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RESEARCH PROGRESS ON HIGH-NITROGEN AUSTENITIC STAINLESS STEEL

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Abstract: Advancements in metallurgical technology, coupled with the ever-growing industrial demand, have continuously driven the development of new materials. High-nitrogen austenitic stainless steel (HNASS), a resource-saving material, has been extensively investigated and rapidly developed owing to its high strength, high plasticity, and excellent corrosion resistance. This paper chronologically outlines the development of Cr–Mn–N series HNASS, which has evolved primarily through nickel-saving high-manganese austenitic stainless steel (such as AISI 200 series stainless steel), low-carbon molybdenum-containing austenitic stainless steel (such as AL6XN), and nickel-free HNASS (such as P900, developed by the VSG company of Germany). The development of HNASS is constrained by advancements in smelting technology. This paper outlines the current smelting methods for high-nitrogen steel, including atmospheric pressure smelting and high-pressure smelting, and summarizes the issues encountered during the smelting process. Welding technology is another key factor limiting the industrial application of HNASS. Extensive research has been conducted to reduce the number of welding defects in high-nitrogen steel. By optimizing welding processes and improving welding filler materials, welding joints with good performance can be obtained. However, welding technology for HNASS with universal applicability and industrialization potential still warrants further research.
Keywords: High-performance materials; High-nitrogen austenitic stainless steel; Smelting technology; Pressure electric-slag remelting; Welding technology

1 INTRODUCTION

Stainless steel provides a crucial material foundation for economic development and is widely applied in various fields, such as aerospace, marine engineering, petrochemical, and biomedical industries[1-2]. The development of stainless steel can be traced to the early 20th century. During the First World War, the British scientist Henry Brearley discovered an alloy steel with a high chromium content that exhibited exceptional corrosion resistance. This steel was subsequently named stainless steel, marking the origin of stainless steel. With advancements in smelting technology and the continuous enrichment of fundamental theories, new types of stainless steel have been continuously developed and applied. Currently, the total global production of stainless steel exceeds 10 million tons, with more than one hundred types of stainless steel being produced. In recent years, the steel industry has entered a stage of demand saturation, with production volumes decreasing continuously in recent years. This change has prompted the steel industry to accelerate its structural adjustment and optimize its product mix, with a particularly notable trend being the substitution of stainless steel for traditional carbon steel and other materials. This transformation is attributed to the excellent properties of stainless steel, which align with the requirements for high-quality economic and social development. Therefore, from a long-term perspective, the stainless steel industry still has vast market demand and development potential[3].

In the development of stainless steel, nickel-free high-nitrogen austenitic stainless steel (HNASS) has garnered increasing attention in recent years[4-10]. On the one hand, Cr–Ni series austenitic stainless steel currently accounts for more than half of the total stainless steel production. Recently, owing to the global impact, the price of raw nickel materials has fluctuated significantly, severely affecting the production cost of stainless steel. The development of nickel-free high-nitrogen austenitic stainless steel can help stabilize production costs and ensure the industrial safety of the stainless steel industry. Second, in the biomedical field, the Ni in traditional Cr–Ni series austenitic stainless steel can cause allergic reactions and other tissue changes in the human body, resulting in poor biocompatibility. As a replacement for Ni, N has excellent biocompatibility. In summary, the industrial development of nickel-free high-nitrogen austenitic stainless steel is highly necessary. This paper chronologically outlines the development of Cr–Mn–N series high-nitrogen austenitic stainless steel, as well as the current research status and key challenges facing smelting and welding technologies that affect the industrial application of high-nitrogen steels, providing a reference for subsequent research on high-nitrogen steels.

2 DEVELOPMENT OF HNASS

High-nitrogen austenitic stainless steel refers to stainless steel with a nitrogen content exceeding 0.4 wt.%. Research on nitrogen-containing steel can be traced to 1912, when Andrew discovered that nitrogen can stabilize the austenitic structure and significantly increase the yield strength of steel during his study of Fe–N series alloys[11]. This discovery ignited the interest of scientists in researching nitrogen-containing steel. In the 1930s, the outbreak of the Second World War resulted in a shortage of nickel resources due to strategic stockpiling, which further accelerated research into nitrogen-containing steel. Germany successfully developed nickel-saving austenitic stainless steel by partially replacing nickel with manganese and nitrogen, whereas the United States also successfully developed an AISI 200 series of austenitic stainless steel with a nitrogen content ranging from 0.10 to 0.25 wt.%[12]. During this period, nitrogen-containing steel was used primarily in military defense applications. The addition of nitrogen to stainless steel not only affects its microstructure and mechanical properties but also has beneficial effects on the corrosion resistance of the material[13]. In the 1950s, owing to its lower production costs, nitrogen-containing steel began to enter the commercial application stage and was widely used in household utensils. Compared with traditional austenitic stainless steel, nickel-saving steel also has excellent mechanical properties and corrosion resistance.

In the 1970s, with the continuous development and refinement of secondary refining technologies, stainless steel production achieved better control of lower carbon content during smelting. During this time, many low-carbon nitrogen-containing austenitic stainless steels, such as AL6XN produced by Allegheny in the United States and 254SMO developed by Avesta in Sweden, emerged. A lower carbon content inhibits the formation of carbides and intermetallics in the material, thereby improving the high-temperature performance of stainless steel. Additionally, the incorporation of the metallic element molybdenum into stainless steel not only improves its mechanical properties but also increases its corrosion resistance. In the 1980s, with the maturation of high-pressure smelting technologies and the continuous enrichment of stainless steel theoretical knowledge, high-nitrogen austenitic stainless steel entered a period of rapid development, resulting in the emergence of many high-nitrogen austenitic stainless steels with excellent overall performance. The most representative is the P900 (18Cr–18Mn–0.6N) series of high-strength retaining ring steel developed by the German company VSG, which has been widely used in large thermal power generating units[14].

Since the rapid development of the global economy in the 1990s, there has been an urgent demand for high-performance stainless steel in various engineering fields. To meet this demand while also considering the production costs for stainless steel enterprises, high-nitrogen stainless steels with even superior comprehensive properties have been continuously developed and applied. The P550, P580, and P650 series of high-nitrogen austenitic stainless steels, which were jointly developed by Österreich's Böhler company and the United States' Schoeller–Bleckmann company, exhibit good mechanical properties and corrosion resistance and are used for drill collars in onshore and offshore oil and gas exploration. Japan researched resource-saving stainless steel resistant to seawater corrosion and successfully fabricated high-nitrogen austenitic stainless steel (23Cr–4Ni-2Mo–1N)[15]. This steel has not only excellent seawater corrosion resistance but also a tensile strength greater than 1200 MPa and an elongation greater than 40%. In China, Northeastern University and the Institute of Metal Research of the Chinese Academy of Sciences jointly applied for the key project of the National Natural Science Foundation of China, "Research on High-Nitrogen Steel and Its Mechanism," and successfully prepared high-nitrogen austenitic stainless steel with a nitrogen content exceeding 1.0 wt.% under the support of this key project[16-17]. The research covered smelting, casting, and other preparation techniques. A systematic study of its deformation mechanism was also conducted, revealing that its yield strength was much greater than that of traditional 316L austenitic stainless steel while maintaining good plastic deformation capability.

In the biomedical field, to prevent allergic reactions to nickel in the human body, nickel-free high-nitrogen stainless steels have also begun to gain widespread application. Nickel-free alloys such as the BioDur 108 alloy developed in the United States and the P-series alloys developed in Österreich exhibit good mechanical properties and corrosion resistance. Some of these alloys have already been commercialized and successfully applied in biological implants and medical devices[18]. Yang Ke and his team at the Institute of Metal Research of the Chinese Academy of Sciences successfully developed a new type of nickel-free high-nitrogen austenitic stainless steel suitable for bioengineering[19]. This stainless steel passed the biological performance tests conducted by the National Institutes for Food and Drug Control and successfully completed the animal implantation experiments at Guangzhou Military Region General Hospital.

With the continuous advancement of metallurgical technology and the development of basic theories, high-nitrogen austenitic stainless steel with low cost, high mechanical properties, and corrosion resistance is replacing traditional high-nickel austenitic stainless steel. In the development of high-nitrogen austenitic stainless steels, numerous laboratory-grade high-nitrogen steels with excellent comprehensive properties have been successfully prepared. However, many issues remain in the industrial production of high-nitrogen steel, including the shortage of high-pressure smelting equipment and the lack of optimization of production process parameters, which result in a high rejection rate during mass production. Additionally, welding defects are prone to form during the welding process, causing a decrease in the mechanical properties and corrosion resistance of structural components, thereby severely affecting the industrial application of high-nitrogen steel. Below is a detailed description of the smelting technology, welding technology, and related issues concerning high-nitrogen steel.

3 SMELTING OF HNASS

3.1 Smelting Techniques

In the development of high-nitrogen austenitic stainless steel, advancements in smelting technology have been pivotal factors limiting its progress. Currently, methods for preparing high-nitrogen steel are divided into two categories:

melting and casting methods and powder metallurgy methods. Melting and casting methods can be further categorized into atmospheric pressure melting methods and high-pressure melting methods. Generally, atmospheric pressure melting is suitable for producing high-nitrogen steel with a nitrogen content of less than 0.7 wt.%, whereas high-pressure melting technology is essential for producing high-nitrogen steel with a nitrogen content exceeding 1 wt.%[20]. According to Sievert's equation, the saturation solubility of nitrogen in molten steel is directly proportional to the square of the partial pressure of nitrogen gas at the steel surface. Therefore, increasing the nitrogen content in stainless steel can be achieved by elevating the nitrogen pressure inside the furnace, which is known as nitrogen gas pressure melting[21-22]. Pressurized melting techniques include pressurized induction melting, pressurized electroslag remelting, and pressurized plasma methods[23-25]. There are two approaches to producing high-nitrogen steel through powder metallurgy: (1) prepare high-nitrogen stainless steel powder first and then sinter it into shape, and (2) press it into shape first, followed by sintering and nitriding. The second method is suitable for producing high-nitrogen stainless steel porous materials or for nitrogen enrichment treatment on the surface of stainless steel. Powder metallurgy for preparing high-nitrogen steel offers advantages such as low cost, high purity, and uniform nitrogen distribution. However, this approach also has drawbacks such as susceptibility to defects and voids, as well as poor mechanical properties. Currently, the most common industrial method for producing high-nitrogen steel is the melting and casting method.

3.1.1 Atmospheric smelting

Generally, the low solubility of nitrogen in molten steel is the main factor limiting the preparation of high-nitrogen steel via traditional melting and casting methods. Selecting the Fe-18.4wt.% Cr alloy as an example, the solubility of N in molten steel at 1500 °C is less than 0.4%, and during the solidification process, the molten steel passes through the δ-Fe phase, which has an even lower solubility of nitrogen. Therefore, preparing high-nitrogen steel under atmospheric pressure is difficult. However, adjusting the alloy composition can increase the solubility of nitrogen under atmospheric pressure significantly. In Fe-Cr-Mn stainless steel, the addition of Mn not only stabilizes the austenitic phase but also increases the solubility of nitrogen significantly[26]. With atmospheric pressure N_2 atmosphere electroslag remelting technology, the nitrogen content of 1Mn18Cr18N austenitic stainless steel can exceed 0.65%[20]. The alloying of nitrogen in high-nitrogen stainless steel at room temperature is achieved by blowing nitrogen gas into the molten steel and adding nitrided alloys, such as chromium nitride and manganese nitride. During the atmospheric smelting process of high-nitrogen stainless steel, owing to the limitation of nitrogen solubility, the molten steel is prone to porosity during cooling and solidification. Electroslag remelting can remove these pores effectively and dissolve nitrogen into the steel ingot. Based on the dual process of "vacuum induction melting and electroslag remelting," Northeastern University in China has prepared high-nitrogen steel with a maximum nitrogen content of 0.65 wt.% via electroslag remelting under atmospheric pressure[20]. In Japan, reports on the smelting of high-nitrogen steel indicate that atmospheric pressure electroslag remelting technology can produce high-nitrogen steel with a nitrogen content of 0.76 wt.%.

3.1.2 High-pressure smelting

1. Pressure induction melting: Pressure induction melting for the preparation of high-nitrogen steel utilizes the induction effect to heat and melt the raw materials. The molten pool is stirred by the action of an alternating magnetic field, generating convection that accelerates the diffusion rate of nitrogen in the molten steel. The induction furnace is enclosed in a high-pressure environment, where high-pressure nitrogen can reduce the time for nitrogen saturation in the molten steel, achieving rapid nitrogen enrichment of the molten steel. Ahmed et al. prepared high-nitrogen austenitic stainless steel through a pressure induction melting process[27]. The mechanical property test results revealed that this stainless steel has superior mechanical properties compared with traditional 316 austenitic stainless steel. During pressure induction melting, deoxidation and desulfurization cannot be performed, which may result in the formation of harmful second phases and subsequently impair the mechanical properties of the material. To address this issue, Feng et al. proposed a new smelting process by combining pressure induction melting with pressure electroslag remelting[28], successfully resolving problems such as the inability to deoxidize, desulfurize, and uneven nitrogen distribution in pressure induction melting. Both the melting process and the casting process in the pressure induction furnace are conducted in a high-pressure nitrogen environment. Therefore, the equipment for this process is relatively complex, and the production costs are relatively high, which are key issues that limit its industrial application.

2. Pressurized electroslag remelting: Pressurized electroslag remelting is currently the most widely used method in industry for producing high-nitrogen steel. Materials such as the large generator retaining ring steels P900N and P2000 series, the high-nitrogen stainless-bearing steel Cronidur 30, and the P550, P580, and P650 series, which were jointly developed by Österreich's Böhler Company and the United States' Schoeller–Bleckmann Company, are produced through pressurized electroslag remelting technology. Pressurized electroslag remelting originated in 1980. The introduction of high-pressure nitrogen into a sealed melting chamber can suppress the formation of nitrogen pores during the stainless steel smelting process, increasing the nitrogen content in the steel to above 1 wt.%. A schematic of pressurized electroslag remelting is shown in Figure 1. Pressurized electroslag remelting uses the heat generated by current that passes through high-resistance slag as the heat source. The raw material electrode is melted, and the melted stainless steel liquid passes through the high-temperature slag into the molten pool, which is then cooled in the mold to form a stainless steel ingot. This method combines the advantages of high-pressure smelting and electroslag remelting, not only inhibiting the outflow of nitrogen and the formation of nitrogen pores during the smelting process but also ensuring the cleanliness of high-nitrogen steel. Maruyama et al. researched two types of high-nitrogen austenitic stainless steels that are used in the medical industry: the first type of stainless steel was prepared under a nitrogen

atmosphere, and the second type of stainless steel was prepared via pressurized electroslag remelting[29]. A comparison of the performance of the two high-nitrogen stainless steels revealed that the high-nitrogen stainless steels prepared through the pressurized electroslag remelting process exhibited superior fatigue resistance. Industrial high-pressure electroslag furnaces are equipped with feeding devices that allow the addition of nitrided alloys during the high-pressure smelting process, which enable the production of high-nitrogen steel. However, when nitrogen alloys are added, the outflow of nitrogen can easily cause the molten steel to boil, affecting the stability of the process. Second, owing to the large diameter size of high-nitrogen steel ingots produced industrially, an uneven distribution of nitrogen often exists in the radial direction of the ingot. Last, the overall equipment for pressurized electroslag remelting is relatively complex, and the control system is relatively precise, which results in relatively high production costs, posing certain challenges for the widespread promotion of its industrial application.

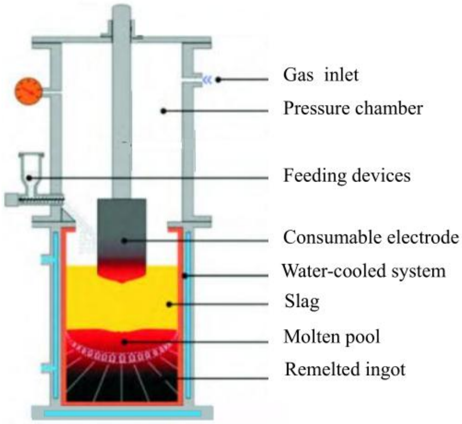

Figure 1 Schematic of Pressurized Electroslag Remelting

3. Pressurized plasma melting method: In the pressurized plasma melting method, a plasma arc is used as the heat source to melt, refine, and remelt materials. Owing to the effect of a strong electric field, the outer electrons of gas atoms absorb energy and become free electrons, whereas the gas atoms become positive ions and form a plasma with nonionized gas molecules. By leveraging both chemical adsorption and electrical adsorption, the nitrogen incorporation rate in the melt can be significantly increased, allowing the nitrogen concentration in the melt to far exceed the traditional thermodynamic equilibrium concentration of nitrogen when equilibrium is reached. Therefore, the pressurized plasma melting method has remarkable nitrogen-enrichment effects and can achieve nitrogen enrichment without the addition of nitrides, even at relatively low pressures. Tyuftyaev et al. employed the pressurized plasma arc remelting process to prepare high-nitrogen austenitic stainless steel 55Kh0G9N4[30]. The results revealed that the microstructure of this stainless steel featured finer grain sizes and significantly improved mechanical properties. However, the pressurized plasma melting method currently has drawbacks such as high energy consumption and complex equipment, making it one of the key research directions for the future smelting of high-nitrogen steel.

3.2 Key Issues

The pressurized melt-casting method is currently the primary industrial method for producing high-nitrogen austenitic stainless steel. Although a large amount of high-nitrogen austenitic stainless steel has achieved industrial production, with rapid economic development, the demand for high-performance, low-cost stainless steel is increasing in almost all sectors, and current manufacturing enterprises are unable to meet the ever-growing industrial demand. The main issues include the following:

1. High production costs: High-pressure smelting technology is currently the primary method for the industrial production of high-nitrogen steel. The cumbersome high-pressure equipment and complex operating systems result in high costs for high-nitrogen austenitic stainless steel. Achieving low-cost production of high-nitrogen austenitic stainless steel is one of the main issue affecting its development.
2. Nitrogen yield problem: Adding nitrogen through alloy feeders with nitrided alloys is the primary method for the industrial production of high-nitrogen steel. Nitrided alloys include chromium nitride, manganese nitride, and molybdenum nitride. During the smelting process, selecting appropriate types of nitrided alloys, as well as factors such as alloy particle size, shape, addition position, and addition rate, has varying effects on nitrogen yield. Further research is needed in this area.
3. Development of specialized slag systems for the electroslag remelting of high-nitrogen steel: Pressurized electroslag remelting is currently the most common method for the industrial production of high-nitrogen steel. The slag system used in smelting high-nitrogen steel needs to have characteristics such as strong desulfurization, efficient inclusion adsorption, efficient heat generation, and rapid melting of nitrided alloys. Designing suitable electroslag remelting slag systems for different high-nitrogen steels is crucial for producing high-quality high-nitrogen steel and is a key issue in current electroslag remelting technology.

4. Avoiding nitrogen precipitation and pore formation during solidification and cooling of the molten steel: Three forms of nitrogen exist in steel: nitrides, nitrogen pores, and solid-solution nitrogen. The ultimate goal of producing high-nitrogen stainless steel is to stably dissolve nitrogen in the stainless steel matrix. However, during solidification, the precipitation of nitrides and intermetallic compounds can easily occur, severely affecting the service properties of the material. Therefore, exploring the forms of nitrogen in high-nitrogen stainless steel and its conversion mechanisms is a key focus in research on high-nitrogen steel smelting and has a significant effect on the development and subsequent engineering applications of high-nitrogen steel.

4 WELDING PERFORMANCE OF HNASS

4.1 Welding Techniques

Welding is an indispensable joining technology for engineering structural components. During the welding process of high-nitrogen austenitic stainless steel, various defects are prone to form due to their high nitrogen content, which is currently another key factor restricting the industrial application of high-nitrogen stainless steel. The primary welding defects of high-nitrogen stainless steel are nitrogen loss and nitrogen porosity[31]. In traditional fusion welding processes, the melting of the base material (high-nitrogen stainless steel) causes the supersaturated nitrogen atoms within it to escape in the form of N_2. If the cooling rate of the weld after welding is low, this N_2 will escape from the sample, reducing the N content in the weld zone. Conversely, if the cooling rate of the weld after welding is high and the N_2 does not have enough time to escape from the sample, it will remain in the weld zone in the form of bubbles, resulting in nitrogen porosity. The formation of nitrogen loss and nitrogen porosity not only affects the mechanical properties of the weld but also reduces its corrosion resistance, impacting the service performance of high-nitrogen steel structural materials significantly. To address this issue, scientists have conducted extensive research to optimize welding performance, focusing mainly on improving welding processes and optimizing welding filler materials.

4.1.1 Improvement of welding processes

Laser beam welding (LBW) is an efficient and precise welding method that uses a high-energy-density laser beam as the heat source. LBW is characterized by low heat input, a small heat-affected zone, and good flexibility. Wang et al. conducted welding experiments on high-nitrogen stainless steel via the laser–arc hybrid welding method and investigated the effects of the arc energy[32], laser energy, and vibration frequency on the welded joints. The experimental results revealed that as the arc energy or laser energy increased, the porosity of the weld first increased but then decreased. When the arc energy was 4800 joules (current I=200 A and voltage U=24 V), the porosity of the weld decreased to a minimum of 0.49%, and when the laser power was 2.8 kW, the porosity of the weld was only 0.14%. The results indicated that adjusting the arc energy or laser power could effectively suppress the number of welding pores. During the hybrid welding process, vibrating the workpiece resulted in a decrease in weld porosity followed by an increase in weld porosity as the vibration frequency increased. By controlling the vibration frequency, the porosity of the weld can be reduced. Cui et al. conducted welding experiments on high-nitrogen stainless steel plates via ultrasonic-assisted, laser–arc hybrid welding[33]. The results showed that the cavitation effect and acoustic streaming effect generated by ultrasonication could refine the grains and weaken the orientation of grain growth. The refined microstructure at the weld improved the microhardness of the material. As the ultrasonic power increased, the porosity of the weld decreased but then increased. When the ultrasonic power was 180 W, the porosity was the lowest, and the mechanical properties of the welded joint were optimal; however, when the ultrasonic power increased to 240 W, many pores formed, resulting in significant nitrogen loss and a noticeable decrease in the microhardness of the welded joint.

MIG welding is a type of melt inert-gas welding. Kamiya and Kikuchi conducted welding experiments on SUS316L stainless steel in a closed container via the MIG welding method and investigated the relationship between the N_2 partial pressure in the shielding gas and the nitrogen content in the weld[34]. When the N_2 pressure in the shielding gas increased from 0.1 MPa to 6.1 MPa, the nitrogen content in the weld increased from 0.2% to 0.65%, achieving high nitrogen content in the weld, and no pores were detected in the weld, indicating that the higher N_2 pressure could promote nitrogen absorption in the weld and inhibit the formation of nitrogen porosity. Ning et al. performed welding experiments on high-nitrogen austenitic stainless steel via both MIG welding and laser-MIG hybrid welding[35]. Both welding methods produced welded joints with no obvious defects. A comparative analysis of the microstructure and mechanical properties of the welded joints revealed that the tensile strength and impact absorption energy of the laser-MIG hybrid welded joints were approximately 27% greater and 20% greater, respectively, than those of the MIG welded joints; this was attributed to the stronger solid solution strengthening effect resulting from the higher nitrogen content in the laser-MIG hybrid welded joints. Compared with those of MIG joints, the microstructures of the laser-MIG hybrid welded joints exhibited finer grains and fewer ferrite and precipitated phases and contributing to improved toughness.

Friction stir welding (FSW) is an innovative solid-state joining technology invented by the Welding Institute in the UK in 1991. Compared with traditional fusion welding processes, FSW does not undergo a solid-to-liquid transformation, effectively inhibiting nitrogen loss and providing significant advantages for welding high-nitrogen stainless steel. Li et al. conducted FSW experiments with nitrogen shielding on high-nitrogen austenitic stainless steel 18Cr-18Mn-2Mo-0.96N[36]. The results revealed that no defects, such as nitrogen pores, formed in the weld zone. Moreover, compared with the microstructure of the heat-affected zone, the grains in the weld zone were significantly refined. The nitrogen content in the weld zone was 0.96 wt.%, which was almost the same as that of the base material

(0.94 wt.%), indicating that no nitrogen loss occurred. The hardness and strength (including yield strength and tensile strength) of the weld zone were greater than those of the base material, but the elongation was lower. Du et al. also obtained welded joints with almost no nitrogen loss through the FSW process[37], where the yield strength and tensile strength were greater than those of the base material, but the elongation was significantly reduced. Postweld heat treatment restored the elongation to 90% of that of the base material.

4.1.2 Improvement of welding filler materials

During the welding of HNASS, high-nitrogen stainless steel is generally used as the welding wire. On the one hand, high-nitrogen stainless steel can supplement nitrogen in the weld; on the other hand, the higher contents of elements such as Cr, Mn, and Mo in the welding wire can also increase the solubility of nitrogen in the weld. Vilpas and Hänninen conducted welding experiments on high-nitrogen steel using high-nitrogen stainless steel as the welding wire and obtained ideal welded joints[38]. The higher nitrogen content in the weld improved both the mechanical properties and corrosion resistance of the welded joints significantly. Bai et al. investigated the effects of different welding wires on the corrosion resistance of high-nitrogen steel welded joints[39]. The experimental results revealed that welding wires containing nitrogen increased the corrosion resistance of the entire welded joint: the extra nitrogen in the welding wire optimized the composition of the passive film on the material surface. The welding of high-nitrogen steel is accompanied by nitrogen loss and porosity formation, which can result in a decrease in mechanical properties. During the welding process, adding nitrides to the molten pool can also optimize the microstructure and mechanical properties of high-nitrogen stainless steel welds. Lei et al. investigated the effect of manganese nitride powder on the welded joints of high-nitrogen stainless steel via laser–arc hybrid welding[40]. The experimental results indicated that, compared to welds without added manganese nitride powder, the addition of manganese nitride powder increased the nitrogen content by 17% in the welds, and no manganese nitride particles were detected in the weld. However, as the nitrogen content increased, the degree of austenitization increased, and the number of nitrogen pores in the weld also increased. By adding titanium, titanium nitride phases were preferentially formed, inhibiting the formation of nitrogen pores. Li et al. conducted twisted wire gas metal arc welding on high-nitrogen steel[41-42]. Compared with traditional welding wires, twisted wires significantly reduced the number of defects in the weld zone and refined the grains; the yield strength and tensile strength of the welded joints were also markedly improved.

4.2 Key Issues

To obtain higher-quality welded joints, researchers have conducted extensive studies on the welding technology of high-nitrogen stainless steel, primarily focusing on reducing defects and nitrogen loss in the weld. Although numerous experiments have confirmed that the microstructure and mechanical properties of welded joints can meet practical application requirements, further exploration is needed to identify a welding technology for high-nitrogen austenitic stainless steel that is both widely applicable and suitable for industrial production. The current welding technologies have the following limitations:

1. In terms of welding processes, although numerous experimental results indicate that optimized welding processes can produce welded joints that meet service requirements, many issues arise when laboratory welding processes are transitioned to industrial production. Laser welding is costly and currently cannot be widely promoted in industrial production. FSW requires clamping tools to fix the test plates during the welding process, making it unsuitable for larger workpieces. Additionally, FSW poses risks of crack and void formation. MIG welding technology increases the nitrogen content in a weld by increasing the N_2 partial pressure, which necessitates welding in a closed environment, posing significant challenges to current industrial production.
2. In terms of filler materials, high-nitrogen welding wires are generally used for welding high-nitrogen steel to increase the nitrogen content in the weld. However, challenges remain in the industrial production of high-nitrogen steel welding wires. On the one hand, high-nitrogen stainless steel typically has high strength, which hinders its ability to deform during the production of welding wires, thereby posing certain difficulties in the production of high-nitrogen stainless steel welding wires. Furthermore, few specialized welding wire types currently exist for high-nitrogen steel, and welding wire materials with superior welding performance must be further developed for different systems of high-nitrogen steel.
3. In terms of research on the corrosion resistance of welded joints, high-nitrogen austenitic stainless steel is often used in environments such as electric power generation and oil and gas extraction due to its excellent corrosion resistance. However, current research on the welding performance of high-nitrogen steel has focused primarily on the mechanical properties of the weld zone, and relatively little research has been conducted on the corrosion resistance of high-nitrogen steel welds, which is insufficient for promoting the application of high-nitrogen stainless steel.

5 CONCLUSION AND OUTLOOK

With the development of the global economy and the acceleration of industrialization, the demand for stainless steel materials with high performance, high corrosion resistance, and low cost across various fields is increasing. Owing to its excellent comprehensive properties and cost-effectiveness, high-nitrogen austenitic stainless steel has broad application prospects in sectors such as petroleum, chemical, biomedicine, and transportation. Furthermore, as the global focus on environmental protection and sustainable development intensifies, the market demand for high-nitrogen austenitic stainless steel, a resource-saving material, will further increase. This paper summarizes the development history, smelting technology, and welding technology of high-nitrogen austenitic stainless steel and provides an outlook for the development of high-nitrogen steel.

1. From the perspective of the development history of high-nitrogen stainless steel, most researchers focused initially on increasing the solubility of nitrogen during the stainless steel smelting process. An increase in nitrogen content can increase the strength of stainless steel. However, excessive nitrogen may promote the formation of precipitated phases, which not only affects the mechanical properties of the material but also reduces its corrosion resistance. A thorough understanding of the nitrogen strengthening mechanism and enhancement of the mechanical properties of high-nitrogen steel through traditional strengthening methods are important aspects of high-nitrogen steel research.

2. The melting and casting method is currently the primary method for the industrial production of high-nitrogen steel. The low solubility of nitrogen in molten steel limits the preparation of high-nitrogen steel via traditional melting and casting methods. Pressurized melting and casting can increase the solubility of nitrogen significantly, but this process requires high-pressure nitrogen during smelting and casting and places high demands on smelting and casting equipment. Consequently, the high production cost of high-nitrogen austenitic stainless steel is currently the main factor limiting its application. How to reduce the production cost of high-nitrogen steel or develop new production processes, such as additive manufacturing, are challenges faced by the industrial production of high-nitrogen steel.

3. Nitrogen loss and nitrogen porosity are common defects in the welding of high-nitrogen austenitic stainless steel. Friction stir welding, which does not involve solid–liquid transformation, has unique advantages in the welding of high-nitrogen austenitic stainless steel. Conducting in-depth research on FSW processes or developing new welding technologies to identify better welding methods to address the welding issues of high-nitrogen steel is essential.

COMPETING INTERESTS

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