Crack Analysis and Weldability Restoration of 800H Alloy High-Temperature Steam Pipelines

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Abstract: The 800 alloy is extensively utilized in high-temperature equipment owing to its exceptional high-temperature strength and resistance to oxidation and corrosion. However, during prolonged service, the alloy undergoes microstructural changes, such as carbide precipitation, which weaken its integrity. Under the influence of operational stress, cracks may develop, ultimately leading to component failure. This study focuses on the failure analysis of cracks that formed after prolonged operation in an 800H alloy high-temperature steam pipeline, specifically in areas near the valve and weld joint. Detailed examinations of crack morphology and oxidation products revealed that the primary failure mechanism was stress relaxation cracking. To restore the pipeline's functionality and extend its operational lifespan, a thermal performance restoration approach was applied. Samples from the 800H alloy were subjected to solution annealing—a heat treatment process designed to enhance its weldability. Post-treatment welding trials demonstrated a notable improvement in the alloy's welding performance. Non-destructive testing confirmed the absence of cracks, while microstructural analysis verified that the heat treatment effectively eliminated microcracks in the weld joints.

Keywords: 800H Alloy; Weldability; High-Temperature Oxidation; Stress Relaxation Cracking; Solution Annealing

1. Introduction

The 800 alloy is a type of Fe-Cr-Ni super austenitic stainless steel renowned for its exceptional high-temperature strength, oxidation resistance, corrosion resistance, creep rupture resistance, and resistance to carburization. The alloy exhibits remarkable structural stability, maintaining its austenitic microstructure and relatively stable mechanical properties even after prolonged exposure to elevated temperatures. It is particularly distinguished by its high strength and excellent fatigue resistance. Additionally, the 800 alloy offers superior workability and can be shaped and processed through various methods. Its low susceptibility to hot cracking ensures ease of welding, with minimal risk of significant issues arising during the welding process. Owing to these attributes, the 800H alloy is widely employed across industries such as petrochemical, chemical processing, and power generation, where it has consistently demonstrated excellent material performance and operational reliability over extended periods [1-5]. Thanks to its outstanding creep resistance and oxidation-corrosion properties, the alloy has been identified as a primary candidate material for heat transfer pipes in steam generators of nuclear power plants [6-7]. As an advanced material with exceptional properties, the 800 alloy plays a pivotal role in modern industries. Its resistance to oxidation, corrosion, and high-temperature degradation has established its utility in aerospace, energy, chemical, and other sectors. Furthermore, it holds significant potential for future development. With ongoing advancements in science and technology, the 800 alloy is poised to unveil even greater applications and continue showcasing its unparalleled versatility across a broader range of fields.

The 800 alloy series consists of three variants: 800 (UNS N08800), 800H (UNS N08810), and 800HT (UNS N08811). These alloys are based on iron, nickel, and chromium as primary alloying elements, with additional trace elements such as carbon, aluminum, titanium, silicon, molybdenum, copper, nitrogen, and manganese. Through solution treatment, these alloys achieve excellent mechanical properties and high-temperature performance. The microstructure of the 800 alloys contains a significant distribution of titanium nitrides, titanium carbides, and chromium carbides, which enhance their mechanical strength and high-temperature resistance. The 800H and 800HT alloys further optimize the content of carbon, aluminum, and titanium, resulting in superior high-temperature strength and improved overall performance.

For components operating at high temperatures, many iron-based and nickel-based alloys are commonly utilized within the 480–760°C temperature range. At these elevated temperatures, one notable microstructural change is high-temperature aging. Due to the presence of numerous alloying elements, prolonged exposure to this temperature range promotes the formation of various precipitates, such as carbides and intermetallic compounds. These precipitated phases typically degrade the alloy's toughness and reduce its yield strength, while simultaneously increasing its susceptibility to crack formation under applied stress. Furthermore, the heat treatment processes used for high-temperature alloys can also lead to the formation of precipitates, which adversely affect the alloys' weldability. Research on the weldability of 800 alloys has shown that the addition of trace alloying elements significantly increases their sensitivity to welding defects. Compared to simple iron-chromium-nickel ternary alloys, which lack these trace elements, 800 alloys are more prone to hot cracking during welding [8].

This paper analyzes the causes of cracks in an 800H alloy high-temperature steam pipeline, specifically at the weld joints of the valve and the pipeline. Furthermore, it investigates the use of solution annealing heat treatment to improve the weldability of the alloy after aging, restore its microstructure, and extend the service life of the pipeline [9-10].

2. Material Failure and Inspection

In today’s energy industry, thermal power plants continue to play a pivotal role as one of the primary sources of electricity generation. These plants are essential for societal development and the uninterrupted functioning of daily life. However, concerns surrounding their energy efficiency and environmental impact remain pressing. Numerous methods have been explored to improve coal combustion efficiency; among them, the adoption of advanced materials has not only enhanced the high-temperature resistance of boilers but also enabled their operation at higher temperatures, thereby increasing thermal efficiency [9-10]. Among such materials, 800 alloys have gained widespread application in modern industries due to their exceptional properties. Nevertheless, there has been relatively little analysis conducted on their long-term performance under extended usage.

The 800H alloy material studied in this research was sourced from the 800H hot steam pipeline of a decommissioned thermal power plant. The pipeline has a diameter of 20.3 cm (8 inches) and a wall thickness of 0.3175 cm (0.125 inches). It operated under steam temperatures ranging from 593°C to 649°C (1100°F to 1200°F) and a steam pressure of 0.9 MPa (130 psi). After approximately two years of operation, cracks were discovered near the weld joints connecting the valve and the pipeline. Non-destructive testing revealed that the cracks were located near the heat-affected zone (HAZ) of the weld and nearly penetrated the entire pipe wall (see Figure 1).

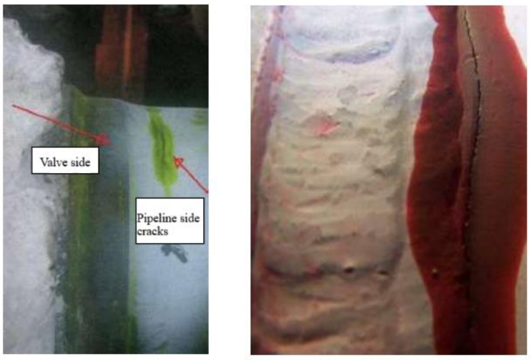

Figure 1. Inspection Results of Cracks Near the Weld Joint in the 800H alloy Pipeline (Right Image Shows a Close-Up View of the Crack)

Technical documentation for the pipeline indicates that the welding of the 800H alloy pipeline and the valve made of the same material was performed using gas tungsten arc welding (GTAW/TIG), with Inconel 82 (ERNiCr-3) used as the welding filler wire. To investigate the crack failure mechanism, samples were taken from the cracked section of the pipeline. These samples were examined and analyzed in a laboratory using optical microscopy and electron microscopy to study their microstructure and oxide formation. Due to the thermal aging effects experienced by the alloy pipeline, solution annealing heat treatment was subsequently performed on the 800H alloy samples. This was done to evaluate the impact of solution heat treatment on the welding properties and microstructural recovery of the alloy, providing technical support for pipeline repair and continued operation.

3. Metallographic Examination of the Alloy Pipeline

A chemical composition analysis was first conducted on the 800H alloy pipeline samples, with the results presented in Table 1. The chemical composition aligns with the material requirements for SB-407 specified in the ASME Section II, Part B standard [6].

Table 1. Chemical Composition Analysis of 800H Alloy Pipeline Samples

Alloy Elements	C	Cr	Ni	Fe	Mn	Al	Ti
ASME II Part B SB-407	0.05-0.10	19.0-23.0	30.0-35.0	39.5 min	1.5 max	0.15-0.60	0.15-0.60
800H Sample	0.07	20.9	33.5	42.3	1.2	0.4	0.3

As shown in Figure 2, metallographic examination of the 800H samples revealed significant precipitation of carbides at the grain boundaries. These carbides were identified as Cr23C6 , a typical product of prolonged high-temperature operation for 800H alloys. The measured grain size was ASTM 3.5, with no evidence of grain growth, indicating that the pipeline had not undergone overheating during operation.

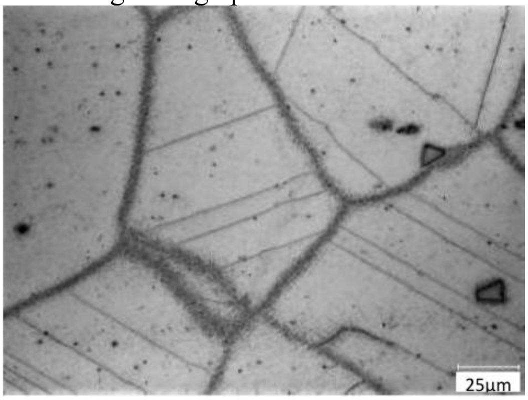

Figure 2. Grain Boundary Precipitation of Carbides in 800H Pipeline Samples

Microhardness measurements were conducted on the 800H samples using a 500 g load, and the results are presented in Figure 3. The hardness of the valve side ranged from 250 to 280 HV, slightly higher than the values observed for the weld and pipeline sides. The hardness of the Inconel 82 weld ranged from 230 to 250 HV, while the pipeline side of the 800H exhibited hardness values between 240 and 260 HV. As shown in Figure 3, cracks were detected on the pipeline side near the HAZ of the weld. However, the hardness values in this region did not reveal any abnormalities. The measured hardness values fell within the normal range for 800H alloy material, suggesting that the carbide precipitation observed in the metallographic examination (Figure 2) does not significantly deteriorate the toughness or ductility of the material. This indicates that the mechanical properties remain unaffected to a degree that could trigger crack formation.

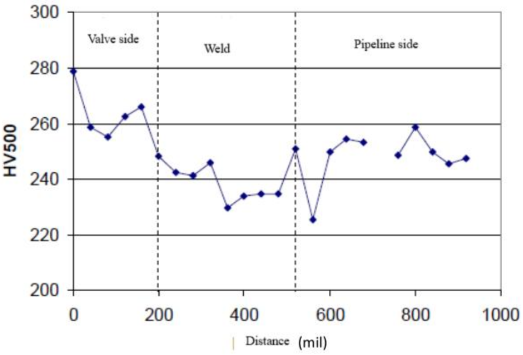

Figure 3. Microhardness Measurements of the Samples

The cross-section of the metallographic sample, prepared through standard metallographic procedures, was examined under an optical microscope, revealing the detailed morphology of the cracks (Figure 4). The examination results show that the crack did not penetrate the entire pipeline wall, with approximately 20% of the wall thickness remaining intact. Due to the relatively low operational steam pressure within the pipeline, the remaining 25% wall thickness ensured the continued operation of the pipeline without resulting in a rupture accident. Furthermore, the timely detection of the crack ensured the safe operation of the unit. The specific morphology of the crack exhibited a dendritic pattern, with its root clearly originating from the inner wall of the pipeline. This indicates that the crack initiated on the inner wall and propagated outward toward the outer wall. The crack displayed significant branching, with the number of branches increasing as it progressed toward the outer wall. These crack characteristics are consistent with the behavior of stress cracks, suggesting that stress played a critical role in the crack formation mechanism.

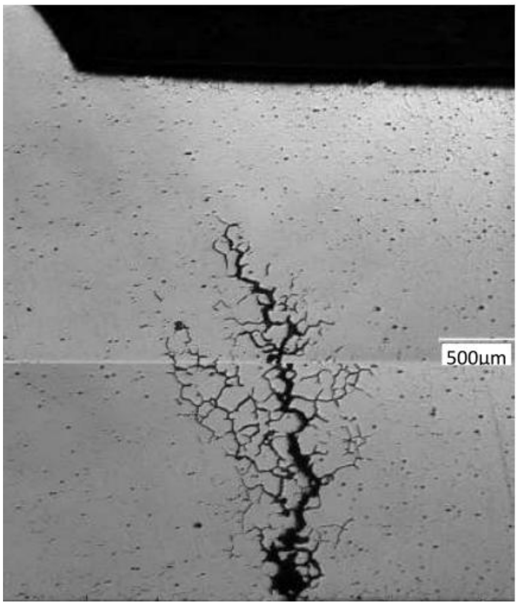

Figure 4. Morphology of Cracks in the Pipeline

Upon closer observation of the crack morphology, it was noted that the crack gaps were filled with oxides (Figure 5). Since high-temperature steam flows along the inner wall of the pipeline, the 800H alloy undergoes an oxidation reaction at elevated temperatures, resulting in the formation of oxides within the crack gaps. Another distinct feature of the cracks is the presence of white, filamentous structures in the center of the gaps. Further analysis using scanning electron microscopy identified the oxides within the cracks as chromium-rich oxides, primarily chromium oxide (Cr2O3). The white filamentous structures in the crack gaps were found to be unoxidized metals enriched in nickel (Ni) and iron (Fe). This crack morphology, along with the oxides and filamentous metal structures within the gaps, is consistent with the characteristics of stress relaxation cracking observed in stainless steels and iron-based alloys. In high-temperature, oxygen-rich environments, metals within the crack gaps undergo oxidation reactions. For chromium-containing alloys, chromium oxide is predominantly formed. As chromium oxide forms, the oxygen partial pressure within the crack gaps decreases. For stainless steels and iron-based alloys such as the 800H alloy, iron, chromium, and nickel are the primary alloying elements. In high-temperature oxidation environments, the partial pressure of oxygen required to form iron oxide and nickel oxide is significantly higher than that required to form chromium oxide. Thus, as chromium oxide forms and grows, the oxygen partial pressure continues to decrease. When the oxygen partial pressure drops below the level needed to form iron oxide and nickel oxide, unoxidized filamentous metal structures, primarily composed of iron and nickel alloy components, are left within the crack gaps.

Figure 5. Cracks Filled with Oxides and Unoxidized Filamentous Metals

The cracks occurred at the connection between the valve and the pipeline, where significant differences in the dimensions of adjacent components were present. Additionally, variations in alloy composition, microstructure, and stress across the weld resulted in high thermal and constraint stresses at the failure location. Based on the metallographic examination and analysis conducted above, the cracking mechanism has been identified as stress relaxation cracking (SRC).

4. Study on Heat Treatment for Performance Recovery of Alloy

To repair the 800H pipeline, TIG welding tests were conducted on samples extracted from the 800H alloy after service. Post-welding non-destructive testing revealed no cracks or defects exceeding permissible limits. However, metallographic examination of the cross-section showed signs of performance degradation in the 800H alloy (Figure 6). Figure 6 illustrates the presence of microcracks along the grain boundaries, with microscopic observations indicating that these microcracks extended from the base material to the fusion zone. Additionally, micropores present within the alloy's structure had spread from the grain boundaries into the grain interiors. These microcracks and micropores not only pose a risk of inducing welding cracks but also contribute to the formation of creep cracks during high-temperature service. This, in turn, could lead to cracking of the aged 800H alloy, creating safety hazards during operation.

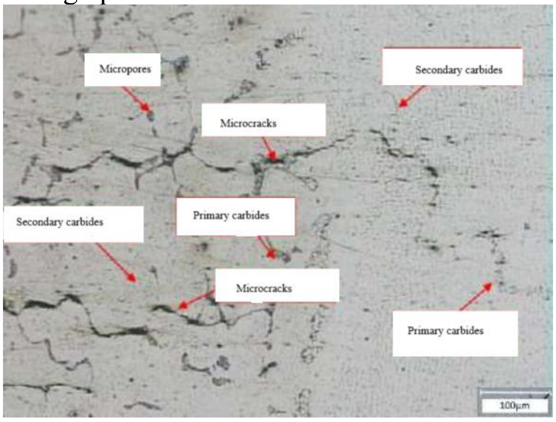

Figure 6. Metallographic Image of TIG Welded 800H Alloy Sample

To repair the cracks and restore the usability of the 800H alloy pipeline, a solution annealing heat treatment study was conducted on the sampled 800H alloy. The primary objective of this process was to remelt the carbide precipitates, enhance the alloy's ductility, and improve its weldability. Solution annealing also helps to eliminate residual stresses, thereby reducing the likelihood of crack formation during welding and operation. The solution annealing heat treatment was performed in accordance with the requirements for 800H alloy specified in ASME Section II Part B, with the solution treatment temperature and duration set at 1150°C for 30 minutes. After undergoing solution annealing, the 800H alloy samples were subjected to TIG welding tests. Post-weld non-destructive testing revealed no cracks or defects exceeding permissible limits. Further metallographic cross-sectional examination confirmed the absence of welding cracks (Figure 7). The microstructure of the solution-annealed alloy exhibited the presence of primary carbides, secondary carbides, and microscopic pores. However, no microcracks were observed after welding. The reduction in residual stress significantly decreased the probability of crack formation during welding. Additionally, solution heat treatment minimized the residual stresses that could otherwise promote the diffusion of micropores, preventing their coalescence and the initiation of microcracks.

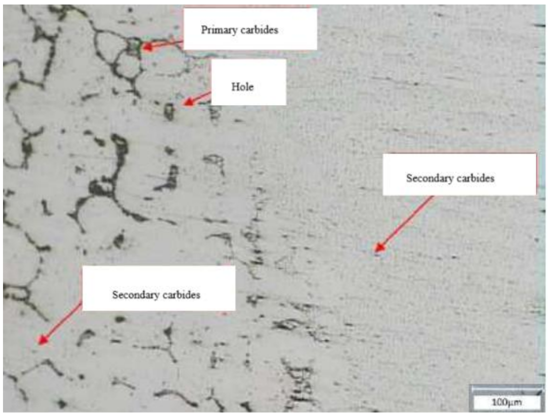

Figure 7. Metallographic Image of Welded 800H Sample after Solution Treatment

5. Conclusion

This study conducts a failure analysis of cracks observed near the welds of high-temperature steam pipelines made of 800H alloy, specifically in the areas around valves and pipelines. The microhardness of the alloy samples was found to be within the acceptable range for the material, and the microstructure revealed a substantial amount of carbide precipitates along the grain boundaries. Metallographic examination showed that the cracks exhibited a dendritic distribution, with the crack gaps filled by oxides and unoxidized nickel-iron filamentous structures. Comprehensive analysis determined the crack formation mechanism to be stress relaxation cracking. Welding tests conducted on post-service samples indicated that the 800H alloy had experienced performance degradation. Microscopic observations revealed the presence of microcracks extending from the base material into the fusion zone. Additionally, microscopic pores in the alloy's structure had spread into the grain interiors, further compromising its weldability. However, through solution annealing heat treatment, the welding performance of the 800H alloy samples improved significantly. After weldability testing, no cracks were observed, demonstrating a marked enhancement in the material's weldability.

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