Research and Development of a Full Lifecycle Quality Traceability System for Prebaked Anode Carbon Blocks

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Abstract: To address industry pain points such as fragmented data across the production–utilization–recycling chain of prebaked carbon anodes, difficulties in data association, and low traceability efficiency, this paper proposes a full-lifecycle quality traceability system. The system implements the "one-item-one-code" principle and employs a hierarchical identification technique that combines laser marking with high-temperature-resistant ink spraying to ensure legibility and integrity of identifiers under harsh conditions of high temperature and strong corrosion. It integrates critical data from key stages—including raw material receipt, forming and baking, warehouse logistics, assembly and matching, electrolytic usage, maintenance and repair, and spent anode recovery—and adopts a three-layer architecture (perception layer, network layer, and application layer) to build an integrated system encompassing identifier assignment, multi-source data acquisition, and intelligent data analysis. Compared with traditional traceability approaches, the proposed system significantly enhances traceability efficiency and product quality, thereby supporting the digital and intelligent transformation of the industry.

Keywords: Prebaked Carbon Anodes; Full Lifecycle; Quality Traceability System; One-Item-One-Code

1. Introduction

Prebaked carbon anodes are among the most critical consumable materials in the aluminum electrolysis process. The stability of their quality directly influences the operational performance of electrolytic cells and the purity of the final aluminum products. The aluminum industry is a strategic and foundational sector of the national economy, with extensive applications in key fields such as aerospace, new-energy vehicles, and power equipment. Efficient integration across the industrial chain is therefore of vital importance to national energy security and the integrity of the industrial system[1].

Currently, data generated during both production stages—including forming, baking, warehousing, and quality inspection—and application stages—including assembly, storage, electrolysis, maintenance, and spent anode recycling—are predominantly stored in disparate enterprise systems or even recorded manually. This fragmentation has led to pronounced data silos, significantly undermining the efficiency and consistency of product quality management[2]. To address these challenges, this paper proposes a comprehensive, end-to-end management approach covering the entire production-to-application chain of prebaked carbon anodes and develops a full-lifecycle quality traceability system. The system not only provides complete information traceability for anode products but also serves as a critical enabler for enhancing the efficient utilization of national energy and material resources[3].

2. Research Status on Quality Traceability of Anode Carbon Blocks

In recent years, the aluminum industry has continued to expand its production scale, and market competition has intensified, leading to growing attention on the quality traceability of prebaked carbon anodes.

International research has primarily focused on the local quality control of prebaked carbon anodes. For instance, by tailoring the chemical composition of coal tar pitch, researchers have optimized its wettability toward aggregates and modulated the pore structure distribution within the anode body, thereby enhancing local densification and electrochemical stability [4]. In the domain of baking process modeling, a thermo-chemo-mechanical coupled model of the anode paste has been developed to reveal the spatial non-uniformity of temperature fields, chemical reactions, and stress evolution across different regions of the carbon block, offering theoretical support for localized defect prediction and process optimization [5]. Furthermore, an acousto-ultrasonic (AU)-based non-destructive testing method has been proposed, which effectively identifies internal cracks and structural inhomogeneities in baked anodes, providing a viable pathway for online assessment of local quality [6].

Domestic research has not only focused on local quality control of prebaked carbon anodes but has also progressively expanded into full-lifecycle traceability. To address the challenges of detecting internal cracks—which are invisible and difficult to assess—recent work has employed impact-induced vibration, frequency-domain analysis, and machine learning techniques to achieve accurate anode classification and quantitative regression of crack parameters [7]. In the domain of surface defect inspection, machine vision and image processing methods have been applied to automatically detect common surface anomalies such as cracks, corner chippings, and blistering, enabling precise localization and quantitative evaluation of defect regions, thereby providing technical support for appearance-based quality grading prior to anode dispatch [8]. Moreover, laser marking technology has been adopted to assign unique identifiers to green anodes; this approach avoids structural damage caused by mechanical stamping and exhibits high resistance to the extreme temperatures and mechanical impacts encountered during baking, thus establishing a robust and reliable foundation for end-to-end quality traceability [9].

Although existing research—both domestic and international—has achieved notable progress, significant gaps remain due to insufficient integration with real-world industrial practices. Specifically, three key challenges persist: First, there is inadequate capability for end-to-end data integration. Current studies predominantly focus on isolated stages of the process and have yet to establish a comprehensive data linkage framework that spans the entire lifecycle of anode carbon blocks. Second, existing technologies exhibit poor adaptability to complex industrial environments. Conventional sensors are highly susceptible to interference from high temperatures and strong magnetic fields, resulting in high data loss rates. Moreover, traditional identification methods such as RFID (Radio Frequency Identification) tags tend to carbonize or degrade in high-temperature baking furnaces, making continuous traceability unfeasible. Third, the precision and intelligence level of current traceability systems remain limited. Although the industry is gradually transitioning from "batch-level" to "individual-block-level" traceability, existing approaches still struggle to achieve accurate binding between physical anode units and their corresponding production data. This limitation leads to low efficiency, prolonged investigation cycles, and high costs in quality issue diagnosis, ultimately failing to meet the demands of intelligent manufacturing for fine-grained management.

3. Research on the Full-Lifecycle System of Anode Carbon Blocks

This research on the full-lifecycle system of anode carbon blocks is grounded in the reconstruction of the entire process of value creation and transformation. The traditional coarse-grained model of "production–use–recycling" fails to enable precise traceability across individual operational stages. To address this limitation, the study integrates practical realities of the aluminum electrolysis industry and divides the full lifecycle into multiple distinct phases: raw material preparation, green block forming, baking, warehousing and logistics, assembly and integration, electrolysis operation, maintenance and repair, and spent anode recycling. A closed-loop management framework is then established by leveraging process interconnectivity and systematic data flow across these stages.

Within this chain, the absence or inadequacy of the three critical components—identification, data integration, and traceability—has become a prominent contradiction in current quality management: inconsistent identification standards across enterprises and label degradation due to high-temperature baking lead to ambiguous or unreadable markings; severe data silos significantly impede effective information integration; and chaotic labeling of externally sourced anodes, coupled with the inability to accurately match spent anodes to their original batches, results in substantial resource waste. These practical challenges directly undermine the effective implementation of quality traceability and underscore the urgent need for a systematic, integrated solution.

3.1 Research on Identification Systems

To address the bottlenecks in the identification system, this study proposes differentiated identification and adaptation strategies tailored specifically for self-produced anodes, externally sourced anodes, and associated stub assemblies.

For self-produced anodes, a two-stage identification and coding mechanism—combining laser engraving and high-temperature-resistant spraying—is adopted. During the green anode stage, a laser-based code is applied following the rule "date+shift+machine+batch number." After baking, a high-temperature-resistant QR code is sprayed onto the baked anode, enabling secure identity binding between the green and baked anodes and supporting bidirectional traceability.

Externally sourced anodes are managed through an "external identification registration+internal unified coding" approach. While the supplier's original identifier is recorded, an internal code—prefixed to indicate external procurement—is simultaneously sprayed onto the anode, integrating it into the unified traceability system. For stub assemblies, permanent identification is achieved via laser engraving, and their identities are dynamically linked to the corresponding anodes during assembly, enabling precise tracking and supporting closed-loop reuse throughout the entire process.

This multi-layer identification strategy effectively withstands harsh operating conditions such as high temperatures, abrasion, and corrosion, thereby establishing a robust physical foundation for full-lifecycle traceability.

3.2 Research on Data Architecture

The construction of the data architecture is oriented toward enabling end-to-end collaboration across the entire chain and is supported by unified data standards and interlinking mechanisms, thereby facilitating automatic data acquisition and integration throughout the full process.

The system achieves dynamic linkage between process parameters and identity identifiers by: capturing data on raw materials such as petroleum coke and pitch during the preparation stage; continuously acquiring real-time process parameters—including forming pressure and mold temperature—during the forming stage; and collecting, analyzing, and generating early warnings based on temperature data from thermal sensors throughout the baking stage. In warehousing, automatic gate scanners record anode block inbound and outbound movements via QR code scanning, enabling dynamic inventory management. During electrolysis operation and maintenance, sensors continuously monitor critical parameters such as temperature and current, and automatically trigger maintenance recommendations upon detecting anomalies. Finally, in the spent anode recycling phase, quality inspection results are fed back into the system to close the data loop.

This data architecture effectively breaks down information silos, ensuring continuity and traceability of data throughout the entire process—from raw materials to spent anodes.

3.3 Research on Traceability Systems

Built upon the identification and data architectures, the traceability system supports three flexible querying modes—individual identifier lookup, batch-level query, and process-stage query—to meet diverse operational needs. Users can retrieve the complete lifecycle data of a single anode block via its unique identifier, review the overall distribution and quality status of an entire batch, or access all operation records associated with a specific process stage for that batch. This multi-level approach enables traceability ranging from macro-level overviews to micro-level details.

This traceability system not only enhances the speed of response to quality issues and the accuracy of fault localization but also provides critical technical support for the efficient full-lifecycle management of energy and materials in the aluminum industry.

4. System Architecture Design and Implementation

To achieve a closed-loop system for the "collection–transmission–application" of full-lifecycle data for prebaked anode carbon blocks, the system adopts a three-tier business architecture—comprising infrastructure support, core operations, and analytics and applications—as its guiding framework, and implements an integrated technical architecture consisting of the perception layer, network layer, and application layer.

The technology support layer serves as the foundational layer of rules and models, providing unified deployment specifications and data standards for the perception and network layers. The core business layer, as the operational heart of the system, relies entirely on raw data collected by the perception layer and the data transmission channels established by the network layer. The analytics and application layer, functioning as the value-delivery tier, primarily enables intelligent analysis capabilities, drawing on integrated data supplied jointly by the perception and network layers. Through this tightly coupled, logically coherent multi-layer collaboration, the system achieves end-to-end integration and closed-loop management—from data sensing to business application.

The system's technical architecture and functional modules are illustrated in Figures 1 and 2, respectively.

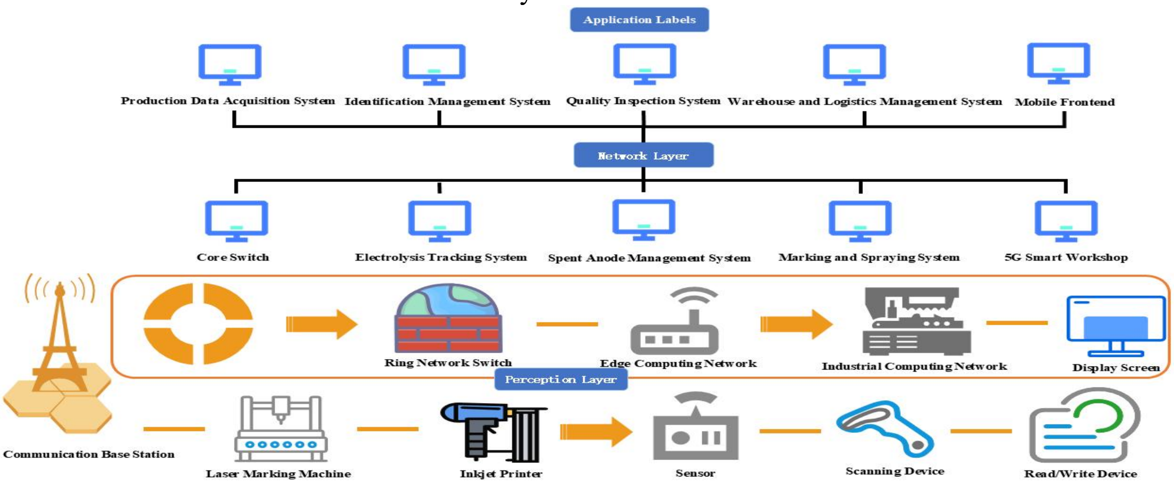

Figure 1. Technical Architecture Diagram

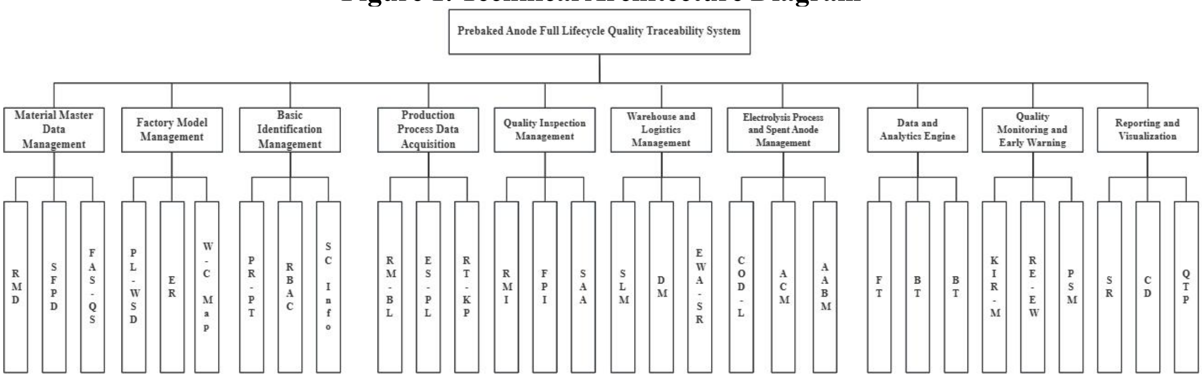

Figure 2. Functional Module Diagram

Architecture of the prebaked anode full lifecycle quality traceability system (bottom-layer abbreviations explained in legend). Abbreviations: RMD: Raw Material Definition, SFPD: Semi-finished Product Definition, FPD: Finished Product Definition, SAD: Spent Anode Definition, QS: Quality Standards, PL-WSD: Production Line / Work Section Division, ER: Equipment Register, W-C Map: Warehouse–Electrolytic Cell Physical Mapping, PR-PT: Process Route and Parameter Template, RBAC: Role-Based Access Control, SC Info: Supplier and Customer Information, RM-BL: Raw Material Batch Linkage, ES-PL: Equipment Status and Personnel Log, RT-KP: Real-time Collection of Key Process Parameters, RMI: Raw Material Inspection, FPI: Finished Product Inspection, SAA: Spent Anode Analysis, SLM: Storage Location Management, DM: Dispatch Management, EWA-SR: Electrolysis Workshop Acceptance and Slotting Record, COD-L: Cell Operation Data Linkage, ACM: Anode Consumption Monitoring, AABM: Anode Abnormality Band Monitoring, FT: Forward Traceability, BT: Backward Traceability, KIR-M: Key Indicator Real-time Monitoring, RE-EW: Rule Engine Early Warning, PSM: Process Stability Monitoring, SR: Standard Reports, CD:

Custom Dashboard, QTP: Quality Traceability Path.

4.1 System Functional Modules

In alignment with the full lifecycle of anode carbon blocks, the system comprises ten integrated functional modules: Material Master Data Management, Plant Model Management, Basic Standards Management, Production Process Data Management, Quality Inspection Management, Warehouse and Logistics Management, Electrolysis Usage and Spent Anode Management, Traceability and Analytics Engine, Quality Control and Early Warning, and Reporting and Visualization.

Material Master Data Management establishes unified material classification and coding rules, clearly defines raw material attributes and blending ratios, and creates comprehensive records for key raw materials—such as petroleum coke and pitch—covering their chemical composition, physical properties, and supplier specifications. It also specifies dimensional standards and quality criteria for both green and baked anodes, concurrently formulates identification and coding rules for green anodes, baked anodes, and stub assemblies, standardizes the criteria for spent anode acceptance during recycling, and explicitly defines the association rules between spent anode identifiers and their original carbon block identifiers.

Plant Model Management performs digital modeling based on actual production scenarios, clarifying the logical relationships among production lines and equipment. It specifies the layout and interconnections of laser marking units, scanning devices, and various sensors, and organizes production lines according to process stages—such as raw material pretreatment, forming, baking, and assembly. Dedicated workstations for laser marking and mounting interfaces for pressure sensors are reserved in the forming section, while interfaces for high-temperature spraying equipment and designated deployment points for temperature and flue gas sensors are established during the baking process. This ensures seamless integration between identification marking and sensor-based data acquisition, with all sensor-collected data instantly transmitted to the platform system via a unified communication protocol. Furthermore, digital maps of specific operational areas—including the forming workshop, baking workshop, and warehouse—are created to precisely indicate the installation locations of marking devices, scanners, and sensors, thereby enabling visualized and intuitive production environment management.

Basic Standards Management establishes standardized specifications for processes, personnel, and suppliers, and defines operational protocols for identification coding, recognition, binding, and sensor data acquisition. Specific permissions are assigned based on roles: marking operators are granted rights for “identifier generation” and “equipment calibration”; scanning personnel receive permissions for “identifier recognition” and “binding confirmation”; and instrumentation maintenance staff are authorized for “sensor calibration” and “data validation.” This role-based access control ensures strict adherence to operational standards. Additionally, the system records the original identification rules provided by external anode suppliers and defines a standardized mapping protocol between external identifiers and internal laser-marked codes.

The production data acquisition and identification coding module integrates sensors with laser marking technology: during raw material pretreatment, temperature sensors are employed to monitor the heating temperature of coal tar pitch; in the green anode forming stage, pressure sensors are installed on the forming press to capture compaction pressure in real time, and immediately after forming, a laser marking system is triggered to assign a unique identification code to each green anode block. Baking is a critical process for the densification and graphitization transition of prebaked carbon anodes, and its thermal schedule directly determines final product quality. Research shows that the evolution of internal porosity is closely correlated with the devolatilization behavior during baking—excessively rapid release of volatiles tends to induce surface cracking, whereas overly slow release may lead to internal carbon deposition or structural looseness [10]. To address this, the system deploys high-precision thermocouples at key temperature measurement points in the baking furnace and integrates real-time monitoring of flue gas flow rate and composition to indirectly reflect the devolatilization status, thereby providing essential data support for process optimization and quality traceability.

During the quality inspection phase, process data collected by sensors is retrieved and combined with manual inspections to enable comprehensive quality control, and the inspection results are linked to and stored with the product's unique identification code

In the warehousing and logistics stage, scanning devices recognize laser-engraved or sprayed identifiers and automatically upload the storage location to the system, enabling precise inventory management.

During the electrolysis phase, the system precisely links the basic information of "in-service" anodes by matching the stub identifier with the anode block identifier. Multi-type sensors continuously collect operational data in real time and trigger timely alerts for any anomalies. For spent anodes, the original identification code must be scanned and verified before quality inspection and recycling records are finalized.

The traceability and analytics engine supports forward tracing, backward tracing, and batch-level tracing. By entering an anode block's unique identifier, a batch time window, or a specific process stage, users can retrieve the product's complete lifecycle information and pinpoint the root cause of any issue.

Quality early-warning monitoring leverages sensor data uploaded to the server to continuously collect real-time information, detect anomalies, and issue timely alerts. Production data is visualized through dashboards, enabling prompt and effective monitoring and early warning of quality deviations.

Reporting and visualization involve comprehensive analysis and aggregation of historical and real-time data from the production processes of various products, generating scheduled data reports and visual charts for export.

4.2 System Software Implementation

The system software is developed using a three-tier B/S (Browser/Server) architecture, MySQL database, and Java programming language, achieving visualized management and efficient traceability of the full lifecycle of anode carbon blocks. Figure 3 shows the main system homepage, while Figure 4 displays the data statistics and analysis interface.

Figure 3. System Home Page

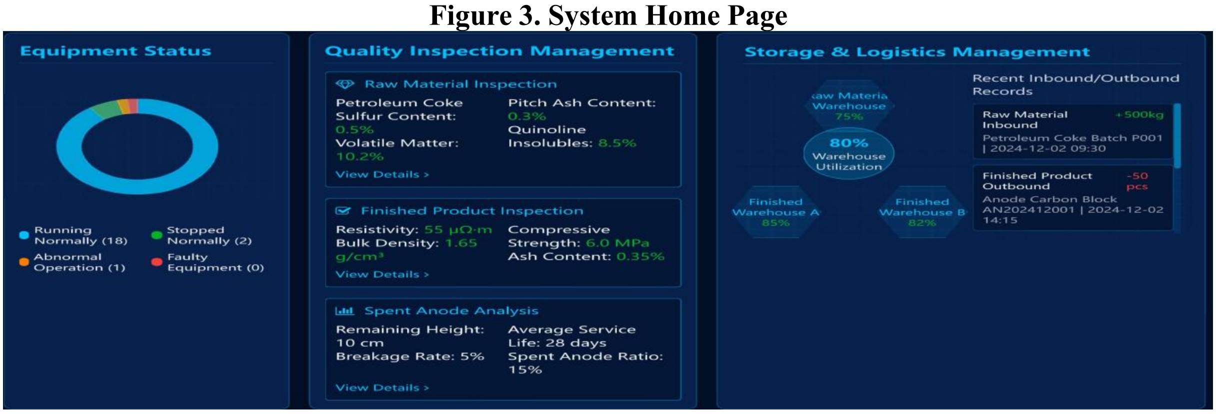

Figure 4. Statistical Data Analysis

5. Conclusion

This paper addresses the quality traceability requirements throughout the full lifecycle of prebaked anode carbon block production. By subdividing the lifecycle into multiple stages—including raw material preparation, green block forming, baking, warehousing and logistics, assembly, electrolysis operation, maintenance, and spent anode recycling—the study effectively breaks down information silos between stages, enhances end-to-end quality monitoring, improves production efficiency, and significantly reduces the overall consumption of energy and resources.

References

[1] Li, J. J., & Wang, X. Q. (2024). Yi quanmian shenhua gaige cuisheng xin zhi shengchanli [Cultivating new quality productive forces through comprehensively deepening reform]. China Nonferrous Metals, (23), 56–57. (in Chinese)

[2] Liu, J., Lu, H., Zhang, Z. L., Yan, C. N., & Yang, Y. C. (2023). Research and application of a digital identification system for the full lifecycle quality of aluminum anodes. Light Metals, (4), 37–41. (in Chinese)

[3] Liu, F. Q., Li, J., Chen, K. B., & Wang, X. (2024). Current status and development trends of resource utilization of solid and hazardous waste in China's aluminum industry. Nonferrous Metals (Extractive Metallurgy), (9), 1–13. (in Chinese)

[4] Ma J, Zhu S, Wu X, et al. Chemical composition-driven wettability and pore structure modulation in coal tar pitch for enhanced prebaked anode performance in aluminum electrolysis. Carbon Letters, 2025,(prepublish): 1-16.

[5] Bowen C, Hicham C, Donald P, et al. Modeling of Thermo-Chemo-Mechanical Properties of Anode Mixture during the Baking Process. Materials, 2021, 14(15): 4320-4320.

[6] Boubaker B M, Picard D, Duchesne C , et al. The Potential of Acousto-Ultrasonic Techniques for Inspection of Baked Carbon Anodes. Metals, 2016, 6(7):175.

[7] Shang, Y. Q. (2023). Research on quantitative localization methods for internal cracks in prebaked anodes [Doctoral dissertation, Taiyuan University of Technology].

[8] Sheng, F. H. (2023). Research on key technologies for surface defect detection of prebaked anodes based on image processing [Doctoral dissertation, Taiyuan University of Technology].

[9] Wang, R., Han, D., & Wang, X. T. (2022). Design and development of a carbon block quality traceability identification system based on life cycle cost theory. Resource Recycling, (2), 32–35. (in Chinese)

[10]Yang, Z., Liao, S. M., Rao, Z. H., & Zhang, C. (2022). Study on the emission characteristics of volatiles in a novel anode baking furnace. Carbon Techniques, 41(3), 13–18. (in Chinese).