Microstructure and Properties of Dissimilar Metal Welded Joints Between a Novel Nickel-Based Corrosion-Resistant Alloy and Alloy 625: Postprint

Authors: Zhao Xia, Zha Xiangdong, Zhang Long, Liang Tian, Ma Yingche, Liu Kui

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Abstract

The microstructure and properties of manual tungsten inert gas (TIG) welded joints between a novel nickel-based corrosion-resistant alloy U26-2# and 625 alloy were investigated through tensile and hardness testing, combined with optical microscopy (OM), scanning electron microscopy (SEM), and energy-dispersive spectroscopy (EDS) analyses. The results indicate that the increased equiaxed grain structure in the weld remelting zone of the U26-2#/625 dissimilar metal weld is beneficial for enhancing the strength of the weld zone. The microstructural transition in the fusion zone on the U26-2# alloy side is favorable, whereas precipitation of NbC and Laves phases at grain boundaries on the 625 alloy side adversely affects the mechanical properties. In the heat-affected zone (HAZ), grains adjacent to the remelting zone undergo coarsening due to secondary thermal cycling, while the HAZ on the U26-2# alloy side exhibits superior thermal stability. The fine-grained microstructure of the 625 alloy base material leads to pronounced grain growth in its HAZ, resulting in reduced Vickers hardness values in the HAZ on the 625 alloy side. The tensile strength of the U26-2#/625 welded joint from room temperature to 700 °C is lower than that of both base materials, with the weld zone being the weakest region of the joint; the fracture morphology exhibits ductile dimple features.

Microstructure and Mechanical Properties of a Dissimilar Metal Welding Joint Between a Novel Nickel-Based Corrosion-Resistant Alloy and Alloy 625

ZHAO Xia1,2), ZHA Xiangdong2), LIU Yang3), ZHANG Long2), LIANG Tian2), MA Yingche2), CHENG Leming3) 1) School of Materials and Metallurgy, Northeastern University, Shenyang 110819 2) Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016 3) ENN Science & Technology Development Co. Ltd., Langfang 065001

Abstract: The microstructure and mechanical properties of a dissimilar metal welding joint between a novel nickel-based corrosion-resistant alloy X-2# and Alloy 625, fabricated by manual argon arc welding, were investigated through tensile and hardness testing combined with OM, SEM, and EDS analyses. The results indicated that the weld remelting zone of the X-2#/625 joint exhibited an increased amount of equiaxed crystal structure, which was beneficial for enhancing the strength of the weld zone. The fusion zone on the X-2# alloy side showed a smooth transition, while NbC and Laves phases precipitated along grain boundaries on the Alloy 625 side, affecting the mechanical properties. In the heat-affected zone (HAZ), grains near the remelting zone experienced grain coarsening due to the influence of dual thermal cycles, whereas the HAZ on the X-2# alloy side demonstrated good thermal stability. The fine grain structure of the Alloy 625 base material led to significant grain growth in its HAZ, resulting in reduced Vickers hardness values on the Alloy 625 side.

The tensile strength of the X-2#/625 welding joint was lower than that of both base materials from room temperature to 700 °C, with the weld zone being the weakest link of the joint. The fracture morphology exhibited dimpled features characteristic of ductile fracture.

Keywords: X-2#/625 welding joint, weld zone, fusion zone, HAZ

Introduction

Wastewater treatment, particularly the disposal of refractory harmful organic substances, organic solid waste, and sludge from industrial and municipal sources, represents a significant challenge in sewage treatment technology [1-5]. Supercritical water oxidation (SCWO) offers unique technical and economic advantages for wastewater treatment; however, material corrosion has become a critical issue limiting its widespread application. Materials used in preheaters and reactors for this process typically require high-temperature creep strength, strong resistance to steam oxidation and corrosion, excellent workability, and economic viability [6-8].

Currently, material development efforts have focused primarily on ferritic/martensitic (F/M) steels, oxide dispersion strengthened (ODS) steels, austenitic stainless steels, and nickel-based alloys. Studies by Tan et al. [9] and Zhu et al. [10] on Cr steel and P92 steel revealed that corrosion of F/M steels increases significantly with temperature, with the surface oxide film cracking at 600 °C. F/M steels exhibit lower corrosion resistance in SCWO environments compared to other alloys [11]. The overall corrosion resistance of ODS steels is generally superior to that of F/M steels, though it depends on specific elemental composition. ODS steels with high Cr content demonstrate better corrosion resistance, while low-Cr ODS steels typically show poor corrosion performance, forming oxide films similar to those of F/M steels [12-16]. Research on austenitic stainless steels such as TP347, HR3C, D9, 316, and 304NG in SCWO environments [17-22] has shown that while their corrosion weight gain is typically less than that of F/M steels, it increases sharply with rising temperature. Nickel-based alloys are widely used in high-temperature environments for three primary reasons: excellent microstructural stability, high-temperature strength, and superior oxidation and corrosion resistance. Investigations of nickel-based alloys including 625, 617, 718, C-276, and X-750 in SCWO conditions [23-26] have demonstrated minimal corrosion weight gain on alloy surfaces. Consequently, the favorable corrosion resistance of nickel-based alloys makes them promising candidate materials for SCWO applications [27,28].

Materials currently used in SCWO preheaters and reactors include 304 austenitic stainless steel, Alloy 625, and P91/P92 steels. However, severe corrosion and oxidation of these materials result in short service life, necessitating the development of a new alloy to replace existing ones. To address this issue, a novel nickel-based alloy containing 10% Fe (mass fraction) has been successfully developed; the addition of Fe reduces its cost compared to nickel-based alloys such as 230, 617, and 740. Preliminary experiments have demonstrated that the new alloy possesses excellent high-temperature strength, ductility, and microstructural stability. Qualitative oxidation tests revealed minimal oxidation at 760 °C and 1000 °C, indicating outstanding high-temperature oxidation resistance. Furthermore, the alloy exhibits superior corrosion resistance under supercritical conditions in phosphate-dominated environments compared to alloys 671, C-276, and 625, suggesting promising application prospects. Considering cost-effectiveness, replacing severely corroded sections of preheaters or reactors with this new alloy represents an economically viable solution. Therefore, investigating the weldability of the new alloy with existing SCWO materials is of particular importance. This work primarily examines the microstructure and properties of dissimilar metal welding joints between the new alloy (X-2#) and Alloy 625 under conditions of 300-500 °C preheat temperature at 25 MPa and 550-650 °C reaction temperature at 25 MPa, providing reliable theoretical and experimental support for future applications of the new alloy.

Experimental Materials and Methods

The novel nickel-based corrosion-resistant alloy X-2# used for dissimilar metal welding experiments was prepared by vacuum induction melting, forging, and hot rolling into plates, followed by solution heat treatment. Alloy 625 plates were purchased and hot-rolled through several passes to match the thickness of the X-2# alloy plates. The chemical compositions of the materials are presented in Table 1 . Both base metals were in the solution-treated condition, with X-2# alloy solution-treated at 1120 °C for 30 minutes (water quenched) and Alloy 625 solution-treated at 1000 °C for 60 minutes (water quenched). The welding process employed manual argon arc welding in a double-sided configuration, using X-2# alloy as the filler material with an X-groove design. Welding parameters included a current of 110-120 A for both front and back sides, welding speeds of 130-140 mm/min for the front side and 150-160 mm/min for the back side, shielding gas flow of 20 L/min, and back shielding gas flow of 10 L/min.

Metallographic specimens of the welding joints were sectioned perpendicular to the welding direction using wire electrical discharge machining. The specimens were mechanically polished on surfaces perpendicular to the welding joint. A corrosive solution of 18 mL H SO + 4 g K MnO + 180 mL H O was used for etching, with samples boiled in the solution for 30 minutes, subsequently cleaned with oxalic acid solution, rinsed with alcohol, and dried. Microstructural observation was conducted using a Z1m optical microscope (OM). Micro-Vickers hardness measurements were performed with an LM247AT fully automatic digital microhardness tester under a load of 300 g and dwell time of 15 s, with measurement positions indicated by dashed lines in Fig. 1 [Figure 1: see original paper] at intervals of 0.7 mm. Tensile specimen dimensions are shown in Fig. 2 [Figure 2: see original paper]. Tensile tests were conducted at temperatures of 20, 300, 400, 500, 600, and 700 °C, with three samples tested at each temperature and average values reported. Tensile testing was performed on an AG-5000A DCS-25T testing machine, and microstructures and fracture morphologies were examined using an S-3400N scanning electron microscope (SEM).

2.1.1 Microstructure of Base Materials

Figure 3 [Figure 3: see original paper] shows optical micrographs of the base materials for the X-2#/625 dissimilar metal welding joint. Both base metals exhibit typical austenitic equiaxed grain structures. Alloy 625 features relatively fine grains with an average size of approximately 26 m, while the X-2# alloy has a larger grain size of about 65 m.

2.1.2 Microstructure of Weld Zone

Figure 4 [Figure 4: see original paper] presents the microstructure of the weld zone in the X-2#/625 dissimilar metal welding joint. As shown in Fig. 4a, the weld zone exhibits a continuous cooling cast structure, with columnar crystals at the bottom that nucleate on the surface of unmelted base metal and grow toward the weld top. The top region consists of equiaxed crystals, whose formation is related to cooling rate. Rapid cooling creates a large undercooling; before the bottom columnar crystals can reach the weld top, the temperature at the weld top drops below the crystallization temperature, enabling nucleation and formation of freely growing equiaxed crystals. Figure 4b reveals epitaxial growth at the bottom edges of the weld near both X-2# and Alloy 625 base materials, with reduced columnar crystal structure and increased equiaxed crystals in the region below the weld remelting zone.

2.1.3 Microstructure of Fusion Zone

Figure 5 [Figure 5: see original paper] illustrates the microstructure of the fusion zone and its vicinity in the X-2#/625 dissimilar metal welding joint. As shown in Fig. 5a, the fusion zone on the X-2# alloy side exhibits a smooth transition without defects such as cracks, pores, or inclusions. In contrast, Fig. 5b reveals precipitate formation in the heat-affected zone near the fusion zone on the Alloy 625 side. Figure 5c presents an SEM image of these precipitates near the fusion zone on the Alloy 625 side, showing two types of white precipitate phases: regularly shaped rhombic NbC carbides and irregularly shaped Laves phases, both predominantly precipitated at grain boundaries.

According to literature [29], the phase transformation sequence in Alloy 625 varies with Si and C content. For compositions containing 0.03% Si and 0.009% C (mass fraction), the transformation follows L→L+ →L+ +NbC→L+ +NbC+Laves→ +NbC+Laves. At 0.03% Si and 0.038% C, the sequence is L→L+ →L+ +NbC→ +NbC. With 0.38% Si and 0.008% C, the transformation proceeds as L→L+ →L+ +NbC→L+ +NbC+M C→L+ +NbC+M C+Laves→ At 0.46% Si and 0.035% C, the sequence is L→L+ →L+ +NbC→L+ +NbC+Laves→ +NbC+Laves. Therefore, when Si and C contents are similar, +NbC forms; when Si content exceeds C content, +NbC+Laves forms; and when Si content is significantly higher than C content, +NbC+M C+Laves forms.

In the present study, the Alloy 625 composition contains 0.16% Si and 0.038% C. Consequently, under welding thermal cycle conditions, the near-weld region of Alloy 625 undergoes the phase transformation L→L+ →L+ +NbC→L+ +NbC+Laves→ +NbC+Laves, resulting in NbC and Laves phase formation. Energy dispersive spectroscopy analysis in Fig. 6 [Figure 6: see original paper] indicates that both NbC and Laves phases are associated with segregation of Nb and Mo elements, leading to non-uniform elemental distribution. The formation of NbC at HAZ grain boundaries may also cause grain boundary liquefaction and cracking, adversely affecting mechanical properties.

2.1.4 Microstructure of Heat-Affected Zone

Figure 7 [Figure 7: see original paper] shows the microstructure of the heat-affected zone (HAZ) and its vicinity in the X-2#/625 dissimilar metal welding joint. As shown in Fig. 7a, the HAZ on the X-2# alloy side exhibits only limited grain coarsening near the remelting zone due to the influence of dual thermal cycles. Other regions demonstrate excellent thermal stability without significant grain growth from the welding thermal cycle, maintaining uniform structure consistent with the base metal grain size and retaining distinct twin characteristics.

In contrast, Fig. 7b reveals that the HAZ on the Alloy 625 side is significantly affected by the welding thermal cycle, showing pronounced grain coarsening with numerous enlarged grains. This pronounced grain growth in the HAZ occurs because substantial grain coarsening takes place when the base metal has a small initial grain size combined with high welding heat input, pre-weld plastic deformation, or large temperature gradients [30]. Since the Alloy 625 base material has relatively fine grains, the tendency for grain growth is more severe. Additionally, a narrow region of fine grains exists between the fusion zone and the coarsened HAZ. Due to the small size of the weld pool and its limited heat capacity, surrounded by cold metal with high heat dissipation, the weld cools extremely rapidly with large undercooling. The formation of this fine-grained region may be attributed to rapid heating and cooling, creating large superheating and undercooling that induce phase transformation in the near-weld base metal. The phase transformation involves nucleation and growth processes; however, the high superheating and undercooling produce high nucleation rates that outpace growth, resulting in fine grains.

2.2 Hardness Testing of Welding Joints

Figure 8 [Figure 8: see original paper] presents the Vickers hardness distribution across the X-2#/625 dissimilar metal welding joint. As shown in Figs. 8a and 8b, the Alloy 625 base metal exhibits higher hardness than the X-2# alloy base metal, while the weld zone and the HAZ on the Alloy 625 side show lower hardness values. This reduction is attributed to severe grain coarsening in these regions, which decreases the strength of the HAZ. Figure 8c indicates that the hardness of the double-sided weld remelting zone is lower than that of the base metals on both sides of the joint. However, Fig. 8d reveals that in the central weld region, the hardness of the double-sided remelting zone is significantly higher than that of the front and back weld zones. This increase results from the greater amount of equiaxed crystal structure in the remelting zone, which enhances its strength. Consequently, the base metal of the X-2#/625 joint exhibits the highest microhardness, with Alloy 625 base metal being harder than X-2# alloy base metal, followed by the weld remelting zone, while the front/back weld zones and the HAZ on the Alloy 625 side show the lowest hardness values.

2.3.1 Tensile Testing at Various Temperatures

Figure 9 [Figure 9: see original paper] shows the macroscopic morphology of X-2#/625 dissimilar metal welding joint specimens after tensile testing at different temperatures. The fracture location occurred in the weld zone at both room temperature (20 °C) and elevated temperatures (300-700 °C), exhibiting ductile fracture characteristics. This indicates that the tensile strength of the X-2#/625 weld is lower than that of both base materials. All tensile specimens exhibited necking, with minor plastic deformation also occurring in the base metals on both sides of the weld.

Table 2 summarizes the tensile test data for X-2#/625 dissimilar metal welding joint specimens at various temperatures. The X-2# alloy base metal consistently shows lower tensile strength than the Alloy 625 base metal at all test temperatures. The joint strength is lower than both base materials, resulting in fracture within the weld zone. However, as the test temperature increases from 20 °C to 700 °C, the tensile strength of Alloy 625 decreases by approximately 200 MPa, whereas that of X-2# alloy decreases by only about 158 MPa. Notably, when the temperature rises from 600 °C to 700 °C, the tensile strength of X-2# alloy decreases by merely 3 MPa, compared to an 86 MPa reduction for Alloy 625, demonstrating the superior high-temperature strength stability of X-2# alloy.

2.3.2 Fracture Morphology

Figure 10 [Figure 10: see original paper] presents the tensile fracture morphologies of the X-2#/625 dissimilar metal welding joint at room temperature (20 °C) and 500 °C. Both fracture surfaces exhibit dimpled morphologies characteristic of ductile fracture. After tensile testing at 20 °C, the fracture shows small, shallow dimples, indicating lower ductility but higher strength. In contrast, the fracture surface after testing at 500 °C displays larger dimples, suggesting improved ductility.

Conclusions

(1) The base materials of the X-2#/625 dissimilar metal welding joint both exhibit austenitic equiaxed grain structures, with Alloy 625 and X-2# alloy base metals having grain sizes of approximately 26 m and 65 m, respectively. The weld zone consists of cast structures, with increased equiaxed crystal content in the weld remelting zone contributing to improved strength. The fusion zone on the X-2# alloy side shows a smooth transition, while NbC and Laves phases precipitate along grain boundaries on the Alloy 625 side. Grain coarsening occurs readily in the HAZ near the remelting zone; the fine grain structure of the Alloy 625 base material leads to significant grain growth in its HAZ, whereas the HAZ on the X-2# alloy side demonstrates good thermal stability.

(2) The base metal of the X-2#/625 dissimilar metal welding joint exhibits the highest micro-Vickers hardness values, with Alloy 625 base metal being harder than X-2# alloy base metal, followed by the weld remelting zone. The front/back weld zones and the HAZ on the Alloy 625 side show the

lowest hardness values.

(3) The tensile strength of the X-2#/625 dissimilar metal welding joint is lower than both base materials from room temperature to 700 °C, with the weld zone being the weakest link. The X-2# alloy demonstrates stable high-temperature strength, and the fracture morphology of the X-2#/625 joint exhibits dimpled features characteristic of ductile fracture.

References

[1] Li F, Wang H F, Zhu D. Shanghai J Electr Power, 2002; 18(1): 19 (Li Feng, Wang Haifeng, Zhu Dan. *Journal of Shanghai University of Electric Power*, 2002; 18(1): 19)

[2] Zhang P, Wang J C, Zhang X D, Liu X W, Xia Y J, Li Z Y. Environ Prot Sci, 2003; 119(29): 15 (Zhang Ping, Wang Jingchang, Zhang Xiaodong, Liu Xuewu, Xia Yuanjing, Li Zhiyi. *Environmental Protection Science*, 2003; 119(29): 15)

[3] Xiang B T, Wang T. Prog Chem Ind, 1997; (3): 28 (Xiang Botao, Wang Tao. *Chemical Industry Progress*, 1997; (3): 28)

[4] Xu J C, Xu B B, Jiang Y, Rong X S, Chen Z Y. Guangzhou Chem Ind, 2013; 41(9): 10 (Xu Jicheng, Xu Binbin, Jiang Yan, Rong Xinshan, Chen Zhengyu. *Guangzhou Chemical Industry*, 2013; 41(9): 10)

[5] Ma D Z, Zhang L, Yin D, Chen G. Coal Technol, 2011; 30(1): 202 (Ma Dongzhu, Zhang Ling, Yin Di, Chen Guang. *Coal Technology*, 2011; 30(1): 202)

[6] Kritzer P. J Supercrit Fluids, 2004; 29: 1

[7] Garcia K M, Mizia R E. ASME Heat Transfer Division. New York, NY: American Society of Mechanical Engineers, 1995; 317(2): 299

[8] Garcia K M. International Mechanical Engineering Congress and Exhibition, Atlanta: 1996: 17

[9] Tan L, Ren X, Allen T R. Corros Sci, 2010; 52: 1520

[10] Zhu F W, Zhang L F, Tang R, Qiao P P, Bao Y C. At Energ Sci Technol, 2010; 44(8): 979 (Zhu Fawen, Zhang Lefu, Tang Rui, Qiao Peipeng, Bao Yichen. *Atomic Energy Science and Technology*, 2010; 44(8): 979)

[11] Sun Y. MS Thesis, Shanghai Jiao Tong University, 2013

[12] Sun C W, Hui R. Corros Sci, 2009; 51: 2508

[13] Chen Y, Sridharan K, Ukai S, Allen T R. J Nucl Mater, 2007; 371: 118

[14] Cho H S, Kimura A. J Nucl Mater, 2007; 367-370: 1180

[15] Isselin J, Kasada R, Kimura A. Corros Sci, 2010; 52: 3266

[16] Siwy A D, Clark T E, Motta A T. J Nucl Mater, 2009; 392: 280

[17] Was G S, Ampornrat P, Gupta G, Teysseyrea S, Westa E A, Allenb T R, Sridharanb K, Tanb L, Chenb Y, Renb X, Pister C. J Nucl Mater, 2007; 371(1-3): 176

[18] Wright L G, Dooley R B. Int Mater Rev, 2010; 55(3): 129

[19] Zhu F W, Zhang L F, Tang R, Qiao P P, Liu R Q. At Energ Sci Technol, 2009; 43(6): 39 (Zhu Fawen, Zhang Lefu, Tang Rui, Qiao Peipeng, Liu Ruiqin. *Atomic Energy Science and Technology*, 2009; 43(6): 39)

[20] Was G S, Teysseyre S, Jiao Z. Corros, 2006; 62(11): 989

[21] Sun M C, Wu X Q, Han E H, Rao J C. Scr Mater, 2009; 61(10): 996

[22] Halvarsson M, Tang J E, Asteman H. Corros Sci, 2006; 48(8): 2014

[23] Tan L, Ren X, Sridharan K, Allen T R. Corros Sci, 2008; 50: 3056

[24] Sun M C, Wu X Q, Zhang Z E, Han E H. J Supercrit Fluids, 2008; 47: 309

[25] Zhang Q, Tang R, Yin K J, Luo X, Zhang L F. Corros Sci, 2009; 51: 2092

[26] Zhang Q, Tang R, Li C, Luo X, Yin K J. Nucl Eng Technol, 2009; 41(1): 107

[27] LI L. Master Thesis, Shanghai Jiao Tong University, 2012

[28] Bao Y C. Master Thesis, Shanghai Jiao Tong University, 2011

[29] Cieslak M J. Weld J, 1991; 70(2): 49

[30] Dupont J N, Lippold J C, Kiser S D. *Welding Metallurgy and Weldability of Nickel-base Alloys.* Hoboken: John Wiley & Sons Inc, 2009: 47

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