Microstructure and Mechanical Properties of a Novel Nickel-Based Corrosion-Resistant Alloy/625 Alloy Dissimilar Welded Joint: Postprint

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Abstract

Tensile properties and hardness of manual tungsten inert gas (TIG) welded joints between a novel nickel-based corrosion-resistant alloy X-2# and 625 alloy were tested, and the microstructure and properties of the welded joints were investigated by means of optical microscopy (OM), scanning electron microscopy (SEM), and energy dispersive spectroscopy (EDS). The results indicate that the equiaxed grain structure in the weld remelting zone of the X-2#/625 dissimilar metal welded joint increased, which is beneficial for improving the strength of the weld zone. The microstructural transition in the fusion zone on the X-2# alloy side was favorable, whereas precipitation of NbC and Laves phases occurred at grain boundaries on the 625 alloy side, affecting the mechanical properties of the material. In the heat-affected zone (HAZ), grains near the remelting zone exhibited grain coarsening due to the influence of secondary thermal cycling, while the thermal stability of the HAZ on the X-2# alloy side was relatively good. The fine grains in the 625 alloy base metal led to significant grain growth in its HAZ, resulting in reduced Vickers hardness values in the HAZ on the 625 alloy side. The tensile strength of the X-2#/625 welded joint was lower than that of both base metals from room temperature to 700 °C, with the weld zone being the weakest link of the joint; the fracture morphology exhibited dimpled ductile fracture features.

Full Text

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

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Abstract: The tensile properties and hardness 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 systematically investigated. Microstructural characterization was performed using optical microscopy (OM), scanning electron microscopy (SEM), and energy-dispersive spectroscopy (EDS). The results demonstrate that the weld remelting zone exhibited an increased fraction of equiaxed grains, which contributed to enhanced strength in the weld region. The fusion zone on the X-2# alloy side showed a smooth microstructural transition without defects, whereas NbC and Laves phases precipitated along grain boundaries on the Alloy 625 side, adversely affecting mechanical properties. In the heat-affected zone (HAZ), grains near the remelting zone experienced growth due to the influence of dual thermal cycles, while the X-2# alloy HAZ maintained good thermal stability. The fine grain structure of the base Alloy 625 led to significant grain coarsening in its HAZ, resulting in reduced Vickers hardness values. The tensile strength of the X-2#/625 welding joint remained lower than that of both base materials from room temperature to 700 °C, with the weld zone identified as the weakest link. All fracture surfaces exhibited ductile dimple morphology.

KEY WORDS X-2#/625 welding joint; weld seam; fusion zone; heat-affected zone

Introduction

Wastewater treatment, particularly the disposal of refractory harmful organic substances, municipal solid waste, and sludge, represents a significant challenge in environmental engineering [1-5]. Supercritical water oxidation (SCWO) has emerged as a technologically and economically advantageous method for wastewater treatment; however, material corrosion poses a critical barrier to its widespread application. Equipment such as preheaters and reactors must meet stringent requirements for high-temperature creep strength, resistance to steam oxidation and corrosion, excellent workability, and cost-effectiveness [6–8].

Current material development efforts have focused 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 steels and P92 steel revealed that corrosion in F/M steels intensifies significantly with temperature, with oxide films cracking at 600 °C. F/M steels exhibit inferior corrosion resistance in SCWO environments compared to other alloys [11]. While ODS steels generally demonstrate better corrosion resistance than their F/M counterparts, performance is highly composition-dependent; high-Cr ODS steels show good corrosion resistance, whereas low-Cr variants perform poorly with oxide films similar to F/M steels [12–16]. Research on austenitic stainless steels including TP347, HR3C, D9, 316, and 304NG in SCWO environments [17–22] indicates that although their corrosion mass gain is typically lower than F/M steels, it increases sharply with temperature. Nickel-based alloys are widely used in high-temperature applications due to their superior microstructural stability, elevated-temperature strength, and oxidation/corrosion resistance. Investigations on alloys 625, 617, 718, C-276, and X-750 in SCWO environments [23–26] show minimal mass gain, making nickel-based alloys promising candidates for SCWO service [27,28].

Currently, preheaters and reactors for SCWO wastewater treatment primarily utilize 304 austenitic stainless steel, Alloy 625, and P91/P92 steels. Due to severe corrosion and oxidation of existing materials resulting in short service life, a new alloy must be developed. To address this need, a novel nickel-based alloy containing 10% Fe (mass fraction) has been successfully developed; the Fe addition reduces cost compared to alloys 230, 617, and 740. Preliminary experiments demonstrate that this new alloy possesses excellent high-temperature strength, ductility, and microstructural stability. Qualitative oxidation tests reveal minimal oxidation at 760 °C and 1000 °C, indicating outstanding high-temperature oxidation resistance. Moreover, under supercritical conditions in phosphate-dominated environments, the new alloy exhibits superior corrosion resistance compared to alloys 671, C-276, and 625, showing considerable application potential. Considering cost-effectiveness, replacing only the most severely corroded sections of preheaters or reactors with this new alloy represents an economically viable approach. Therefore, investigating the weldability between the new alloy and existing SCWO materials is essential. This work focuses on characterizing the microstructure and properties of dissimilar metal welding joints between the new X-2# alloy and Alloy 625 for preheating conditions (300–500 °C, 25 MPa) and reaction conditions (550–650 °C, 25 MPa), providing reliable theoretical and experimental support for future applications.

1. Experimental Methods

The novel nickel-based corrosion-resistant alloy X-2# was prepared by vacuum induction melting, followed by forging and hot rolling into plates, which were then solution-treated before welding. Alloy 625 plates were purchased commercially and hot-rolled to match the thickness of the X-2# plates. The chemical compositions of both base materials are presented in . Both base metals were in the solution-treated condition, with X-2# alloy treated at 1120 °C for 30 minutes (water quenched) and Alloy 625 treated at 1000 °C for 60 minutes (water quenched).

Welding was performed using manual argon arc welding with a double-sided welding configuration. The filler wire was X-2# alloy, and an X-groove was employed. Welding parameters included a current of 110–120 A for both front and back sides, welding speeds of 130–140 mm/min (front) and 150–160 mm/min (back), shielding gas flow of 20 L/min, and back shielding gas flow of 10 L/min.

Metallographic samples were sectioned perpendicular to the welding direction using wire electrical discharge machining. Specimens were mechanically polished on the cross-section perpendicular to the welding joint. A corrosive solution of 18 mL H_2SO_4 + 4 g K_2MnO_4 + 180 mL H_2O was used, with samples boiled for 30 minutes, then 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 using an LM247AT fully automatic digital microhardness tester with a 300 g load and 15 s dwell time. Hardness indentations were made along the dashed line shown in [Figure 1: see original paper] at 0.7 mm intervals.

Tensile test specimens were prepared according to the dimensions shown in [Figure 2: see original paper]. 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 universal testing machine. Fracture surface analysis was carried out using an S-3400N scanning electron microscope (SEM).

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2. Results and Discussion

2.1 Microstructural Characterization 2.1.1 Base Metal Microstructure

[Figure 3: see original paper] presents the 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 shows relatively fine grains with an average size of approximately 26 m, while X-2# alloy has a coarser grain structure of about 65 m.

2.1.2 Weld Seam Microstructure

The microstructure of the X-2#/625 weld seam is shown in [Figure 4: see original paper]. As seen in [Figure 4a: see original paper], the weld zone exhibits a continuous cooling cast structure, with columnar grains at the bottom that nucleate on the unmelted base metal surface and grow toward the weld top. The top region consists of equiaxed grains, whose formation is attributed to cooling rate effects. With rapid cooling and high undercooling, the temperature at the weld top drops below the solidification temperature and nucleation occurs before the bottom columnar grains reach the top, allowing free growth of equiaxed grains. [Figure 4b: see original paper] reveals that epitaxial solidification occurs at the bottom edges of the weld near both X-2# and Alloy 625 base metals. Below the weld remelting zone, the columnar grain structure decreases while the equiaxed grain fraction increases.

2.1.3 Fusion Zone Microstructure

[Figure 5: see original paper] illustrates the fusion zone and adjacent microstructures of the X-2#/625 dissimilar metal welding joint. The fusion zone on the X-2# alloy side shows a smooth transition without defects such as cracks, pores, or inclusions [Figure 5a: see original paper]. However, precipitates formed in the HAZ near the fusion zone on the Alloy 625 side [Figure 5b: see original paper]. [Figure 5c: see original paper] shows an SEM image of these precipitates near the Alloy 625 fusion zone. Two types of white precipitates are distributed in the HAZ: regularly shaped rhombic NbC carbides and irregularly shaped Laves phases, both predominantly precipitated along grain boundaries.

According to literature [29], the phase transformations in Alloy 625 depend on Si and C content. For compositions containing 0.03% Si and 0.009% C (mass fraction), the transformation sequence is $L \rightarrow L+\gamma+NbC \rightarrow \gamma+NbC+Laves$. With 0.03% Si and 0.038% C, the sequence becomes $L \rightarrow \gamma+NbC$. At 0.38% Si and 0.008% C, the transformation is $L \rightarrow L+\gamma+NbC+M_6C \rightarrow \gamma+NbC+M_6C+Laves$. For 0.46% Si and 0.035% C, the sequence is $L \rightarrow L+\gamma+NbC+Laves \rightarrow \gamma+NbC+Laves$. When Si and C contents are similar, γ+NbC forms; when Si content exceeds C content, γ+NbC+Laves forms; and when Si content is significantly higher than C content, $\gamma+NbC+M_6C+Laves$ forms. The Alloy 625 used in this study contained 0.16% Si and 0.038% C. Under welding thermal cycles, the near-fusion region of Alloy 625 underwent an $L \rightarrow \gamma+NbC+Laves$ transformation, producing NbC and Laves phases. EDS analysis in [Figure 6: see original paper] confirms 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 liquation and cracking, compromising mechanical properties.

2.1.4 Heat-Affected Zone Microstructure

[Figure 7: see original paper] shows the HAZ microstructures and adjacent regions of the X-2#/625 dissimilar metal welding joint. On the X-2# alloy side, only grains near the remelting zone exhibited noticeable growth due to the influence of dual thermal cycles, while other regions maintained excellent thermal stability without significant grain growth from welding thermal cycles. The microstructure remained uniform with grain sizes consistent with the base metal, and twinning characteristics remained prominent [Figure 7a: see original paper]. In contrast, the HAZ on the Alloy 625 side showed significant grain growth with numerous coarsened grains due to the welding thermal cycles [Figure 7b: see original paper]. The pronounced grain growth in the HAZ can be attributed to the combined effects of fine initial grain size in the base metal, high welding heat input, and steep temperature gradients [30]. Since the Alloy 625 base metal had relatively fine grains, the tendency for grain growth was more severe. Additionally, a narrow region with fine grains exists between the fusion zone and the coarsened HAZ. Because the weld pool is small with limited heat capacity and is surrounded by cold metal with high heat dissipation, the weld cools extremely rapidly with large undercooling. This fine-grained zone likely forms due to rapid heating and cooling with high superheat and undercooling, causing a phase transformation in the near-fusion base metal with a nucleation and growth process. The high undercooling promotes high nucleation rates that outpace grain growth, resulting in fine grains.

2.2 Hardness Distribution in Welding Joint The Vickers hardness distribution across the X-2#/625 dissimilar metal welding joint is presented in [Figure 8: see original paper]. The base Alloy 625 exhibits higher hardness than the X-2# alloy base metal, while the weld zone and Alloy 625 HAZ show lower hardness values due to severe grain coarsening that reduces strength in these regions. In the double-sided weld remelting zone [Figure 8c: see original paper], hardness is lower than in both base metals. However, at the weld center [Figure 8d: see original paper], the remelting zone hardness is significantly higher than that of the front and back weld regions, attributed to the increased equiaxed grain fraction that enhances strength. Therefore, the base metals exhibit the highest microhardness (with Alloy 625 > X-2#), followed by the weld remelting zone, while the front/back weld regions and Alloy 625 HAZ show the lowest hardness values.

2.3 Tensile Properties 2.3.1 Tensile Testing at Various Temperatures

[Figure 9: see original paper] shows the macroscopic appearance of X-2#/625 dissimilar metal welding joint specimens after tensile testing at different temperatures. Fracture occurred in the weld zone at both room temperature (20 °C) and elevated temperatures (300–700 °C), indicating ductile fracture and demonstrating that the weld zone has lower tensile strength than both base metals. All specimens exhibited necking, with slight plastic deformation also occurring in the base metals on both sides of the weld.

The mechanical properties of the X-2#/625 dissimilar metal welding joints at various test temperatures are summarized in . The tensile strength of the X-2# alloy base metal exceeded that of Alloy 625 at all temperatures, yet the joint strength remained lower than both base metals, causing fracture to occur consistently in the weld zone. However, as the test temperature increased from 20 °C to 700 °C, the tensile strength of Alloy 625 decreased by approximately 200 MPa, whereas the X-2# alloy strength decreased by only about 158 MPa. Notably, when the temperature increased from 600 °C to 700 °C, the X-2# alloy strength decreased by merely 3 MPa compared to an 86 MPa decrease for Alloy 625, indicating superior high-temperature strength stability for X-2#.

2.3.2 Fracture Morphology

[Figure 10: see original paper] displays the tensile fracture morphologies of the X-2#/625 dissimilar metal welding joint at 20 °C and 500 °C. Both fracture surfaces exhibit ductile dimple morphology. At 20 °C, the dimples are small and shallow, indicating lower ductility but higher strength. At 500 °C, the dimples are larger, reflecting improved ductility.

Conclusions

(1) The base metals of the X-2#/625 dissimilar metal welding joint both consist of austenitic equiaxed grain structures, with Alloy 625 and X-2# alloy having average grain sizes of approximately 26 m and 65 m, respectively. The weld zone exhibits a cast structure, with increased equiaxed grain fraction in the remelting zone contributing to improved strength. The fusion zone on the X-2# alloy side shows good microstructural transition, while NbC and Laves phases precipitate along grain boundaries on the Alloy 625 side. Grain growth occurs in HAZ regions near the remelting zone, particularly pronounced in the Alloy 625 HAZ due to its fine initial grain structure, whereas the X-2# alloy HAZ maintains good thermal stability.

(2) The base metals exhibit the highest micro-Vickers hardness values, with Alloy 625 exceeding X-2# alloy, followed by the weld remelting zone. The front/back weld regions and the Alloy 625 HAZ display the lowest hardness values.

(3) The tensile strength of the X-2#/625 dissimilar metal welding joint remains lower than both base metals from room temperature to 700 °C, with the weld zone being the weakest link. The X-2# alloy demonstrates stable high-temperature strength, and all fracture surfaces exhibit ductile dimple morphology.

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Note: Figure translations are in progress. See original paper for figures.