Reduction of Anode Gross Consumption with Anti-Oxidation Coating in 500 kA Cells

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Abstract

Anode consumption is a key economic indicator in aluminium electrolysis production. Reducing anode consumption can directly lower production costs and bring significant economic returns to smelters. This paper presents the primary mechanisms of anode consumption, along with the influence of anode quality and operational techniques. A technology aimed at reducing anode consumption was developed based on structural optimization, where anode anti-oxidation coatings and increased anode carbon block height are essential measures. After implementation in 500 kA aluminium reduction cells, anode gross consumption was reduced by 12.7 kg C/t Al, giving considerable economic returns and offering a valuable reference for the industry. The anode cycle was extended from 36 to 37 days, providing further advantage of this technology.

Keywords: 500 kA aluminium reduction cell, Anode consumption, Anode coating, Increased anode height, Anode cycle.

1. Introduction

With global economic growth and the continuous rise in aluminium demand across industries, the aluminium sector has expanded significantly, becoming an essential component of modern industrial systems. Electrolytic aluminium production is the only method in the aluminium manufacturing process. High amperage, high productivity 500 kA aluminium reduction cell is widely used in China. It offers advantages such as high production capacity and relatively high energy efficiency, which reduced production cost. In aluminium electrolysis production, the anode carbon block is a key consumable material, accounting for a significant portion of total production costs. Anode consumption refers to the amount of carbon anode consumed per tonne of aluminium produced. Reducing it contributes to lowering production costs, while also supporting resource utilization and environmental protection.

1.1 Current Developments Domestically and Internationally

Although China started aluminium production in advanced aluminium electrolysis technologies, later than Europe and North America, it has made rapid advancements in recent years. Chinese universities and research institutes have made breakthroughs through industry-academia collaboration—such as enhancing anode material performance (e.g., by incorporating additives to improve oxidation resistance) and developing proprietary intelligent control technologies for the cells. Major aluminium producers have increased investment, introduced innovative technologies, and reduced raw material consumption by improving anode assembly and optimizing electrolyte composition. China's push for sustainable development in the aluminium smelting industry continues to drive progress in this field, with expectations of narrowing the gap with other nations or even surpassing them.

Developed countries have a solid foundation: Europe, Canada and the U.S.A. began the development of cell technologies early. They have achieved significant results in developing advanced anode materials (e.g., high-density, high-conductivity carbon blocks), optimizing cell structures (e.g., geometric design and MHD flow improvements), and applying advanced monitoring and control technologies. Japan emphasizes precision management and innovation, optimizing anode manufacturing and use through meticulous control of raw material ratios and baking parameters, while integrating multidisciplinary knowledge into cutting-edge equipment development.

1.2 Significance of Research on Reduction of Anode Consumption

Reducing anode consumption has far-reaching implications for the sustainability of the aluminium smelting industry and society as a whole. It contributes to sustainable use of resources by decreasing the consumption of scarce carbon materials in anode production. Additionally, reducing anode consumption increases energy efficiency and lowers energy costs. Finally, it enhances the industry's ability to respond to emergencies, ensuring stable production and a reliable aluminium supply during energy shortages.

2. Main Mechanisms of Anode Consumption

In aluminium electrolysis, anode consumption primarily occurs through electrochemical reactions, physical loss, oxidation, and electrochemical reactions. The main mechanism of anode consumption is the oxidation reaction between carbon in the anode and the oxygen produced during electrolysis. Adding to it is anode air-oxidation, Boudouard reaction and anode dust generation. Impurities and additives in the electrolyte may also increase consumption. Thermal stress may lead to the loss by anode cracking and breaking.

2.1 Chemical Reactions in Anode Consumption

Chemical consumption refers to carbon anode loss due to aluminium electrolysis, air oxidation and Boudouard reaction.

The primary electrochemical reaction is given in Equation (1).

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

The aluminium dissolved in the electrolyte may further react with CO_2 produced at the anode in the so called back reaction:

$$3CO_2(g) + 2Al(diss) \rightarrow 3CO\ (g) + Al_2O_3(diss) \quad (2)$$

Air oxidation of the anode is given in Equations (3) and (4). In prebaked anodes, this occurs above 400 °C at the top and side surfaces exposed to air.

$$C\ (anode) + O_2(g) = CO_2(g) \quad (3)$$

or

$$2C\ (anode) + O_2(g) = 2CO(g) \quad (4)$$

The Boudouard reaction, also known as CO_2 burn of the anodes is given in Equation (5).

$$CO_2(g) + C(anode) = 2CO(g) \tag{5}$$

These processes are illustrated in Figure 1. Studies show the reaction occurs not only on the anode surface but can penetrate 5–10 cm into the anode. This reaction significantly impacts anode consumption, typically accounting for 5–10 % of total consumption.

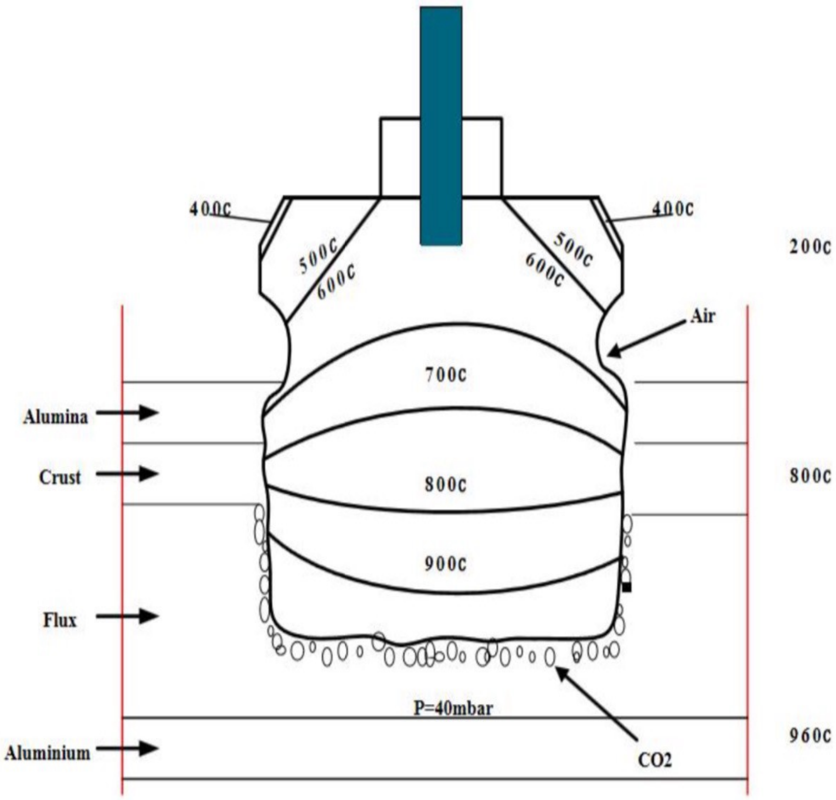

Figure 1. Carbon anode reactions.

2.2 Analysis of Key Factors Affecting Anode Consumption

Anode consumption is inevitable, and the key influencing factors include current density, electrolysis temperature, anode material quality, electrolyte composition, operational quality, butts handling, as well as anode shape and size. To reduce anode consumption, a comprehensive approach should be taken to analyse, optimize, and improve these aspects (Table 1).

Table 1. Analysis and optimization of key factors affecting anode consumption.

Factor	Influencing Mechanism	Data Analysis	Optimization Suggestions
Current density	Higher current density accelerates oxidation of anode material, resulting in increased consumption.	Electrolytic anode consumption rate is proportional to current density	Reduce current density while maintaining stable cell operation; optimize cell structure and operational parameters to improve current efficiency.
Bath temperature	High temperatures accelerate anode oxidation	For every degree increase in bath temperature, anode consumption rises significantly.	Optimize thermal balance to maintain low and stable bath temperature
Anode quality	Physical and chemical properties of the anode	Under the same electrolysis conditions, anodes made	Select high-quality anode: dense, low-porosity, high-strength, and

	directly affect consumption rate; poor-quality materials are more prone to oxidation and physical loss.	from different-quality materials show significant differences in consumption rates.	oxidation-resistant; optimize production processes and material formulas.
Bath composition	Impurities and additives in the bath may cause side reactions with anode carbon, increasing consumption.	Types and concentrations of impurities and additives in the bath have a significant impact on anode consumption.	Optimize the composition and concentration of additives in the bath; reduce harmful impurities; add appropriate antioxidants and stabilizers; strengthen purification and filtration.
Operational management	Improper operation may cause physical damage or accelerate oxidation of anodes.	Poor operational management can lead to a significant increase in anode consumption.	Improve cell operation management, operator skills and sense of responsibility, conduct regular inspection and maintenance of cells.
Butts handling	Improper handling of butts may cause increased consumption, such as carbon dust loss or anode cracking.	Improper handling of butts can significantly increase anode consumption.	Optimize butt processing to reduce carbon dust loss and damage from cracking; adopt advanced butt recovery technologies and equipment.
Anode shape and size	Anode shape and size can influence current distribution and oxidation rate during electrolysis.	Anodes of different shapes and sizes show significant differences in consumption under the same electrolysis conditions.	Optimize anode geometry by chamfering, slotting, or reducing the upper protruding volume; appropriately increase anode height and bulk density.

3. Impact of Anode and Operation Quality on Anode Consumption

Anode quality has a significant impact on anode consumption. High-quality anodes reduce consumption, improve cell performance, and enhance economic benefits. Poor and unstable anode quality results in high anode resistivity, up to 65 μΩ·m, whereas high-quality anodes can achieve lower resistivity of 55 μΩ·m or even less.

Voltage drop of domestic anode carbon blocks remains relatively high and does not meet advanced international benchmarks. A specific plant is currently conducting on-site monitoring of anode voltage drop. Compared to national standards, the quality is unstable and frequently exceeds the permissible limits. A significant gap remains compared to foreign standards, particularly in the control of microelement impurities. Due to the inconsistency in the quality of petroleum coke and pitch, along with improper formulation, the anodes are prone to dusting, which is also a major factor leading to higher anode consumption.

3.1 Selection and Preparation of Anode Materials

Prebaked anodes are made of petroleum coke and coal tar pitch as a binder. The selection and preparation of anode materials are critical for reducing consumption and improving efficiency. For example, selecting petroleum coke with uniform particle size and low impurity content can yield better-performing anodes.

Raw materials must first be pretreated. Coke is calcined to remove volatiles and pitch is heated until molten. Then both are mixed in a mixer at controlled temperature and timing. Next, the mix is formed into green anode blocks by extrusion or vibration. These blocks are then baked in furnaces at high temperature to form prebaked anodes, with strict control of temperature curves. Finally, machined processes such as turning and drilling are carried out on baked anodes, and coatings may be applied to increase oxidation resistance. Throughout the process, various factors must be comprehensively considered to optimize anode performance and support sustainable industry development.

3.2 Impact of Anode Physical Properties on Consumption

The physical properties of the anode significantly affect its consumption. High-density anodes have low internal porosity, limiting contact with electrolyte and oxidizing gases, thereby reducing consumption. High-strength anodes better withstand thermal stress and mechanical forces, preventing particle detachment and crack formation. Good thermal conductivity ensures even heat dissipation, avoiding local overheating that could accelerate oxidation or crack formation from thermal stress. High porosity increases contact area with electrolyte and oxidizing gases, accelerating electrochemical and oxidation reactions, as well as electrolyte penetration, which increases consumption. Excessive resistivity causes more power loss and heat generation, leading to faster oxidation; uneven current distribution and increasing localized anode consumption. Optimizing physical properties of anodes plays a vital role in reducing consumption and improving energy efficiency.

3.3 Impact of Production Technology and Operations on Anode Consumption

In aluminium electrolysis production, various stages of production technology and operations are closely related to anode consumption and have multifaceted impacts, as detailed below:

3.3.1 Cell Operating Parameters Setup and Optimization

The setup and optimization of cell operating parameters play a key role in anode consumption, production efficiency, and product quality. Cell voltage is a critical parameter. Reducing cell voltage appropriately can reduce energy consumption and help lower the rate of electrochemical reactions on the anode, thus decreasing anode consumption. However, too low a cell voltage may lead to reduction process instability, affecting current efficiency and quality. Therefore, the cell voltage must be adjusted precisely based on the specific conditions of the cell, such as electrolyte composition and anode performance. For example, optimizing electrolyte conductivity and improving anode quality can reduce cell voltage while ensuring stable electrolysis. Additionally, attention must be given to voltage fluctuations, as large voltage variations can increase anode consumption. Voltage fluctuations can be minimized by stabilizing the power supply and optimizing the control system.

3.3.2 Anode Change Operation and Anode Management Strategy

Anode change operations and anode management strategies are critical for reducing anode consumption, ensuring stable operation of the electrolytic cell, and improving production efficiency. Before the anode change, proper preparation is necessary. The quality of the new anode should be good without any cracks. During the anode replacement, the operation must be standardized. The crust around the old anode should be broken to allow easy raising the old anode without damage to the potlining and other cell components. After removing the old anode, the cavity should be cleaned and the crust and carbon removed to ensure good contact between the anode and electrolyte. Then the anode rod is securely connected to the anode beam to make good contact and uniform current distribution. Once the anode change is completed, check the current drawn by the new anode at 24 h and make adjustments if needed. Handle the anode butts properly between the potroom and the anode centre, and clean the butts for recycling into new anodes.

4. Anode Anti-Oxidation Coating and Enhancement Technology

Anti-oxidation coatings and enhancement technologies that reduce anode oxidation involve several principles [1–4]. They form a continuous, dense protective film on the anode surface, and reduce air penetration. Certain coating components can react with oxygen or active sites on the anode surface to inhibit oxidation reactions. They also improve the anode thermal stability, ensuring uniform surface temperature and reducing local overheating that accelerates oxidation. These coatings remain stable under high temperatures, maintaining continuous anti-oxidation properties. Additionally, low surface energy coatings reduce oxygen adsorption and electrolyte attachment erosion. Through synergistic principles like physical isolation, chemical inhibition, improved thermal stability, and reduced surface energy, the coatings reduce anode oxidation, prolong anode life, and improve production efficiency.

4.1 Protection Mechanism of Anti-Oxidation Coatings

The application of anti-oxidation coatings not only reduces anode consumption but also improves the overall cell operation. Taking nano-ceramic-based high-temperature anti-oxidation coatings as an example, the mechanism can be further explained as follows:

1) Coating formation: The nano-ceramic-based high-temperature anti-oxidation coating material is applied to the anode carbon block surface using methods such as spraying to form a uniform coating layer.
2) High-temperature curing: In the high-temperature environment of the cell, the coating gradually cures and forms a dense ceramic-based barrier layer.
3) Oxidation barrier: The cured coating effectively blocks oxygen and electrolyte vapor from directly contacting the anode carbon block, slowing the oxidation rate of the anode.
4) Reducing consumption: By reducing the oxidation reactions and physical losses of the anode, the coating significantly decreases the anode consumption rate, extending the anode service life.

In conclusion, anti-oxidation coatings effectively reduce the anode consumption rate in the aluminium electrolysis process through multiple mechanisms, such as blocking direct contact with oxygen, enhancing oxidation resistance, reducing physical losses, and improving the cell operation.

4.2 Coating and Enhancement Technology Experiment in 500 kA Cells

The test was performed on carbon anodes with the height of 685 mm and the anode cycle extended from 36 to 37 days. This experiment was carried out eight 500 kA cells, numbered 615–623, excluding cell 616 which was an outlier. The daily anode consumption was approximately 32 anodes.

After the first cycle (36 days), anode butts were measured during one week (from 4–10 April 2025). After conditions were met, the cycle was extended to 37 days, and the data were continuously tracked.

4.2.1 Analysis of the Results

According to the plan, butt dimensions were measured during the second anode cycle on the 8 test cells, and the results were compared, as shown in Table 2.

Table 2. Butt dimensions for the second cycle (average values).

Anodes	Butt length (mm)	Butt width (mm)	Butt height (mm)	New anode height (mm)	Actual consumption height (mm)	Butt minimum height 10 % (mm)
A: Coated	1771	771	170.2	685	514.8	151.2
B: Uncoated	1755	753	153.2	686	532.8	139.3
A-B	16	18	17	-1	-18	11.9

Note: A represents the experimental group, and B represents the comparison group (36-day cycle).

When comparing the coated anodes to the reference ones, the coated anodes consumed 18 mm less carbon than the reference ones. The consumption of the experimental anodes over a 36-day period was 514.8 mm, which corresponds to a daily consumption of 14.3 mm. For the uncoated anodes, the 36-day consumption was 532.8 mm, equating to a daily consumption of 14.8 mm.

By calculating and averaging the butt thickness at the minimum 10 % height, the coated anode average thickness was 151.2 mm, while the uncoated anode was 149.3 mm, with the experimental anode being 11.9 mm thicker.

This indicates that the experimental anode, protected by the coating, experienced less consumption and demonstrated stronger resistance to the exposure of the sub bottom over the following 37 days.

Table 3. Comparison of other data for the butt after one week.

Anodes	Number of anodes	Bottom exposure count	Corner drop count	Shadowing count
A: Coated	34	0	0	0
B: Uncoated	34	0	0	0
Total	68	0	0	0

Note: A represents the experimental group, and B represents the comparison group.

As shown in Tables 3 and 4, neither the experimental nor comparison anodes showed any stub bottom exposure, corner drop, or shadowing, indicating that the aluminium quality remained consistent. After calculation, both the experimental and comparison anodes met the requirements for extending the cycle by one additional day.

Table 4. Fe and Si content in the aluminium produced (in %)

Fe content variations of enhanced anodes								
Cell number	2025.4.4	2025.4.5	2025.4.6	2025.4.7	2025.4.8	2025.4.9	2025.4.10	Average
615	0.071	0.065	0.065	0.067	0.067	0.069	0.068	0.067
617	0.075	0.076	0.075	0.075	0.078	0.08	0.085	0.078
618	0.105	0.105	0.105	0.101	0.097	0.1	0.091	0.100
619	0.058	0.06	0.071	0.072	0.069	0.071	0.068	0.069
620	0.099	0.102	0.097	0.096	0.092	0.094	0.089	0.095
621	0.091	0.088	0.088	0.089	0.088	0.082	0.083	0.086
622	0.081	0.084	0.081	0.082	0.083	0.077	0.079	0.081
623	0.093	0.094	0.099	0.098	0.094	0.09	0.089	0.094
Si content variations of enhanced anodes								
Cell number	2025.4.4	2025.4.5	2025.4.6	2025.4.7	2025.4.8	2025.4.9	2025.4.10	Average
615	0.039	0.037	0.036	0.037	0.037	0.037	0.037	0.037
617	0.033	0.034	0.034	0.035	0.035	0.035	0.033	0.034
618	0.036	0.037	0.038	0.037	0.036	0.037	0.036	0.037
619	0.034	0.035	0.036	0.036	0.037	0.037	0.036	0.036
620	0.034	0.035	0.035	0.035	0.035	0.034	0.034	0.035
621	0.038	0.038	0.038	0.038	0.037	0.035	0.036	0.037
622	0.036	0.037	0.036	0.037	0.039	0.037	0.037	0.037
623	0.041	0.042	0.042	0.041	0.041	0.039	0.038	0.041

Note: Cells 615#, 617#, 618#, and 619# are the A experimental group with coated anodes, while cells 620#, 621#, 622#, and 623# are the B comparison group with uncoated anodes.

5. Economic Benefit Analysis

According to Table 5, if coated anodes are fully implemented throughout the plant, based on an annual production capacity of 400 kt/y, the annual net benefit can reach RMB 3.558 million (492 kUSD/y approx.).

Table 5. Calculation of anode carbon savings and coating expenditure.

Category	Item	Data
Cost savings from carbon consumption reduction	Average daily tapping volume per cell	3.68 tonnes
	Anode carbon block weight	1301 kg/block
	Anode carbon block price	3 800 RMB/t
	Annual metal production	400 000 tonnes
	Original anode gross carbon consumption per tonne of aluminium	471.3 kg C/t Al
	Anode gross carbon consumption per tonne of aluminium after one-day anode life extension	458.6 kg C/t Al
	Reduction in anode gross carbon consumption per tonne of aluminium	12.7 kg C/t Al
	Annual reduction in anode carbon block consumption	5 080 t-C/year
	Annual cost savings	RMB 19.304 million/year
Coating expenditure	Coating consumption per anode (test)	4.816 kg
	Coating consumption per tonne of aluminium	2.32 kg
	Coating unit price	16.5 RMB/kg
	Coating cost per tonne of aluminium	38.28 RMB/t Al
	Annual coating cost	15.312 million RMB
	Equipment cost	74 000/ RMB/year
	Labor cost	360 kRMB/year
	Total annual coating cost	15.746 million RMB

6. Conclusions

This paper provides an in-depth analysis and application study of technologies aimed at reducing anode consumption in 500 kA aluminium reduction cells. As a key economic indicator in aluminium electrolysis production, the reduction of anode consumption is directly linked to lowering production costs and improving economic efficiency.

The paper first elaborates on the main mechanisms of anode consumption, clarifying the modes and causes of consumption; it then analyses influencing factors such as anode quality and production operations and their specific impacts. It focuses on the role of anti-oxidation coating technology and of anode height increase. To effectiveness of this antioxidation coating was tested on 500 kA cells. The anode cycle was successfully increased from 36 days to 37 days, and anode consumption decreased by 12.7 kg C/t Al.

7. References

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