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Practices for Reducing Non-Metallic Impurities in 3N Aluminum Ingots

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Abstract

3N aluminum is widely used in the power, electronics, and construction industries, with increasing demands for higher quality. During aluminum smelting and casting, the infiltration of non-metallic impurities such as hydrogen and oxygen significantly affects material properties. This study addresses the impact of the high-temperature, high-humidity environment in southern China on the impurities in 3N aluminum ingots. It suggests that through equipment upgrades, process optimization, and production management improvements, non-metallic impurities in the ingots can be reduced. Specifically, oxygen and hydrogen impurity levels were reduced by 0.0021% and 0.0004%, respectively. These measures significantly enhanced the purity of 3N aluminum, ensuring the supply meets the high-end aluminum market's requirements.

Keywords: 3N aluminum ingots; Non-metallic impurities; Refining process; Equipment upgrades; Process optimization; Impurity control

Introduction

In modern industry, 3N aluminum (purity ≥99.9%) is widely used in domains such as power, electronics, aerospace, packaging, and construction. Due to its excellent electrical conductivity, thermal conductivity, corrosion resistance, and good formability, 3N aluminum is a crucial raw material for products like wires, cables, and electronic devices. As demand for 3N aluminum continues to grow, the quality requirements are also becoming more stringent [1].

However, the high-temperature operations and complex environmental conditions during aluminum smelting and casting can lead to the severe infiltration of non-metallic impurities (such as hydrogen, oxygen, and nitrogen) from the air into the molten aluminum. These impurities significantly affect the final performance of the 3N aluminum. Reducing the content of non-metallic impurities in 3N aluminum ingots has become a critical issue for many smelter.

Issues

A smelter producing 3N aluminum ingots in southern China faces challenges due to higher atmospheric pressure, temperature, humidity, and oxygen levels compared to northern regions. These environmental factors increase the solubility of hydrogen in the molten aluminum, resulting in higher hydrogen content. After solidification, this leads to a higher porosity in the aluminum ingots. Additionally, the high temperature and humidity exacerbate oxidation reactions, increasing the amount of oxide impurities in the ingots. In contrast, the colder, drier climate in northern regions (such as Xinjiang and Inner Mongolia) reduces hydrogen solubility and suppresses oxidation, typically resulting in lower non-metallic impurities in 3N aluminum ingots. Table 1 compares the comtent of hydrogen, oxygen, and nitrogen analysis using the E03-021 Inorganic Analyzer between smelters in the southern and northern regions.

Non-metallic Impurity Elements	*Southern Smelter*	*Northern Smelter*
Hydrogen	0.014	0.009
Oxygen	0.0016	0.0006
Nitrogen	<0.00005	<0.00005

Table 1: Comparison of Major Non-Metallic Impurities in 3N Aluminum (Unit: wt.%).

Additionally, the smelter uses electric furnaces for heating and insulation. Compared to feul-heated furnaces, electric furnaces have higher oxygen content in the atmosphere, which increases the tendency for oxidation in the molten aluminum, leading to a higher generation of oxide impurities in the ingots. In contrast, the atmosphere in feul-heated furnaces is more reducing, helping to minimize oxidation reactions and reduce the oxide impurity content in the ingots.

Therefore, this study aims to explore and verify effective methods to reduce the content of non-metallic impurities such as hydrogen and oxygen in 3N aluminum ingots through equipment upgrades, process optimization, and production management, addressing the issue of high non-metallic impurity levels in the production process.

Technical Analysis

Sources of Impurities

In 3N aluminum, impurities are generally categorized into metallic and non-metallic types. Metallic impurities include iron (Fe), silicon (Si), and copper (Cu), which primarily originate from bauxite raw materials, wear and tear of smelting equipment, and potential cross-contamination during the smelting process. These metallic impurities tend to accumulate at the grain boundaries of aluminum, which reduces its electrical conductivity and ductility, while increasing its susceptibility to corrosion.

Non-metallic impurities mainly consist of hydrogen (H), oxygen (O), and nitrogen (N). These impurities exist in the form of dissolved gases, oxide inclusions (Al_2O_3), and nitrides (AlN). They primarily result from moisture, air oxidation, and chemical reactions during the smelting process. Non-metallic impurities can lead to the formation of porosity, inclusions, or chemical defects, significantly affecting the purity and surface quality of the aluminum, which in turn diminishes its electrical conductivity and processing stability.

Impurity Control Techniques

Improving the purity of aluminum relies on various methods for impurity separation and purification, primarily including solidification separation, smelting, and gas flushing techniques. The principles of impurity separation and purification depend on the physical and chemical properties of the impurities and their solubility differences in aluminum.

The solidification separation method takes advantage of the differing distribution coefficients between impurities and the aluminum melt, causing impurities to preferentially accumulate at the rear end or grain boundaries during solidification. This allows for multiple smelting or zone refining processes to improve aluminum purity. The smelting method involves adjusting the melting temperature and adding fluxes (such as NaCl, KCl, or fluorides), which react with impurities to form stable compounds (like nitrides or oxides) and separate them from the aluminum.

Gas flushing techniques introduce inert gases (like argon) or active gases (such as chlorine) into the aluminum melt, causing impurities like hydrogen and oxygen to convert into gas and be expelled, or to form slag that can be removed.

In practice, the choice and combination of impurity control techniques must consider factors such as purification efficiency, cost, and equipment requirements. For example, controlling melt temperature and environmental humidity is fundamental when reducing hydrogen content, while adding flux and applying smelting with gas injection can significantly improve the removal of oxide inclusions. Overall, effective impurity control in aluminum production focuses on upgrading equipment, optimizing processes, improving material use, and leveraging physical and chemical properties to enhance ingot quality and performance.

Improvement Measures

Based on the current production process and environmental conditions of a specific smelter, optimization and practical adjustments were made to reduce non-metallic impurities in 3N aluminum ingots. The specific measures are as follows:

Equipment Optimization and Upgrades

Technological Upgrades to the Refining System

To significantly improve the refining quality of 3N high-purity aluminum, the refining equipment was systematically upgraded. An advanced, integrated smart aluminum melt particle refining agent spraying machine (see Fig. 1) was introduced. This machine allows precise control and adjustment of key parameters such as refining time, air pressure, and powdering rate, thereby enhancing the stability and controllability of the refining process. Through precise adjustments, the equipment effectively improves the removal of existing non-metallic impurities and reduces the generation and introduction of new non-metallic inclusions. This is a critical step in ensuring the quality of 3N aluminum ingots.

Figure 1: Image of the Aluminum Melt Particle Refining Agent Spraying.

Addition of Plate-Style Filtration System

A 40-mesh plate-style filtration unit was added to the aluminum melting production line (see Fig. 2), significantly enhancing the physical filtration capacity of the high-temperature aluminum melt. This system efficiently removes larger impurity particles from the aluminum liquid, greatly improving the purity of the ingots and better meeting the stringent requirements of the high-end aluminum processing market for 3N aluminum products.

Figure 2: Image of the Plate-Style Filtration Unit in Production.

Installation of Real-Time Temperature Monitoring System

In aluminum melting and casting, production temperature plays a crucial role as it directly affects the fluidity, solidification speed, and oxidation activity of the aluminum melt, ultimately impacting the quality of the ingots [2]. To address this, an online aluminum melt temperature monitoring system was installed at the flow trough near the scale, enabling real-time temperature data collection and digital management. This system eliminates the errors associated with traditional temperature estimation based on experience, improving temperature control accuracy and consistency, and further standardizing the production process. The precise management of melt temperature enhances thermal stability during the casting process, improving the consistency of 3N aluminum ingots and the repeatability of the production process.

Process Optimization

Control of Melt Temperature and Casting Machine Speed

To meet the demands of high-end aluminum ingot customers, controlling the melt temperature, casting machine speed, and refining process are critical factors in improving ingot quality. At this smelter, the temperature of the aluminum melt when poured into the holding furnace typically reaches around 800°C. To optimize the casting temperature, the smelter uses a re-melting method combined with the length of the trough and site conditions, effectively controlling the melt temperature between 750°C and 760°C. Once the melt enters the mold, the temperature is maintained between 690°C and 700°C, while the casting machine speed is kept within the 9-10Hz range. This control method significantly reduces the risk of oxidation and hydrogen contamination at high temperatures, thereby effectively lowering the porosity and non-metallic impurity content within the ingots.

Refining Process Improvement

The refining process is crucial in aluminum smelting, primarily for removing impurities from the aluminum melt to enhance its quality. To address the high non-metallic impurity content in 3N aluminum ingots, the smelter implemented a refining method using "two-stage nitrogen treatment + refining agents," which effectively removed impurities, particularly non-metallic ones, and significantly improved the purity of the ingots.

In this process, nitrogen plays a key role by reacting with dissolved gases (such as hydrogen) in the aluminum melt, helping to remove gaseous impurities. The strong agitation caused by nitrogen stirring also facilitates the formation and expulsion of bubbles, reducing the formation of porosity and inclusions. The addition of refining agents further enhances the refining effect by reacting with oxides, sulfides, and other impurities in the aluminum melt, forming slag or compounds that can be effectively separated and removed, thereby improving the purity and quality of the melt.

To ensure the refining process's effectiveness, the smelter conducted comparative tests with existing refining agents and selected a widely recognized granular refining agent. This experiment not only improved the cost-effectiveness of the refining agent but also optimized the refining process, ensuring the uniformity and stability of the melt. The choice and use of refining agents played a vital role in removing various impurities from the melt, enhancing the potential properties of the aluminum alloy, and ensuring that the produced ingots met the requirements of high-end aluminum materials, providing strong support for the high-end market's demands.

Figure 3: Image of Aluminum Melt After Refining and Slag Removal.

Application of Water Cooling Method

In the production of 3N aluminum ingots, a direct water cooling method is employed. This cooling technique effectively controls the solidification rate of the ingots, preventing excessive temperature differences during casting and improving the uniformity and quality of the ingots. The consistency of water cooling ensures that both the surface and interior of the ingots cool at the same rate, reducing thermal stress and preventing the formation of cracks. Additionally, water cooling helps to quickly control the solidification process, allowing the ingots to reach a stable state during the cooling phase. This reduces the formation of oxide films, preventing surface oxidation and enhancing both the appearance and purity of the ingots. As a result, this method improves the overall quality and application performance of the aluminum ingots.

Figure 4: Image of Cooling Process for 3N Aluminum Ingots.

Improvements in Production Management Measures

Employee Training and Skill Enhancement

In addition to technological improvements, optimizing production management is equally essential. Strengthening employee training, particularly on the operation and safety procedures for new technologies and equipment, is fundamental to ensuring the production of high-precision aluminum ingots. Regular technical training and operational procedure sessions help employees quickly master new production techniques and equipment, ensuring that each employee can skillfully handle critical aspects of the production process. Through these training programs, employees become more familiar with the production workflow, ensuring consistent and stable product quality.

Figure 5: Training for New 3N Aluminum Ingot Production Process.

Comprehensive Quality Control

Quality control throughout the production process should cover every stage—pre-production, in-process, and post-production—and strictly adhere to the quality management system to ensure all stages are under standardized control. Before production, it is essential to verify that the purity of raw materials and the condition of equipment meet the required standards. During production, key parameters such as melt temperature, casting machine speed, refining, filtration, and casting should be closely monitored to ensure each process is within optimal control ranges. After production, thorough inspection of the finished products is necessary to ensure the aluminum ingots meet market standards and requirements, guaranteeing product stability and compliance.

Figure 6: Final Inspection of 3N Aluminum Ingots.

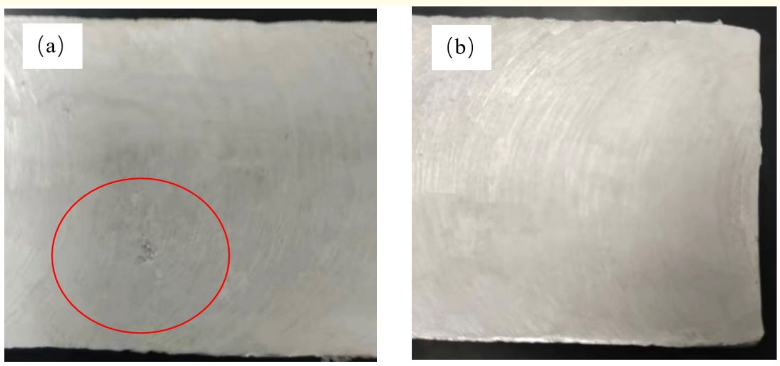
Effectiveness Analysis

Control of Non-Metallic Impurities

Non-metallic Impurity Elements	*Before*	*After*
Hydrogen	0.014	0.0119
Oxygen	0.0016	0.0012
Nitrogen	<0.00005	<0.00005

Table 2: Comparison of Non-Metallic Impurities in 3N Aluminum at a Specific smelter (Unit: wt.%).

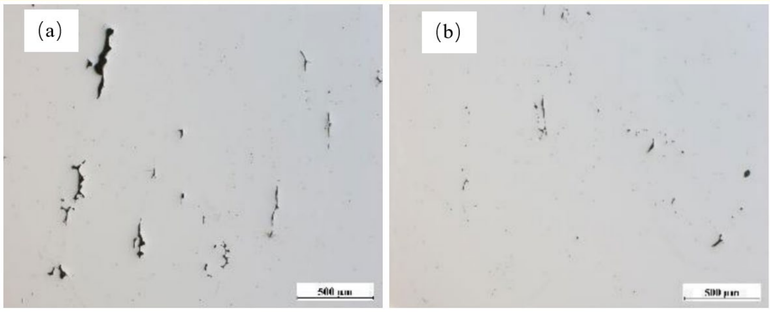
After implementing the measures described above, the content of oxygen and hydrogen in the 3N aluminum ingots was significantly reduced, with decreases of 0.0021% and 0.0004%, respectively, as shown in Table 2. This improvement is primarily attributed to optimized measures such as temperature control during the smelting process and the proper use of refining agents, which effectively suppressed oxidation and hydrogen dissolution in the aluminum melt, thus enhancing the purity of the 3N aluminum. However, due to limitations in the testing equipment, no changes in nitrogen content were detected.



(a) Before; (b) After

Figure 7: Low-Magnification Microstructure Comparison of 3N Aluminum Before and After Measurements Implementation.

As shown in Fig. 8, the optimized process has led to a noticeable change in the low-magnification microstructure of the 3N aluminum product. The optimization significantly reduced impurity content, and the visible microstructure quality has improved, appearing more orderly and cleaner. This indicates that the optimization measures effectively enhanced the purity of the 3N aluminum and overall process quality. The enlarged surface morphology in Fig. 2 further confirms the reduction in impurities, providing additional evidence of the process improvements.



(a) Before; (b) After

Figure 8: Surface Morphology of Polished Samples Before and After Measurements Implementation.

Cost Comparison Analysis

Based on the upgrade of production equipment and the optimization of production processes, a comprehensive cost calculation was made, considering the various auxiliary materials required in the production of 3N aluminum. Compared to traditional production methods, the new technology and processes have increased the production cost by approximately 200 yuan per ton of aluminum. Although this cost increase may put some pressure on the smelter's profitability in the short term, from a long-term perspective, the upgraded equipment and processes will significantly improve the quality and production efficiency of the aluminum ingots. This will not only help reduce rework and scrap rates caused by defective products but also save resources and lower production costs. Therefore, in the customized 3N aluminum product market, the smelter is likely to gain a unique competitive advantage and higher pricing power. In the long run, this investment is well worth it.

Issues and Discussion

Although the improvement measures proposed in this work have shown positive results in practical production, there are still some issues that require further exploration and resolution.

1. Environmental factors during the aluminum ingot production process, such as air humidity and atmospheric pressure, continue to have a significant impact on impurity content. For instance, in the high-temperature, high-humidity environment of southern regions, the hydrogen content in the aluminum melt is higher, and oxidation reactions are more pronounced, limiting the effectiveness of current technologies. Therefore, future research should focus on further improving environmental control in the holding furnace and production process (e.g., modifying heating and insulation methods) to reduce external interference on the high-temperature aluminum melt.
2. While the new equipment and improved processes have enhanced ingot quality, there remains cost pressure during the investment in equipment and the implementation of new technologies. Therefore, finding a reasonable balance between technological improvements and production costs will be a key area for the smelter to address moving forward.
3. This work primarily focuses on controlling oxide and hydrogen impurities in the production process. However, other impurities, such as nitrogen, may also exist in the ingots and could affect their performance under certain conditions. Future research could expand the scope of impurity control to address additional sources and control measures based on downstream customer requirements.

Conclusion and Outlook

This study successfully reduced non-metallic impurity content in 3N aluminum ingots and improved ingot quality through a combination of equipment upgrades, process optimization, and enhanced production management. The results demonstrate the importance of technological improvements in the aluminum smelting industry. However, impurity control still faces significant challenges, particularly regarding environmental factors and cost management. With advancements in aluminum smelting technology, increased automation, and higher quality demands from downstream customers, more precise impurity control and further cost reductions are expected in the future.

In addition to the impact of environmental factors on costs, the aluminum smelting industry must also navigate changes in international trade relations. The complexity of global political dynamics affects raw material procurement costs and supply chain stability, with trade barriers, tariffs, and geopolitical conflicts potentially causing fluctuations in production costs. Therefore, the industry must strengthen its ability to adapt to shifts in the global market and maintain flexible production strategies.

Looking ahead, advancements in intelligent and automated aluminum smelting technologies will improve impurity control. Additionally, enhancing international cooperation and supply chain management will be key to ensuring stable growth and addressing global economic challenges.

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