis on the material and energy requirements. The production process is categorized as primary production and secondary production process. Primary routes are the Bayer; refining bauxite ore, and Hall-Héroult Process; reduction of alumina to aluminum. The secondary routes are aluminum production from scrap recycling and aluminum hydroxide. Scrap material should contain more than 20% Al to be used in the production which then requires only about 5% of the total energy required. Aluminum hydroxide is a waste in aluminum production can be calcinated directly. Adding the energy required for carbon anode production and smelting, the total energy required is 17kWh/kg. This is only 43% of the energy required in primary Al production.

The global aluminum production in 2010 is 41.4 million tons with an average energy requirement of 15kWh/kg. This is equivalent to 621 billion kilowatt hours of electricity consumption and about 3% of the global electricity production used in aluminum production. The material requirement for this production is about 210 million tons of bauxite, 80 million tons of alumina and 21 million tons of carbon anode are required.

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Introduction

Aluminum is a light metal with density of 2.7g/cm^3 (three times less than of steel) . It is one of those elements which are excessive on earth. It belongs to boron group and is symbolized as Al. It is an excellent heat and electrical conductor with very good reflectivity, resistance to corrosion and ductility. It is used extensively in electronics and offshore structures because its non-magnetic and non-combustible property. It is used primarily for infrastructure, packaging and transportation. It is one of the most highly produced non-ferrous metal in the world, with production of 41.1 million tons in 2010 [7] ; an increase of 3.8million metric tons from 2009. [5]

Aluminum has high affinity for oxygen, thus exist as oxides with different degree of hydration and purity in nature. Bauxites are one such hydrated oxides ($Al_2O_3.xH_2O$) and exist in three main forms; gibbsite, boehmite and diaspora. The latter two have higher hydrated alumina(aluminum oxide) than gibbsite. They have to undergo chemical processing to get pure aluminum from impurities such as iron oxides, silicon oxides and titanium oxides. For economical extraction, bauxite ores should contain greater than 45% alumina, less than 12% iron oxides and less than 8% of combined silica.

The Bayer Process, used to extract the Aluminum from the ore, is so energy-intensive that it takes 95 times more energy to complete this process than to recycle. Bauxite containing ores are first converted into pure aluminum oxide and then electrolyzed in solution of molten cryolite. In this process crushed bauxite is treated with moderately concentrated sodium hydroxide solution, followed by separation of the resulting sodium aluminate solution and selective precipitation of aluminum as aluminum oxide. The process in general requires higher temperature and pressure and is dependent on type of bauxite processed. For bauxites with higher silica content, it is combined with agglomeration process which improves the process. Details of agglomeration process mechanism is discussed in [6]. Once the alumina is produced by the Bayer process, the production of aluminum proceeds by Hall-Héroult process. In this process, alumina is dissolved in molten cryolite after which using electrolyzers, aluminum is collected as precipitate at the cathode.

Production of aluminum is an energy intensive process with total energy consumption depending on source of raw material (bauxite, pure alumina or carbon coke) Although there are processes in

use for more than one hundred years already, the mining industry is still in a constant search for effective material recovery but at the same time, reduced electricity consumption. The overall energy efficiency in efficient US plant is below 30%. Long term energy saving plans aim at reducing the energy consumption to 8.5kWh/kg aluminum from current average value of 13-15kWh/kg. [1] With continuous research and development, the energy and costs for processing aluminum would hopefully be significantly reduced.

Assuming energy consumption of 15kWh/kg, in 2010 around 621 billion kilowatt hours of electricity was consumed to produce such amount of aluminum,. In perspective, around 20261 billion kilowatt hours of electricity is produced globally [8], meaning that a rough three percent of the total electrical supply goes to aluminum extraction. In the same year, Australia, one of the largest aluminum producers in the world, produced around two million tons of the metal and 250 billion kilowatt hours of electricity. In short, around 12 percent of the country's total electrical supply went to the extraction and production of aluminum.

Mostly aluminium is produced in two ways.

1. Primarily Production Process
    1. By refining aluminium from grinding and extracting from bauxite ore - Bayer process
    2. By using reduction process for crystalline alumina - Hall-Héroult process
2. Secondary Production Process
    1. By doing pre-treatment of scraps such as cleaning and sorting
    2. By process of smelting, refining or alloying of aluminium

1 Primary Production

1.1 Bayer process: Refining Bauxite

In this process, the bauxite ore is dried, crushed and ground into a powder. It is then mixed with preheated spent solution. Lime is added to increase the solubility of alumina and the resulting mixture is pumped to digesters along with a solution of caustic soda to extract the alumina. The operation proceeds at elevated temperatures (using high temperature steam) and pressures in digesters. The range of temperature and pressure used depends on the type of bauxite: boehimite, gibbsite or diaspora. For gibbsite, the temperature range is the lowest (about 140^{o}C) while for boehmite, the highest temperature is used.(about 300^{o}C)Bauxite mining step for producing 1kg of aluminum requires about 0.32kWh energy. [2] The following chemical reaction takes place,

$Al(OH)_{3(aq)} + NaOH_{(aq)} \leftrightarrow NaAlO_{2(liq)} + H_2O$

A slurry containing dissolved sodium aluminate and a mixture of metal oxides called red mud is removed in clarifiers. The red mud is washed to recover the chemicals and is disposed. This is accomplished by the following reaction,

$2NaAlO_2 + 4H_2O \rightarrow 2NaOH + Al_2O_3.3H_2O$

The aluminate solution is cooled and seeded with fine crystals of aluminatrihydrate to crystallize the hydrated alumina in precipitator tanks. The alumina is precipitated as trihydrate as crystals which are then washed and then calcined in rotary kilns or fluid bedcalciners to produce the aluminum oxide or alumina. The final reaction is as follows,

$Al_2O_3.3H_2O \rightarrow Al_2.O_3 + 3H_2O$

The rotary kiln temperature is around 1200-1300^{o}C to remove water of hydration which then makes the alumina stable for use in the Hall-Heroult process.

For high silicon content alumina, additional agglomeration step should be included to improve processing and adapt Bayer process for low quality raw material. Agglomeration enables to enlarge the particle size needed for sandy(high silicon) alumina.

Figure 1 shows the production steps involved in Bayer process.: grinding, digestion, clarification, seed preparation, filtration and calcination.

In the Bayer process, bauxite crushed, digested (washed with a hot sodium hydroxide solution (NaOH) at 250 ºC), precipitated (cooled), and calcined (reheated to 1050 ºC) resulting in alumina (Al2O3). Bauxite extraction and the Bayer process require large amounts of energy (10% of the total energy), process water (steam), process materials (caustic soda and lime). In overall perspective, it takes about 2-5 tons of bauxite to get 2tons of alumina which produces 1ton of aluminum.[1] Generally, 5,900kg earth has to mined to produce 5,100kg bauxite which is then refined to produce1,930kg of alumina. [4]

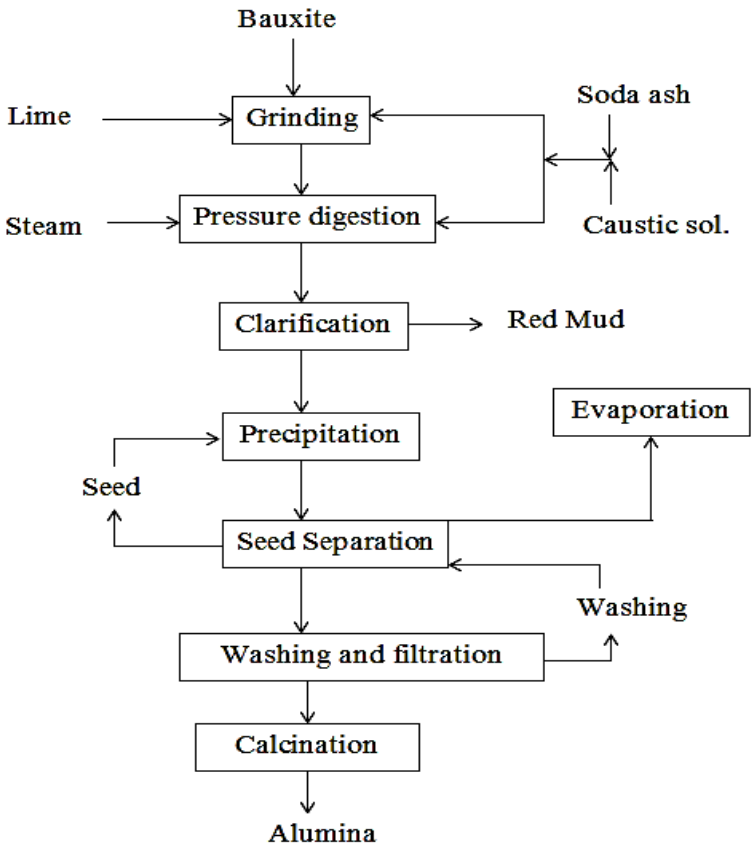

Figure 1 Bayer process flow sheet [2]

In the Bayer process, majority of the energy is consumed in the form of steam. Energy is also consumed in the form of gas or fuel in the calcination process. Electrical energy is used in the main and auxiliary processes. Most refineries co-generate steam and electricity for in plant use or export.

1.2 The Hall-Héroult Process: Reduction of Alumina to Aluminum

Aluminum is produced from alumina by electrolysis in a process known as the Hall-Héroult Process. The alumina is dissolved in an electrolytic bath of molten cryolite (sodium aluminum fluoride) to reduce melting point and thus energy requirement of producing aluminum. A typical composition of the molten cryolite with calcium fluoride and aluminum fluoride is, 75-90% cryolite, 2-8% alumina, 10% aluminum fluoride and 5% calcium fluoride. [2] An electric current is passed through the electrolyte and flows between the anode and cathode. Molten aluminum is produced, deposited at the bottom of the electrolytic cell and periodically siphoned off and transferred to a reverberatory holding furnace. There it is alloyed, fluxed and degassed to remove trace impurities. Finally, the aluminum is cast or transported to the fabricating plants. The reaction is simplified as,

$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$

The equation shows that 2 tons of alumina and 0.5 ton of carbon produces 1 ton of aluminum. The heat of reaction is 290.4kcal/mol or 6.27kWh/kg of aluminum. [1] This is however, the theoretical amount or minimum amount of energy required.

Figure 2 shows the total energy required in primary Al production; Bayer process and Hall-Heroult process. It shows that Al smelting consumes the largest amount of energy. If additional refining is included the total energy is 18kWh/kg of aluminum.[3]

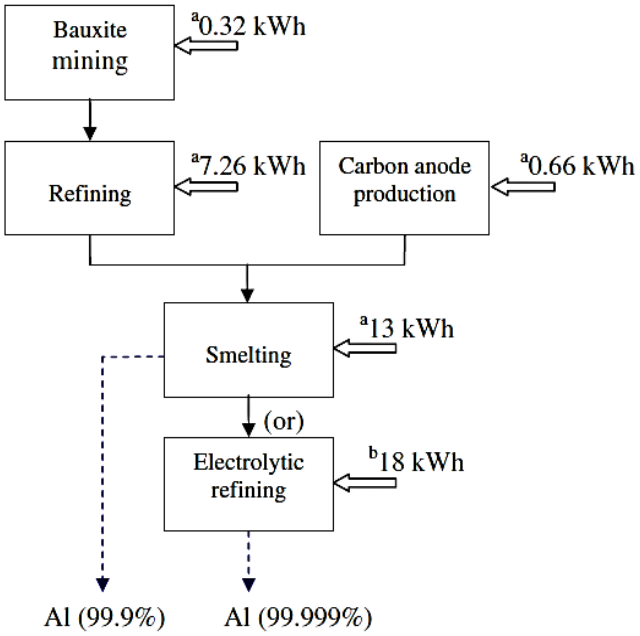

Figure 2 Total energy requirement of primary Al production[3]

The Hall-Heroult process takes over 13MWh electric power to produce 1 metric ton of raw aluminum. The average value for U.S. is about 15kWh/kg with an aim to reduce it to 11kWh/kg.[1,3,4]Electrical efficiency of electrolyzers is between 94-96% in modern plants.[2] The smelting process requires large volumes of carbon (0.4 to 0.5 ton carbon / ton aluminum) and cryolite (Na_3AlF_6).

The material requirement for production 1kg of aluminum is 5.1kg Bauxite, 1.93kg alumina and 0.45kg carbon anode. Energy requirement of primary production of aluminum on the basis of 1kg aluminum is summarized as 0.32kWh for bauxite mining, 7.26kWh for refining, 0.66kWh for carbon anode production, 13kWh for smelting process or 18kWh including electro refining to produce 99.999% purity aluminum. [2,3] This means that for 2010 annual world production of 41.1 million tons aluminum, about 210 million tons of bauxite, 80 million tons of alumina and 21 million tons of carbon anode are required.

2 Secondary production process

In today's world where there is so much Aluminum just lying around everywhere, and can be used over and over indefinitely through recycling there is not much need for the production of Aluminum.

2.1 Scrap recycling

Alternatively scrap materials with Al content of more than 20% can be recycled. To obtain this level of quality, all adherent materials must be removed and the scrap sorted according to alloy type and content. For example turnings are centrifuged and dried to remove the oil and water, iron is separated magnetically while used beverage cans are processed to remove the interior lacquer coating and the outside product display printing inks. This requires about 0.39kWh/kg energy [3] which is about 5% of the total energy required. In Europe, the recycling production is about 40% of aluminum demand in 2010.[9]

2.2 Aluminum hydroxide

Alternative Al can be produced from aluminum hydroxide $Al(OH)_3$. Aluminum hydroxide is a waste in aluminum production and can be assumed to be free of impurities as it has been produced. Thus, it can be calcinated directly requiring a theoretical amount of 3.38kWh/kg aluminum. Adding the energy required for carbon anode production and smelting, the total energy required is 17kWh/kg. This is only 43% of the energy required in primary Al production. (see figure 2).

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