Ultra-High-Purity Aluminum

Subjects: Chemistry, Medicinal
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Properties of high-purity aluminum are the low magnetic permeability, the absence of low-temperature brittleness, as well as the increased strength and plasticity at low temperatures. These explain the classical application of high- to ultra-high-purity aluminum for the stabilization of superconductors running at cryogenic temperatures as low as −269 °C.

Keywords: high-purity aluminum ; purification ; segregation

1. High- and Ultra-High-Purity Aluminum

The primary form of aluminum—from the Hall–Héroult process—has a purity range of 99.7 to 99.9%, with major impurities of iron (Fe), silicon (Si), zinc (Zn), and gallium (Ga). While this purity range is sufficient for most industrial applications and alloying, the use of aluminum in high-technology fields, such as semiconductor, electronics, superconducting, and so forth requires higher purity levels exceeding the ones obtained via classical aluminum production processes [1][2]. To reach such purity, several technologies have been developed. There is no officially standardized terminology for the various levels of purity in aluminum. As seen in **Table 1** , different countries classify the aluminum following their own criteria [3][4].

Table 1. Classification of various aluminum purity terminologies in USA, China, Russia, and Japan, data from [2][3].

Country	Designation/Category	Purity (%)	Nines
USA	Commercial purity	99.50 - 99.79	2N5 - 2N7
	High purity	99.80 - 99.949	2N8 - 3N4
	Super purity	99.950 - 99.9959	3N5 - 4N5
	Extreme purity	99.996 - 99.999	4N6 - 5N
	Ultra purity	≥ 99.999	5N+
China	Primary Al	99.0 - 99.85	2N - 2N8
	Refined Al	99.95 - 99.996	3N5 - 4N6
	High purity Al	≥ 99.996	>4N6
Japan	Second grade	99.950 - 99.990	3N5 - 4N
	First grade	99.990 - 99.995	4N - 4N5
	Special grade	≥ 99.995	>4N5
Russia	Commercial purity	99.0 - 99.85	2N - 2N8
	High purity	99.95 - 99.995	3N5 - 4N5
	Ultra purity	≥ 99.999	5N+

Due to the extremely low amount of impurities in the base metal, its purity level is described as a function of “Nines”. For example, a base metal, in which the sum of the all targeted impurities is equal to 10 ppm, will have a purity of 99.999%, or 5N (“five Nines”). Moreover, a metal with 5 ppm of impurities would have 99.9995% purity and would therefore be described as 5N5.

2. High- and Ultra-High-Purity Aluminum

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3. Main Applications from High-Up to Ultra-High-Purity Aluminum

The aluminum in its high purity has outstanding properties, such as high electric and thermal conductivity. Additionally, when an oxide layer is formed over its surface, high corrosion resistance and electrical insulation can be achieved. Such characteristics grant the usage of high-purity aluminum in integrated circuits, replacing Cu and Au as bonding wires for transistors, where thin films of high-purity aluminum are able to find applications as interconnecting lines in very large-scale integrated (VLSI) circuits [5][6][7].

Further properties of high-purity aluminum are the low magnetic permeability, the absence of low-temperature brittleness, as well as the increased strength and plasticity at low temperatures [8]. These explain the classical application of high- to ultra-high-purity aluminum for the stabilization of superconductors running at cryogenic temperatures as low as −269 °C [9].

Due to its beneficial performances, the application of this material in modern high-technology fields grows together with the advances of modern society. The eve-increasing power efficiency and zero-defect tolerances in the high-tech applications will most likely push the technical requirements and purity tolerances of high- and ultra-high-purity aluminum. The subsections below illustrate some classical utilizations of high-purity aluminum at specific purity ranges.

This class of material is required by the manufacturing of optoelectronic storage media, such as CDs, DVDs, and so forth. Furthermore, the aluminum can be processed into the electrical conductor of the computer storage hard disk via the cathode-sputtering process [10].

4. The Production of High- and Ultra-High-Purity Aluminum

The high-volume and industrial production of high-purity aluminum follow two main routes: three-layer electrolysis and fractional crystallization. While both processes can individually reach 4N8 purity, higher purity levels can be obtained when employing them in series. Alternative routes, such as vacuum distillation and organic electrolysis, are reported in the literature and can be used for low volume production and/or highly specialized applications.

The availability of public information regarding price, production volume, and main consumers are very scarce and quite often regarded as a trade secret among the industry. The small amount of public information available was compiled in the **Table 2** [10].

Table 2. The production capacity of high- and ultra-high-purity aluminum in the world in 2003.

Country	Three-Layer Electrolysis (kt/a)	Segregation (kt/a)	World Total (kt/a)
Japan	5.2	34.3	39.5
Norway	8.0	—	8.0
Russia	15.0	—	15.0
China	28.0	5.0	33.0
United States	—	20.0	20.0
Germany	4.5	7.0	11.5
France	2.0	—	2.0

Country	Three-Layer Electrolysis (kt/a)	Segregation (kt/a)	World Total (kt/a)
World total	**62.7**	**66.3**	**129.0**

The price of high-purity aluminum increases exponentially according to its purity degree (see **Table 3**). According to the London Metal Exchange (LME), the price of 2N7 Al was 2.45 $/kg in June 2021 [11]. Despite the variance between suppliers and the format (ingot, foil, etc.), a price range for several aluminum purities was obtained from the company Laurand Associates Inc, where, for the same period, the price per kilogram of pellets ranges from 275 US$ for 4N up to 900 US$ for 6N purity [12].

Table 3. The price per kilogram of aluminum in the western market in 2021, data from [11][12].

Purity	Price (Western Spot Market, $/kg)
2N7	**2.45**
4N	**275**
4N6	**300**
5N	**600**
6N	**900**

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