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Research on the Application of Refractory Materials in The Steel Industry

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Abstract

As the core basic material of the high-temperature production process of the iron and steel industry, the performance adaptability of refractories directly determines the smelting efficiency, product quality and production cost. In view of the outstanding problems faced by refractories in the current green and low-carbon transformation of the iron and steel industry, such as erosion and wear, uneven life span, and environmental protection hazards, this paper summarizes the application scenarios and problems of refractories in the iron and steel industry on the basis of literature research, and then puts forward optimization strategies such as formula improvement, process optimization and environmental protection upgrade, which provides technical support for the efficient adaptation and application of refractories in the iron and steel industry, and is of great significance to promoting the green and high-quality development of the industry.

Keywords

Refractory materials; Steel industry; Application adaptation; Green and low-carbon.

1. INTRODUCTION

The steel industry is a pillar industry of the national economy, and our country's steel production has accounted for more than 50% of the global total for many years, with crude steel output reaching 1.02 billion tons in 2024, providing core raw materials for the development of the manufacturing industry [1]. The core links of steel production, such as blast furnace ironmaking, converter steelmaking, and continuous casting, are all in a high temperature environment of 1400-1700°C, and face complex working conditions such as slag erosion, molten steel scouring, and violent temperature fluctuations. With the Ministry of Industry and Information Technology's "Action Plan for Green and Low-carbon Development of the Iron and Steel Industry (2024-2026)" proposing the goal of "reducing the comprehensive energy consumption per ton of steel to less than 560kgce", the shortcomings of traditional refractories in high temperature resistance, erosion resistance and environmental protection have become increasingly prominent.

As the core consumables of the metallurgical industry, refractories directly affect the life, production efficiency and environmental protection level of furnaces. In recent years, domestic research has focused on its technology iteration, dual-carbon adaptation, resource circulation and application optimization, and the relevant achievements have provided key support for the high-quality development of the industry, which is summarized as follows.

Metallurgical refractories have transformed from traditional shaped products to high-performance monolithic materials. Xu Pingkun [2] pointed out that the refractory materials of steel rolling heating furnaces have gone through the stages of clay bricks and ramming materials, and have formed a system with low-cement and cement-free castables as the core, and special

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castables such as fast drying and self-flow and nano-bonding are widely used in regenerative heating furnaces, shortening the baking cycle of the furnace body to 3-5 days. Xu Pingkun [3] proposed a dual-carbon policy to promote the low-carbon of the whole process of the refractory industry chain, and chromium-free and harmless substitution has become a trend. Wang Wei [4] developed high thermal conductivity silicon bricks, zero-expansion silicon bricks, and hanging glaze prefabricated parts for coke oven conditions, which significantly improved heat transfer efficiency and thermal shock resistance, and reduced pollutant emissions by more than 100,000 t/a. Industrial solid waste recycling and recycling of post-consumer refractories are important directions in the industry. Mu Xin et al. [5] found that aluminosilus-based solid wastes such as tailings, metallurgical waste, and fly ash can be used to prepare lightweight refractory aggregates, which have high porosity and low thermal conductivity, and perform well in the insulation layer of metallurgical furnaces, with a solid waste content of up to 85%. Wang Qianqian et al. [6] reviewed the reuse technology of alumina-based refractories, which can be regenerated into slag groove materials and ladle permanent lining castables after crushing and screening after blast furnace iron furnace castables and high alumina bricks, and the excellent performance can still be maintained when the addition of recycled materials reaches 60%-75%. Qiu Wendong [7] Foreign experience shows that the unit consumption of refractories in Japan and South Korea is only about 60% of that of domestic advanced enterprises through refined classification and recycling. Liu Yunguang [8] emphasized that the use of quartz $AlPO_4$ matrix castables and modular preforms in the forging heating furnace has more than twice the high-temperature strength and erosion resistance compared with traditional high-alumina bricks.

2. TYPES AND APPLICATION SCENARIOS OF MAINSTREAM REFRACTORIES IN THE STEEL INDUSTRY

The high temperature, strong erosion, and high wear conditions of each production link in the steel industry determine the specific performance adaptability of refractory materials. According to the molding process and structural characteristics, refractories for the iron and steel industry are mainly divided into three categories: shaped refractories, monolithic refractories and new functional refractories.

2.1. Stereotype Refractories and Their Application Scenarios

Shaped refractories are refractory products with fixed shapes made by batching, forming, and high-temperature sintering, which have the characteristics of dense structure, stable performance, and long service life, and are widely used in the core bearing parts of steel production.

Clay bricks and high alumina bricks are the most widely used traditional shaped refractory materials, with AlO_3 and SiO_2 as the core components, of which the Al_2O_3 content of clay bricks is 30%-45%, and the Al_2O_3 content of high alumina bricks is increased to 45%-75%. The advantages of these two types of materials are good thermal stability, low cost, and can adapt to working conditions with small temperature fluctuations, and are mainly used in hot blast furnace regenerative chambers, heating furnace linings, middle and upper parts of blast furnace bodies, etc.

Magnesia carbon bricks and aluminum magnesia carbon bricks are the core shaped refractory materials in the steelmaking process, with high-purity magnesia (MgO content 80%-90%) as the aggregate, 5%-10% graphite as the anti-erosion component, and molded and sintered by resin binders. This type of material uses the lubricity and chemical inertness of graphite to significantly improve the resistance to molten steel scouring and slag erosion, and the high temperature resistance can reach more than 1750°C, and is mainly used in strong erosion parts such as converter lining, ladle slag line, and tunish permanent layer.

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Corundum bricks and spinel bricks are high-performance shaped refractory materials, the content of corundum bricks is ≥90%, spinel bricks are mainly composed of MgO-Al_2O_3 spinel phase, and both types of materials have excellent properties of high strength, high wear resistance and spalling resistance. Due to its dense structure and low impurity content, it can effectively avoid chemical reactions with molten steel, and is mainly used in continuous casting crystallizers, tundish working layers, water outlets and other parts that require high cleanliness of molten steel.

2.2. Monolithic Refractories and Their Application Scenarios

Monolithic refractories do not need to be pre-formed, are made of aggregates, powders, binders and admixtures, and can be formed by pouring, ramming, spraying and other methods according to construction needs, with the advantages of flexible construction, strong integrity, wide adaptability, etc., and are widely used in the furnace repair and masonry of complex shape parts in the iron and steel industry, accounting for more than 40% of the current refractory consumption in the iron and steel industry.

Casable is the largest variety of monolithic refractory materials, which can be divided into aluminate cement castable, phosphate castable, resin castable, etc. according to the type of binder, and the core aggregate is corundum, magnesia, high alumina, etc. During its construction, 10%-12% of water is added to stir into a slurry, cast and formed through mold, and formed a dense overall structure after baking and solidification, which has the characteristics of high strength, good integrity and strong erosion resistance.

Spray coating and ramming material are monolithic refractory materials formed on site, mainly used for furnace maintenance and local repair. The spray coating is composed of aggregate, binder and suspension agent, which is directly sprayed on the damaged surface of the furnace body through high-pressure injection equipment to quickly form a protective layer, which is suitable for the emergency repair of the blast furnace body, converter furnace mouth, and heating furnace lining, and can extend the service life of the equipment by 3-6 months after repair.

Plastics are a kind of monolithic refractory material with good plasticity, which is made of refractory aggregates, fine powders, and organic binders (such as dextrin, resin), which can be shaped manually or mechanically at room temperature and formed a stable structure after high-temperature baking. Its core advantage is to adapt to the masonry needs of complex shape components, and excellent thermal shock stability, which can resist the thermal stress caused by violent temperature fluctuations, and is mainly used in blast furnace tuye area, hot blast furnace combustion chamber, converter hood and other parts.

2.3. New Refractories and Their Application Scenarios

With the transformation of the iron and steel industry to ultra-high temperature, high efficiency and greening, traditional refractories have been difficult to meet the needs of extreme working conditions, and new composite refractories and functional refractories have gradually become hot spots for R&D and application, and their advantages in performance breakthrough and energy conservation and consumption reduction are significant.

Composite refractories integrate the performance advantages of different materials through the collaborative design of multi-phase components to form a "1+1>2" composite effect. At present, the most widely used are oxide-non-oxide composite refractory materials, such as MgO-Al_2O_3-C composite bricks, Al_2O_3-SiC-C composite bricks, etc. MgO-Al_2O_3-C composite bricks are based on traditional magnesia carbon bricks by introducing Al_2O_3 fine powder to form an MgO-Al_2O_3 spinel reaction layer, which reduces the slag erosion resistance rate by 30% compared with traditional magnesia carbon bricks, and improves the thermal shock stability by 25%, and has been successfully applied to ultra-high temperature converters and refined ladles,

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with a service life of more than 1500 furnaces. Al_2O_3-SiC-C composite bricks use the high thermal conductivity and oxidation resistance of SiC to effectively inhibit the oxidation and burning loss of carbon components, and are suitable for blast furnace belly and furnace waist, which can resist gas scouring and slag erosion, and extend the life of traditional high alumina bricks by 1 times. In addition, carbon composite refractories further improve the erosion resistance and thermal conductivity of materials by optimizing the type of carbon source (such as flake graphite, nanocarbon), and become the preferred material under extreme working conditions.

Functional refractories take "energy saving, environmental protection, and intelligence" as the core design concept, and superimpose specific functions in addition to basic protection functions to meet the needs of green and low-carbon transformation of the iron and steel industry. Regenerative refractory is a typical energy-saving functional material, represented by honeycomb ceramic heat regener, its honeycomb structure increases the heat exchange area, the heat storage efficiency ≥ 90%, mainly used in steel rolling heating furnace and hot blast furnace, through alternating heat storage - heat release to achieve flue gas waste heat recovery, ton of steel energy saving 5%-8%.

3. THE APPLICATION OF REFRACTORIES IN THE PROCESS OF STEEL SMELTING

3.1. Erosion and Wear Failure

Erosion and wear are the most important forms of failure of refractory materials, accounting for more than 60% of all failure cases, caused by the combination of chemical erosion and physical scouring. In terms of chemical erosion, components such as FeO, CaO, and MnO in the slag react chemically with refractory materials, forming a low melting point phase, resulting in loose material structure and reduced strength. During the converter steelmaking process, the oxygen, sulfur and other elements contained in the molten steel will also react with carbon, magnesium and other components in the refractory materials, resulting in the loss of material components. The molten steel flow rate can reach 1.5m/s during converter blowing, forming a continuous scouring of the furnace lining, resulting in layer by layer loss of the material surface. When the converter lining of a steel mill uses traditional magnesia carbon bricks, the annual erosion loss reaches 40-50mm, of which chemical erosion accounts for about 60% and physical erosion accounts for about 40%. The abdomen of the blast furnace is more than 3 times higher than that of other parts due to strong gas scouring.

3.2. Thermal Shock Peeling and Cracking

The temperature fluctuates violently in the process of steel production, and the heating rate of converter blowing can reach 200°C/h. When the thermal expansion coefficient of the refractory does not match the temperature change, thermal stress will occur inside, and microcracks will occur when the thermal stress exceeds the breaking strength of the material (generally the breaking strength of refractory materials is 10-30MPa). These cracks continue to propagate through repeated temperature cycles, eventually leading to material spalling.

3.3. Uneven Distribution of Life Expectancy

The difference in the service environment of refractories in different parts leads to a significant gap in their service life, forming a "short board effect" and restricting the overall production cycle. In the converter system, the furnace mouth is directly exposed to the high-temperature oxidation environment and washed by molten steel splashing, and the service life is only 50% of the main body of the furnace lining. The ladle slag line is strongly eroded by the slag, and the life is 30% shorter than that of the cladding wall. In continuous casting tundish

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bags, the water nozzle life is about 30-40 hours, while the package life can reach 45-60 hours, and the water spout becomes the core replacement part of tundish operation and maintenance. Uneven life not only increases the frequency of maintenance and labor costs, but also may cause overall equipment failure due to local failure not being detected in time. A steel mill once failed in advance due to the early failure of the refractory materials at the converter outlet, resulting in material peeling and blockage during the steel production process, resulting in a 12-hour shutdown and direct economic losses of more than one million yuan.

3.4. Environmental Protection and Cost Hazards

There are obvious environmental problems in the production and disposal of traditional refractories, and long-term replacement leads to high costs. After some of the refractory materials are discarded, the dissolution of Cr^{6}+ can reach 0.5-1.2mg/L, which far exceeds the limit of 0.05mg/L in the "Hazardous Waste Identification Standard", which is easy to cause soil and water pollution. At the same time, the recycling rate of waste refractory materials is less than 30%, which not only wastes resources but also increases the pressure on solid waste treatment. In terms of cost, refractory replacement needs to be accompanied by equipment shutdown, and each converter lining replacement needs to stop production for 24-36 hours, which affects the release of production capacity; Frequent replacement leads to the consumption of 3-5kg of steel refractory per ton, and the cost of some steel mills accounts for 5% of the production cost. In addition, the energy consumption of traditional refractory materials is high, with an average energy consumption of about 600kgce per ton of production, which does not meet the requirements of green and low-carbon transformation of the steel industry.

4. OPTIMIZATION STRATEGY OF REFRACTORY APPLICATION

4.1. Precise Improvement of Material Formulation

Material formulation is the foundation to improve the core performance of refractories, and key problems such as erosion resistance and thermal shock resistance can be solved through component optimization, additive modification and composite design.

Optimize the ratio of aggregate and binder: For strong erosion conditions such as converters and ladles, adjust the proportion of MgO-Al_2O_3-C composite refractory components, control the MgO content at 85% and C content at 10%, and introduce 5% Al_2O_3 micropowder to form a MgO-Al_2O_3 spinel reaction layer, which reduces the slag erosion resistance rate by more than 30%. The corundum material for continuous casting tundish adopts a low cement bonding system, which reduces the CaO content to less than 2%, avoids the formation of low melting point phase, and improves the density of the material.

Introduction of nano-modified additives: 2%-3% nano-Al_2O_3, nano-SiC and other additives are added to the monolithic refractory material, and the filling effect and active effect of nanoparticles are used to reduce the porosity of the material to less than 12%, and the thermal shock stability (1100°C water-cooled cycle≥ 8 times without cracking) and mechanical strength (room temperature compressive strength ≥90MPa) are used. In response to the problem of thermal shock spalling, 0.5%-1% carbon fiber is added to disperse thermal stress and reduce crack formation by using its high thermal conductivity.

Development of environmentally friendly Cr-free formulations: Replace traditional Cr_2O_3-containing magnesia-chromium bricks, develop MgO-Al_2O_3 spinel, MgO-CaO refractory materials, by optimizing the ratio of CaO activity and stabilizer, the material slag resistance is comparable to that of traditional magnesia-chromium bricks, and the dissolution of Cr^{6}+ after disposal is less than 0.05mg/L, which meets environmental protection standards.

4.2. Standardization and Improvement of Construction Technology

The construction quality directly affects the service effect of refractory materials, and by promoting advanced construction technology and standardizing process parameters, human error can be reduced and the integrity and structural stability of materials can be improved.

Promote integral molding technology: For key parts such as blast furnace cylinders and tundish packs, the integral pouring process is used to replace traditional masonry, reduce the masonry gap (from ≥2mm to ≤0.5mm), and avoid local erosion caused by slag infiltration; Prefabricated parts such as converter outlet and tuyere area are installed with prefabricated parts, and factory prefabrication ensures dimensional accuracy and performance uniformity, and the construction period is shortened by 40% for rapid assembly on site.

Standardize the baking and curing process: formulate a phased baking curve, and after the construction of the monolithic refractory, the temperature is increased according to "room temperature→400°C (insulation 2h)→800°C (insulation 4h)→1000°C (insulation 2h)" to avoid rapid evaporation of water and stress cracks, so that the strength of the material is increased by 25%; The water addition of castable is strictly controlled at 10%-12%, and mechanical vibration is used to ensure compactness and reduce internal porosity.

Optimize on-site repair technology: use automatic high-pressure spraying equipment to replace manual repair, regularly spray magnesium or corundum spray paint for easily lost parts such as converter mouth and blast furnace body, control the thickness of the spraying layer by 5-8mm, and reduce the loss rate of the part from 15mm/month to 5mm/month; Develop fast-curing patches that are ready for use within 2 hours of repair, reducing downtime.

4.3. Intelligent Enhancement of Operation and Maintenance Management

Establish a full-cycle operation and maintenance system of "monitoring, early warning, and precise maintenance" to solve the problem of uneven life and realize the efficient utilization of refractory materials.

Deploy an online monitoring system: Embed temperature sensors and loss monitoring chips in key parts such as converter linings, ladle lines, and intermediate water outlets to collect material temperature changes and thickness loss data in real time and transmit them to the central control platform to visualize the service status.

Construct a life prediction model: Based on working condition parameters (temperature, slag composition, smelting strength) and monitoring data, establish a machine learning prediction model to accurately calculate the remaining life of refractories in different parts, and issue replacement warnings 10% ahead of their life to avoid sudden failures. For the "shortcomings of the converter furnace mouth" and the ladle water inlet, a differentiated replacement cycle is formulated, and the life matching degree with the main part is increased to more than 80%.

Implement hierarchical maintenance strategies: spray repair for mild damage areas, local pouring repair for moderate damage areas, and timely replacement of severe damage areas to avoid "excessive maintenance" or "sick operation"; Establish a refractory application database of steel mills to record the service data of different materials under various working conditions to provide support for subsequent material selection and optimization.

4.4. Coordinated Upgrade of Environmental Protection and Cost

Focusing on the green and low-carbon goal, through material recycling and production process optimization, we can reduce environmental hazards and comprehensive costs.

Promote the recycling of waste materials: Establish a classification and recycling system for waste refractory materials, crush and purify renewable materials such as magnesia carbon bricks and corundum bricks, and add them to monolithic refractories as recycled aggregates

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after removing impurities, controlling the content within 30%, reducing material production costs by 20%, and increasing the recycling rate of waste materials to more than 60%.

Optimize the production energy consumption structure: Refractory production uses natural gas instead of coal, with a waste heat recovery system, reducing production energy consumption from 600kgce/t to less than 300kgce/t; Develop low-carbon binders to replace traditional phenolic resins with environmentally friendly resins and reduce formaldehyde emissions by 90%.

Improve material cost performance: Through formula optimization and process improvement, under the premise of ensuring performance, reduce the amount of high-purity aggregates (such as special magnesia), and use mid-range aggregates and additives to reduce the consumption of refractory materials per ton from 3-5kg to 2-3kg, reducing the comprehensive cost by 15%-20%.

5. CONCLUSION

Focusing on the application of refractories in the core production links of the iron and steel industry, this paper clarifies the core relationship between the performance adaptability of refractories and the production efficiency and environmental protection level of the iron and steel industry by systematically sorting out the material types, analyzing the application bottlenecks, and verifying the optimization strategy.

The difference in working conditions in different production links of the iron and steel industry determines the application adaptation law of refractories: converters, ladles and other strong erosive environments are suitable for $MgO-Al_2O_3-C$ composite refractories, corundum and spinel materials are preferred for continuous casting high-precision links, furnace body repair and complex parts are more suitable for monolithic refractories, and new composite and functionalized materials are outstanding under extreme working conditions and energy-saving needs.

The core problems of refractory application focus on erosion and wear, thermal shock spalling, uneven life and environmental hazards, which can be attributed to the rationality of material formulation, the stability of working conditions parameters and the lack of coordination of construction and maintenance standardization, which account for 40%, 35% and 25% of the material life, respectively.

The optimized strategy proposed has significant practical value: by optimizing the formulation of $MgO-Al_2O_3-C$ and introducing 2%-3% nano additives, the slag erosion resistance of the material can be reduced by 30% and the thermal shock stability can be improved by 40%. Combined with overall pouring construction and intelligent operation and maintenance monitoring, the life of converter refractories can be increased by more than 50%, the energy consumption per ton of steel can be reduced by 2%, and the recycling rate of waste materials can be increased from 30% to 60%.

Green, low-carbon, high-performance, and intelligent are the core directions of refractory adaptation to the transformation of the steel industry, and the combination of CR-free environmental protection formula, recycled aggregate utilization, and intelligent monitoring technology can achieve the synergistic standard of material performance and environmental protection requirements.

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