A Preparation of Ultra-Low-Consumption Anode for Aluminium Electrolysis and Its Production Pilot

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https://doi.org/10.71659/icsoba2025-al033

Abstract

The Chinese government has been increasingly stringent in managing carbon emissions from aluminium electrolysis. To reduce these emissions and improve anode utilization efficiency, this study addresses issues such as rapid consumption and severe oxidation in traditional anodes by developing a novel ultra-low-consumption anode preparation technology. By reconstructing the 3D internal structure of the anode and analysing its porosity and pore size distribution, the study innovatively introduces impregnation and filling of coke particles, gap weight gain, and surface anti-oxidation technology, which achieves a dual high-efficiency combination of weight enhancement and oxidation resistance. During the pilot in aluminium electrolysis production, key indicators such as consumption rate and oxidation degree were tracked and monitored. The results demonstrate that the novel ultra-low-consumption anode significantly enhances the oxidation resistance of the anode and increases its density. The consumption rate of the novel anode is markedly reduced, achieving the expected goal of extending the anode cycle by 2 days. This technology offers advantages such as simple operation, low cost, and significant effectiveness, demonstrating promising potential for widespread application.

Keywords: Ultra-low-consumption anode, Anode cycle, Weight enhancement, Oxidation resistance.

1. Research Background and Current Status

China's aluminium electrolysis industry has maintained global leadership since the 21st century. In 2024, its output reached 43.393 million tonnes (according to International Aluminium Institute statistics), accounting for a 59 % of global production. In the first half of 2025, electrolytic aluminium output reached 21.552 million tonnes, with a cumulative growth rate of 6.9 %, demonstrating steady expansion. However, China's current efficiency remains in the range of 90–93 %, while the anode gross consumption stands at 470 kg/t Al. However, the issue of excessive consumption caused by low-quality anodes remains prominent, reducing current efficiency by 0.5–1.2 %. Additionally, anode surface oxidation not only increases CO_2 emissions per tonne of aluminium by 3–5 % but also carries fluorides, contributing to environmental pollution. Currently, the global electrolytic aluminium industry still predominantly uses traditional anodes characterized by high porosity (12–15 %) and high carbon consumption. For China, however, it is imperative to enhance anode performance through technological innovation, such as reducing porosity to below 8 % and lowering carbon consumption to under 450 kg/t Al. This has become a critical focus for breaking through production capacity bottlenecks and supporting the achievement of the "dual-carbon" goals, holding paramount significance for advancing the sustainable and high-quality development of China's electrolytic aluminium industry.

Zhang proposed that the air oxidation resistance of anodes is primarily influenced by the quality of green petroleum coke and the density of prebaked anodes, among other factors. He found that ensuring minimal volatile content and fine powder in green petroleum coke could enhance the anode's oxidation resistance. However, in actual production processes, numerous uncontrollable factors make it difficult to maintain a stable composition. Therefore, in practice, post-treatment of anodes is often employed, and such treatment has been shown to improve the oxidation resistance of anodes [1]. Durkić and Lee discovered the inhibitory effects of boron and phosphorus on the oxidation reactivity of carbon atoms [2, 3]. Later, Tosta proposed that the suppression of carbon oxidation by boron and phosphorus could also be applied to carbon anodes [4]. Ishak impregnated the anode surface with a boron oxide solution, followed by heating and drying to form a boron oxide protective layer, while Mirtchi sprayed and dried the anode with a boron-containing mixed solution incorporating AlF_3 and other insoluble compounds [5, 6]. All these researchers experimentally demonstrated a reduction in the air reactivity and CO_2 reactivity of the anodes.

Domestic researchers have also conducted research on antioxidant coatings for anodes. Hongquan Gao employed an alumina sol composite coating, which demonstrated effective anti-oxidation performance across the entire operating temperature range of the anode. However, the study only investigated the variation of coating pore size with temperature and did not include cell pilot tests, thus lacking persuasiveness [7]. Ping Lin adopted a composite coating structure combining a transition layer, barrier layer, and sealing layer. SEM analysis showed that the anodic oxidation loss of the anode coating prepared with the optimal formulation was reduced by 70 % compared to the bare sample [8]. Ling Li further incorporated fluoride-resistant materials into the antioxidant coating to mitigate fluorine gas corrosion, though this coating lacks industrial test data support [9]. In recent years, researchers have proposed the application of nano-ceramic-based high-temperature anti-oxidation coatings. Shunhua Li, Boyi Wang, et al. coated the carbon anode surface of a 420 kA electrolytic cell with BY-4 nano-ceramic-based anti-oxidation coating material. The results demonstrated that the nano-coating has good anti-oxidation effects in practical industrial applications, effectively mitigating carbon anode slagging and extending the anode replacement cycle by 1.33 days [10]. The raw materials for the antioxidant coating on the anode consist of aggregates and binders mixed. The aggregates in the coating primarily use alumina powder, which has no impact on the bath or the quality of primary aluminium. As for the binder, there are generally two types: inorganic binders and organic binders. Research shows that under the high-temperature and highly corrosive environment of the electrolytic cell, organic binders undergo pyrolysis or chemical reactions, losing their adhesive properties and causing the coating to peel off extensively, thereby failing to provide protection. Inorganic binders can maintain their bonding performance in the electrolytic environment [11].

The presence of anode pores is the root cause of carbon residue formation. Therefore, from the perspective of reducing anode porosity, the impregnation roasting process has been proposed. Domestic and international studies have shown that the impregnation roasting process can effectively reduce the porosity of carbon materials and increase the bulk density [12]. This process has been widely used in the production of carbon products such as graphite electrodes and C/C composites. However, its application in the production of aluminium carbon anodes remains limited.

Hanxiang Jiang et al. proposed a solution impregnation method, where $AlCl_3$ solution reacts with ammonia water to generate $Al(OH)_3$ that impregnates anode pores. After roasting at 950 °C, Al_2O_3 forms and remains in the anode pores. However, this process has low filling efficiency and high post-impregnation roasting costs [13]. Jinliang Wang et al. proposed an impregnation and roasting process for anodes, where prebaked anodes are placed in a high-pressure impregnation tank and impregnated with coal tar pitch, followed by post-impregnation baking according to a specific temperature curve to produce "one-impregnation two-baking" anodes. This process can effectively improve the physicochemical properties of anodes, but its high cost prevents industrial application in aluminium production [14]. Linyong Wei et al. introduced an anode adsorption process and conducted industrial tests, demonstrating that this method could bring significant economic returns to electrolytic production. For impregnation tests, the two most critical aspects are the theoretical research on impregnation and the selection of impregnating agents [15].

Inert anode aluminium electrolysis technology is the key to achieving the "carbon neutrality" and "carbon peak" goals in the aluminium electrolysis industry. he inert anode material is the core of inert anode aluminium electrolysis technology and has always been a research hotspot in the aluminium electrolysis industry. Its material types mainly include alloy systems, oxide ceramic systems, and cermet systems [16]. Since the late 20th century, researchers worldwide have conducted electrolysis tests on alloy-based $NiFe_2O_4$-M inert anodes, but none have achieved satisfactory results. The main issues include severe anode oxidation and cracking, as well as excessive iron impurities in the produced molten aluminium [17]. For oxide ceramic system materials, certain research has been conducted both domestically and internationally. Studies have revealed that oxide ceramic anodes such as SnO_2 and $NiFe_2O_4$ have extremely low electrical conductivity, merely 0.57 S/cm at 950 °C, whereas industrial carbon anodes can achieve a conductivity of up to 200 S/cm at the same temperature, indicating a severe deficiency in conductive capability. Additionally, oxide ceramic system materials suffer from poor thermal shock resistance and inferior weldability, significantly limiting their potential for industrial application [18, 19]. Metal ceramic anode materials, composed of metals and ceramic oxides, are considered highly promising inert anode materials [20]. However, the currently developed metal-ceramic system anode materials have poor corrosion resistance, resulting in molten aluminium with high impurity levels when used as anodes. In summary, while significant progress has been made in inert anode research, many challenges remain unresolved. The current inert anode aluminium electrolysis technology is far from ready to transition from laboratory studies to industrial tests, let alone achieving industrial application.

The anode contains trace elements such as Na, S, Ni, Ca, Fe, V, and Si, which generally originate from petroleum coke and coal tar pitch. These trace elements significantly impact the anode's performance [21]. Fengqin Liu et al. analysed the trace elements in anode-grade petroleum coke, noting that certain trace elements can affect the CO_2 and air reactivity of the resulting anodes. Elements such as Na, V, and Ca have strong catalytic effects on the CO_2 reactivity and air reactivity of raw petroleum coke. Similarly, Batista and Kaibin Chen et al. conducted related studies, detailing the specific influence of Na content in petroleum coke on the CO_2 and air reactivity of anodes. They emphasized that removing Na from spent anodes is particularly crucial for anodes produced from low-sulphur petroleum coke [22, 24]. Jing Xiao et al. proposed an anode composite additive composed of compounds containing four key elements (Al, Mg, F, and O), which was reported to enhance the physicochemical properties of the anode [25]. Qinghong Li et al. investigated the effects of Li_2CO_3 and AlF_3 additives on anode carbon blocks. Their results showed that Li_2CO_3 increased the oxidation activity of the carbon blocks, while AlF_3 improved the oxidation resistance of the anode. Since Li_2CO_3 can reduce anode overvoltage, they proposed using a composite additive of Li_2CO_3 and AlF_3[26].

An anode impregnation process is adopted, which enhances the anode's oxidation resistance and reduces its reactivity with CO_2 and air by optimizing the impregnation agent formulation and developing a room-temperature, atmospheric-pressure impregnation-drying coating technique, thereby minimizing excessive anode consumption. The project independently designed the relevant equipment and process flow, utilizing the gravitational force of the impregnation agent to infiltrate the anode pores at room temperature and atmospheric pressure. Additionally, it rationally arranged the production and drying workshops and validated the feasibility of waste heat recovery technology. Through cell pilot scale tests, the practical application effects and economic performance of antioxidant anodes were investigated. Meanwhile, by combining historical data with expert experience, key factors affecting current efficiency were analysed, and a strategy for adjusting anode weight based on current distribution was proposed to realize the digital fine management of aluminium electrolysis anode loading.

2. Core Scheme for Ultra-Low-Consumption Anode Preparation

2.1 3D Structure Reconstruction and Pore Regulation

The performance and service life of aluminium electrolysis anodes are significantly influenced by their internal pore structure. Due to raw material characteristics and production processes, pores form within carbon products, disrupting the continuity of the carbon matrix and potentially serving as channels for fluid transport. The total porosity of anodes typically ranges 16–25 %, with pores generated during the baking process constituting the majority. These pores can be categorized as open or closed pores. The Boudouard reaction has selective oxidation characteristics, primarily oxidizing binder coke and occurring within the anode's internal pores. Reducing anode porosity can mitigate the Boudouard reaction, thereby decreasing carbon residue generation.

This study investigated the high-temperature oxidation resistance of anode materials by conducting high-temperature oxidation tests in a resistance furnace. The mass loss method was used to determine the oxidation resistance of the sample, which involves measuring the sample mass before and after oxidation and calculating the oxidation mass loss rate using the equation:

$$w = \frac{mass\ before\ heating\ -\ mass\ after\ heating}{mass\ before\ heating} \times 100\ \% \tag{1}$$

The standards for carbon and graphite established by the International Union of Pure and Applied Chemistry were referenced to evaluate the adjustment of pore size in carbon anodes.

2.2 Carbon Particle Gap Impregnation Weight Gain Technology

This technology addresses the structural defects of anodes by employing a patented atmospheric pressure impregnation process and a nano-composite impregnation agent. Through carbon powder oxidation tests and orthogonal experimental design (4 factors at 3 levels: antioxidant/dispersant concentration, types of reinforcing agents/binders), the optimal formulation was screened and optimized. Due to confidentiality concerns, the types of reinforcing agents and binders are represented as A-C and a-c, respectively. Integrated with modular equipment (impregnation, impregnation agent circulation, and waste heat recovery systems) and intelligent anode data analysis, the technology simultaneously improves anode air reactivity, CO_2 reactivity, compressive strength, and conductivity. The optimal nano-composite impregnation agent formulation and process conditions were ultimately determined through carbon block impregnation tests (validated by burn-off comparison in Table 1), solidifying resistivity and oxidation resistance indicators. This systematically resolves anode performance bottlenecks while achieving process automation and differentiated control.

Table 1. Orthogonal test design for ultra-low-consumption formulation.

	Factors			
Level	**A–Antioxidant concentration /%**	**B–Dispersant concentration /%**	**C–Reinforcing agent type**	**D–Binder type**
1	2	0.1	A	a
2	3	0.2	B	b
3	4	0.3	C	c

The development test data for coated carbon blocks were collected, and the optimal coating for loss on ignition effect was determined by comparing the loss on ignition measures of coated and uncoated carbon blocks in a muffle furnace. Table 2 gives the comparative loss on ignition (LOI) data of the carbon blocks.

Table 2. Comparison data of carbon block LOI

Sample	Initial weight, g	Weight after coating, g	Weight gain. g	Weight after ignition, g	Loss on ignition, g	LOI rate, %
1	186.84	205.66	18.82	180.75	24.91	12.11
2	189.28	202.94	13.66	179.65	23.29	11.48
3	186.74	198.03	11.29	180.78	17.25	8.71
4	187.08	199.22	12.14	155.54	43.68	21.93
5	187.79	202.01	14.22	155.6	46.41	22.97
6	189.59	202.18	12.59	175.25	26.93	13.32

According to comparative test data with other coated carbon blocks on the market, the LOI after 72-hour roasting at different temperatures using standard sampled carbon blocks shows that a lower LOI rate indicates better performance. Anode testing was conducted by comparing the baseline formulation with ordinary anodes in an electrolytic cell for 96 hours to evaluate the structural stability and high-temperature resistance of the coating. The coating cost was controlled by adjusting the material ratio while ensuring trace elements remained within specified limits, and the optimal coating dosage was determined. In the high-temperature oxidation resistance test using a muffle furnace, samples with different treatments were placed in the muffle furnace, with static air as the oxidizing atmosphere. The oxidation temperature was set at 550 °C, and the samples were taken out every 2.5 hours for cooling and weighing to calculate the oxidation weight loss rate. Table 2 gives the results of the orthogonal test on the ultra-low consumption formulation, and the optimal solution was determined to be $A_3B_2C_3D_5$.

2.3 Surface Anti-Oxidation Coating Technology

For the anode operating in the electrolytic cell, high-temperature corrosive gas scouring and raw material differences lead to selective reactions, causing enlarged surface pores and reduced structural stability. To address such issues, a surface sealing treatment is applied to the impregnated anode, including two methods: sealing after impregnation and drying, and sealing after drying and assembly. By utilizing the waste heat of the anode surface, a structurally stable sealing agent is sprayed to rapidly form a high-temperature-resistant and corrosion-resistant sealing layer, which enhances the anti-oxidation capability at high temperatures and structural strength, reduces mechanical wear, and lowers carbon consumption per tonne of aluminium. This study selected four materials, including AI–1, ZC–1, B–1, and F–2, as spray coatings to determine the coating formulation and the respective additive amounts. A vertical shear agitation and dispersion machine was employed for stirring, and an airless high-pressure spray gun was used for coating application. Through a specific feeding sequence, an excellent anti-oxidation coating was achieved on the anode surface, enhancing the overall performance and service life of the anode.

3. Pilot Production Design and Testing Methods

3.1 Industrial Test Plan

The electrolysis workshop No. 3 of a smelter was selected as the test site, with cells 1309#, 1310#, 1319#, and 1320# designated as test cells for the carbon rod operation test. Four carbon rods from the same anode production batch were chosen as the test group samples, while carbon rods with similar dimensions but without impregnation treatment were selected as the blank control group. The results of the carbon rod test support the subsequent fully enclosed anode loading tests.

In the 500 kA cell test, taking an anode with single-block dimensions of 1770 × 770 × 650 mm and a weight of 1300 kg as an example, a dual-block simultaneous impregnation process was used. With a test cycle of 65–75 anodes, the data statistics were divided into five stages. Through calculation and simulation, the dimensions of the impregnation tank were determined to be 2600 × 2600 × 1500 mm, which not only meets the minimum spacing requirements during anode impregnation but also complies with the principles of fluid circulation dynamics. For the supporting system parameters, the minimum circulation flow rate was set at 6000 L/h, and the volume of the impregnation agent storage tank was no less than 9000 L, with a minimum process operation threshold of 6500 L.

The production planning system must establish a linkage between the electrolytic aluminium cell parameters and the anode replacement cycle. Taking a 500 kA electrolytic cell as an example, each cell is equipped with 48 prebaked anodes. Based on a 24-hour anode replacement system, the daily immersion treatment capacity is 2 anodes. A five-level anode storage management system is established, with the specific process path as follows: after immersion, the anodes awaiting treatment are transferred to a static storage area, where they are stacked for 2–3 days to allow natural volatilization of solvent components. After drying, they meet the quality standards for cell use and enter the ready-to-coat state. Through multi-pass coating repair processes, the anodes finally undergo 48 hours of absolute drying to form qualified anodes ready for cell use. This workflow is dynamically scheduled via the MES system, ensuring that the time coordination accuracy for each process node is controlled within ± 2 hours.

3.2 Data Acquisition and Process Control

This technology achieves precise regulation of impregnation agent ratios and production planning through a data-driven process optimization system. During equipment commissioning, a 30-minute agitation and concentration test (multi-point sampling from agitation tank/impregnation tank) is required daily before impregnation. The self-circulating discharge flow is controlled by adjusting the overflow rate, combined with a stepped-time impregnation experiment (recording the time-weight gain curve) to determine the standard impregnation time and equilibrium weight gain for each batch of anodes. The impregnation process implements full-cycle quality monitoring (initial mass M_1, post-impregnation M_2, and daily recorded M_X during air-drying). After 2–3 days of air-drying until the weight loss reaches 1/3, the anodes proceed to the drying stage. A dynamic drying strategy is adopted (hourly pause for weighing, cumulative ≤ 6 h) to establish a solvent content-drying weight loss model. Finally, statistical analysis of drying rate data is used to formulate differentiated drying schemes while simultaneously performing closed-loop optimization of production planning parameters, which reduces process time by 15–20 % while ensuring predictable performance enhancement.

4. Results and Discussion

4.1 Test Results of Carbon Core Operation

The sampling analysis of anode carbon cores (the cores were drilled from the middle of the anode carbon blocks for sampling) showed that although the post-impregnation weight loss appeared elevated due to moisture interference, waste heat from electrolytic cells effectively eliminated this moisture effect. The consistent physicochemical properties among the four carbon cores from the same anode verified experimental reliability. Comparative data with blank groups demonstrated that the impregnation agent significantly reduced the anode reaction loss ratio (18–22 %), though the variation in loss rates among different carbon cores might correlate with the state of the bath crust.

The fully enclosed anode carbon core was formed by the impregnation-drying process, and a dense anti-oxidation thin layer was formed on the outer surface and inside of the anode carbon core. After 16 hours of high-temperature testing in the cell, the fully enclosed anode carbon core had good appearance integrity after high-temperature reaction due to the protection of the anti-oxidation thin layer, compared with the blank group. That is, the lost mass/initial mass was significantly lower than the blank control group. The results of the carbon core test run support the subsequent fully enclosed anode loading test, providing practical verification for the feasibility of the follow-up pilot scale tests.

Table 3. Comparison of carbon corte data before and after impregnation.

No.	Initial mass, g	Mass after impregnation, g	Weight gain after impregnation, g	Impregnation fraction, %
NC040J1	757.2	782	24.8	3.28
NC040J2	755.6	780	24.4	3.23
NC040J3	748.7	775.5	26.8	3.58

Table 4. Comparison of carbon core data before and after LOI.

	Blank	Impregnation I	Impregnation II	Impregnation III
Initial mass, g	640.8	748.3	753.9	746.7
Post-reaction mass, g	448.8	545.4	585.2	553.9
Mass loss, g	192	202.9	168.7	192.8
Loss, %	29.96	27.11	22.38	25.82

4.2 Performance Results of Anode Loading Process

To study the performance of ultra-low-consumption anodes, they were assembled and subjected to loading tests, observing changes in indicators such as cell temperature, current distribution, average voltage, bath height, and current efficiency to analyze product application. Data from six electrolytic cells (1318#, 1322#, 1309#, 1310#, 1319#, and 1320#) were tracked and statistically analysed, as shown in Table 5. Among them, cells 1318# and 1322# are control cells, while the others are test cells. Data tracking began from the initial use of the test anodes in the aluminium reduction cells. Phase 1 involved replacing the original anodes in the cells, while phase 2 commenced tracking and measuring the application effects after complete replacement. The phase 3 extended the anode cycle by 1 day (37 days), the phase 4 extended it further by another day (38 days), and the phase 5 involved stable operation with a 38-day anode cycle. The bath temperature in both the test cell (ultra-low-consumption anode) and the reference cell was maintained within the reasonable range of 940–960 °C. The test cell had a 2.4 °C lower bath temperature compared to the reference cell. A moderate reduction in electrolysis temperature is beneficial for improving current efficiency.

Table 5. Average electrolysis temperature before and after the test, °C.

	1318#	**1322#**	**1309#**	**1310#**	**1319#**	**1320#**
Phase 1 (September, October)	957.12	954.88	955.83	951.58	952.13	955.83
Phase 2 (November, December)	958.2	955.38	952.13	951.8	951.8	953.89
Phase 3 (January - March)	957.55	957.69	951.8	953.32	953.57	953.85
Phase 4 (April, May)	956.05	953.97	951.8	952.89	951.58	951.8
Phase 5 (June, July)	955.2	954.65	953.88	951.83	951.07	953.32

4.2.1 Current Distribution

In the production of prebaked electrolytic cells, the measurement of anode current distribution is crucial and needs to be performed frequently. It affects the stable operation of the electrolytic cells, as current imbalance can lead to voltage fluctuations, reduced current efficiency, and increased energy consumption. During the preheating and start-up, measurements are required daily, while in normal production, each new anode set must also be measured after installation to determine anode height and replacement quality. When abnormalities occur, the anode current distribution should be checked first.

According to the data records, for cell #1319, the difference between the maximum anode current (12.413 kA) and the minimum anode current (8.493 kA) is 3.920 kA; and for cell #1320, the difference between the maximum anode current (11.906 kA) and the minimum anode current (8.206 kA) is 3.700 kA. Additionally, the total current on side A of cell #1319 is slightly higher than that on side B, while the opposite is true for cell #1320, where side B total current exceeds side A. Notably, the current disparity between sides A and B in cell #1320 is more pronounced: side A accounts for 50.91 % and side B for 49.09 %, a difference of 1.82 %. The current distribution in cell #1319 is more balanced, with only a difference of 0.50 % between the two sides. As for cell #1318, the maximum anode current (12.355 kA) and the minimum anode current (7.850 kA) differ by 4.504 kA. Additionally, the measured current on side A of both anode assemblies was slightly higher than that on side B. Among them, the current difference between sides A and B of cell #1318 was more pronounced, with side A at 52.80 % and side B at 47.20 %, a difference of 5.60 %. The currents on sides A and B of cell #1322 were relatively closer, with a difference of only 0.49 %.

Based on the current distribution data above, the ultra-low-consumption anode reduces overheating and oxidation caused by localized current concentration by improving current distribution uniformity. The even current distribution avoids the accelerated consumption observed in conventional anodes due to current deviation, thereby laying the foundation for achieving ultra-low consumption targets.

4.2.2 Bath Height

The electrolytic cell requires a sufficient amount of liquid bath to ensure composition stability, enhance the dissolution capacity of alumina raw material, maintain consistent concentration, and improve adaptability to fluctuations in the feeding rate. The bath height is critical for sustaining the dynamic equilibrium between the liquid and solid phases. Insufficient height may lead to compositional fluctuations, adversely affecting stable operation. Additionally, the bath serves as a heat carrier, and an adequate volume of molten bath helps maintain thermal stability. A stable bath composition facilitates the retention of an appropriate alumina concentration. A moderate bath height can reduce cell voltage, whereas bath heights that are too low or too high are detrimental. The bath heights for each cell are detailed in Table 7.

The bath heights in both the four test cells and the two reference cells were consistently maintained within the range of 160–180 mm before and after the test, indicating that the ultra-low-consumption anode has minimal impact on the bath height of aluminium electrolysis cells.

Table 6. Anode stem equidistant voltage drop (mV) data of test cells 1319#, 1320# and comparison cells 1322#, 1318#.

Anode No.	**1319#**		**1320#**		**1318#**		**1322#**	
	Side A	**Side B**	**Side A**	**Side B**	**Side A**	**Side B**	**Side A**	**Side B**
1	1.96	1.95	2.23	1.73	2.1	1.76	1.9	1.95
2	2	2.03	2.07	1.9	2.16	1.69	2.18	2.04
3	1.94	2.13	2.05	1.79	2.16	1.75	1.87	1.83
4	1.9	2.36	2.04	2.04	2.25	1.78	2.07	1.93
5	2.28	2.38	2.3	1.89	2.22	1.7	2.4	1.99
6	2.37	2.29	2.44	1.93	2.38	1.8	2.36	2.12
7	2.39	2.24	2.12	2.15	2.51	2.19	2.48	2.05
8	2.22	2.27	2.17	2.3	2.28	2.2	2.03	2.06
9	2.61	1.89	2.13	2.23	2.12	2.26	2.27	2.23
10	2.34	2	2.1	2.51	2.25	2.4	2.27	2.41
11	2.29	2.13	2.07	2.28	2.21	2.48	2.1	2.54
12	2.31	2.33	2	2.31	2.18	2.37	2.14	2.42
13	2.45	2.66	2.36	2.25	2.51	2.34	2.11	2.34
14	2.31	2.42	2.37	2.35	2.66	2.23	2.24	2.37
15	1.82	2.32	2.28	2.06	2.65	2.17	2.54	2.14
16	1.96	2.41	2.32	2.11	2.5	2.16	2.38	2.09
17	2.01	2.19	2.39	2.04	2.46	2.3	2.4	2.37
18	2.11	2.24	2.44	2.15	2.4	2.38	2.35	2.49
19	2.2	2.24	2.23	1.99	2.15	1.77	2.22	2.15
20	2.29	2.26	2.35	2.07	2.13	1.88	2.13	2.06
21	2.23	2.13	2.17	2.18	2.39	2.14	2.01	2.22
22	2.17	1.98	2.14	2.11	2.44	2.26	2.24	2.35
23	2.03	2.03	1.99	2.24	2.36	1.92	2.35	2.33
24	2.14	1.98	1.92	2.19	2.33	1.95	2.37	2.41
Average	2.18	2.2	2.2	2.12	2.32	2.08	2.22	2.2

Table 7. Average bath heights before and after test (mm).

Month	**1318#**	**1322#**	**1309#**	**1310#**	**1319#**	**1320#**
Phase 1 (September, October)	176	163	171	168	176	168
Phase 2 (November, December)	165	169	168	172	165	172
Phase 3 (January - March)	174	176	172	172	174	172
Phase 4 (April, May)	170	177	173	174	175	173
Phase 5 (June, July)	175	179	174	175	175	173

Table 8. Average current efficiency before and after test.

	1318#	1322#	1309#	1310#	1319#	1320#
Phase 1 (September, October)	90.22	91.4	91.31	91.8	91.8	90.34
Phase 2 (November, December)	89.42	91.52	88.71	91.75	91.75	91.31
Phase 3 (January - March)	89.29	89.52	89.42	89.4	89.61	89.71
Phase 4 (April, May)	91.01	91.63	91.4	91.52	91.09	92.2
Phase 5 (June, July)	90.75	90.12	91.51	91.93	91.82	92.25

4.2.3 Current Efficiency

The test cell began tests in phase 2. After applying the ultra-low-consumption anode, the current efficiency of the test cell increased significantly, showing a 1.4 % improvement compared to the reference cell. The enhancement in current efficiency reduced the DC power consumption per tonne of aluminium, indicating that the use of the ultra-low-consumption anode decreased additional carbon consumption, thereby achieving the goal of lowering energy consumption.

4.3 Ultra-Low Anode Gross Consumption

During phase 3 of the test, the anode cycle was extended from 36–37 days. The residual anode thickness of the test cell was 16.32 mm, compared to 14.70 mm in the reference cell. Further extending the cycle from 37 to 38 days resulted in a residual thickness of 14.84 mm for the test cell and 14.73 mm for the reference cell. The iron and silicon content in the primary aluminium remained virtually unchanged in the test cell before and after the use of the test cell.

Under a 36-day anode cycle, the gross anode consumption was 470.8 kg/t Al, while under a 38-day cycle, it decreased to 446.1 kg/t Al. This represents a reduction of 24.8 kg/t Al in gross anode consumption, achieving the ultra-low consumption target of below 450 kg/t Al.

5. Benefit Analysis of Industrial Tests on Ultra-Low-Consumption Anodes

The industrial application of ultra-low-consumption anodes demonstrates significant economic and social returns. In terms of economic returns, ultra-low-consumption anodes create value by extending service life, improving current efficiency, and reducing power consumption. The direct returns are reflected in the extension of the anode usage cycle from 36–38 days and a reduction of 24.8 kg C/t Al. Based on an anode unit price of 4500 RMB/t, this translates to a cost savings of 111.6 RMB/t Al. Indirect returns arise from the prolonged anode replacement cycle, which reduces heat loss from cells and residual anodes. When applied to a 400 kt/y aluminium smelter, the annual carbon cost savings amount to 44.64 million RMB (6.18 MUSD/y approx.). After deducting costs such as sealants, equipment, and labour (totalling 30.44 million RMB or 4.21 MUSD/y approx.), the net annual benefit reaches 14.2 million RMB (1.96 MUSD/y approx.).

Meanwhile, this technology reduces the frequency of anode replacement, lowers workers' labour intensity, and addresses the issue of high carbon consumption in carbon anodes for aluminium electrolysis. It contributes to carbon neutrality and energy conservation and emission reduction in the electrolytic aluminium industry while enhancing the overall technical level of China's aluminium industry, which holds significant importance for achieving the "dual carbon" goals.

6. Conclusion

This study successfully developed an ultra-low-consumption anode preparation technology for aluminium electrolysis. By employing an impregnation coating process to seal the anode surface, a composite coating, with nano-vitreous bodies and rare-earth-modified materials as core components. This significantly enhanced the anode's oxidation resistance and mechanical strength, effectively mitigating the impact of petroleum coke raw material quality fluctuations on anode performance. The technology simultaneously reduces anode carbon consumption and CO_2 emissions, with tests demonstrating notable decreases in DC power consumption for some electrolytic cells and improved current efficiency.

The ultra-low-consumption anode has an extended service life and reduced replacement frequency, which not only lowers workers' labour intensity but also minimizes operational disturbances in electrolytic cells. Its standardized production model establishes an intelligent process system for the aluminium electrolysis industry, providing technical support for the "dual carbon" goals through reduced energy consumption and carbon emissions. Additionally, the green manufacturing experience gained can be extended to other energy-intensive industries. Currently, this technology has completed industrial validation, enhancing China's international technological competitiveness in the aluminium electrolysis sector and driving the industry toward low-carbon and high-efficiency transformation.

7. References

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