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Performance Analysis of Dissimilar Metal Welded Pipe Joints

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Abstract - This study investigates the performance of dissimilar metal welded (DMW) joints between carbon steel (ASTM A106) and austenitic stainless steel (AISI 304) using ER309L filler metal, focusing on their mechanical integrity, microstructural stability, and reliability under high-temperature and high-pressure conditions. DMW joints combine the strength of carbon steel with the corrosion and thermal resistance of stainless steel but are prone to challenges such as residual stress, carbon migration, and intermetallic phase formation. Experimental testing—including tensile, hardness, impact, and corrosion assessments—was combined with finite element analysis (FEA) in ANSYS to evaluate residual stress, thermal distribution, and fatigue life. Results show that the carbon steel heat-affected zone (HAZ) is the weakest region due to grain coarsening and carbide precipitation. Microstructural analysis confirmed carbon migration across the fusion interface, forming brittle carbides and delta ferrite phases. The fusion zone displayed higher hardness (≈225 HV) than both base metals, while the carbon steel HAZ exhibited localized softening (~180 HV). FEA results correlated with experimental observations, identifying maximum residual stresses near the carbon steel HAZ (≈315 MPa). Weibull reliability analysis indicated accelerated failure rates above 450 °C due to creep and thermal fatigue. Compared with other dissimilar joints (Cu–CS, Al–CS, Br–Al), CS–ASS welds demonstrated superior tensile strength (~490 MPa), toughness, and fatigue resistance. Optimized welding parameters, low heat input, nickel-based fillers, and post-weld heat treatment (PWHT) significantly enhanced reliability. These findings support the adoption of ER309L-based CS–ASS joints in critical piping systems requiring high mechanical performance and corrosion resistance.

Keywords: Dissimilar metal welding, carbon steel, stainless steel, ER309L, residual stress, finite element analysis, fatigue, reliability.

1. INTRODUCTION

Dissimilar metal welded (DMW) joints are widely used in industries such as power generation, petrochemical processing, and oil and gas where materials experience combined effects of high temperature, pressure, and corrosion (Sharma et al., 2021). Welding carbon steel (CS) to austenitic stainless steel (ASS) enables cost optimization and performance enhancement, combining mechanical strength with corrosion resistance. However, mismatched thermal expansion coefficients and carbon migration across the fusion interface create metallurgical incompatibilities that lead to residual stress accumulation and microstructural embrittlement (Kumar & Sharma, 2021).

The study aims to analyze the performance and failure mechanisms of CS–ASS joints fabricated using ER309L filler metal, assessing their mechanical, metallurgical, and reliability characteristics, and comparing them with other dissimilar welded joints to determine optimized joining parameters for critical piping systems.

2. MATERIALS AND METHODS

2.1 Materials

The base materials selected were ASTM A106 Grade B carbon steel and AISI 304 austenitic stainless steel, joined using ER309L filler metal through the Gas Tungsten Arc Welding (GTAW) process. The composition of ER309L (22–24% Cr, 12–14% Ni, ≤0.03% C) provides an austenitic microstructure with excellent corrosion resistance and reduced carbide precipitation (Sridhar et al., 2006).

2.2 Experimental Methods

Mechanical testing included tensile strength, Vickers micro-hardness, and Charpy Impact testing per ASTM E8 and ASTM E23 standards. Metallographic samples were examined using optical microscopy and scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy (EDS) to identify microstructural transitions and elemental migration.

2.3 Simulation and Reliability Modeling

Finite Element Analysis (FEA) using ANSYS was performed to simulate thermal and residual stress distributions. A double ellipsoidal heat source model was applied to simulate arc energy input during welding. Reliability modeling employed the Weibull distribution to quantify temperature-dependent failure rates, with shape parameters (β) indicating failure modes.

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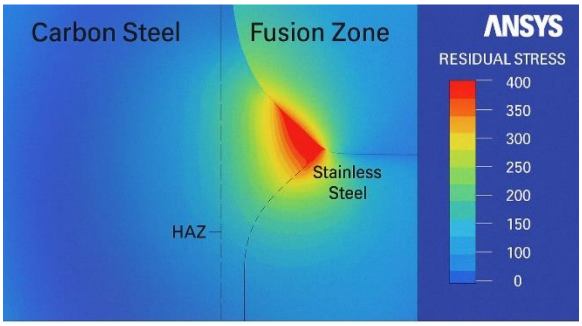

Figure 4.5 Finite Element Analysis (FEA) Simulation Diagram of Residual Stress Distribution for a DMWJ

3. RESULTS AND DISCUSSION

3.1 Mechanical and Microstructural Analysis

Tensile testing showed that all failures occurred in the carbon steel heat-affected zone (HAZ), confirming it as the weakest region. The ultimate tensile strength ranged between 475 and 498 MPa, slightly below that of the stainless steel base metal (≈600 MPa). The Vickers micro-hardness profile revealed significant gradients across the weldment: fusion zone (225 HV), stainless steel base (210 HV), and carbon steel HAZ (180 HV).

SEM–EDS analysis indicated carbon migration from the carbon steel side into the stainless steel, forming carbides along the fusion boundary. The fusion zone exhibited delta ferrite networks embedded within an austenitic matrix, while prolonged thermal exposure encouraged sigma-phase precipitation (Chen *et al*., 2018).

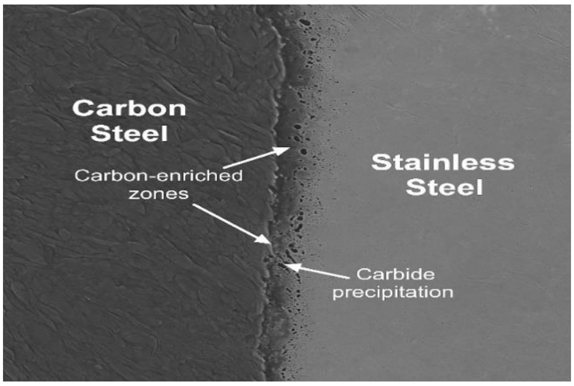

Figure 4.1 Carbon Steel/Stainless Steel Welded Joint Microstructure using Scanning Electron Microscope (SEM).

3.2 Residual Stress and Fatigue Analysis

FEA simulations identified maximum residual stress concentrations (~315 MPa) in the carbon steel HAZ due to the thermal expansion mismatch between CS (12×10^{-6} /°C) and ASS (17×10^{-6} /°C). These stresses correlated with observed crack initiation sites under cyclic loading (Shin & Lee, 2017).

Low-cycle fatigue testing revealed crack initiation along the fusion line within fewer cycles compared to homogeneous joints. The fatigue life decreased by ~40% under cyclic thermal loading conditions, consistent with the FEA predictions.

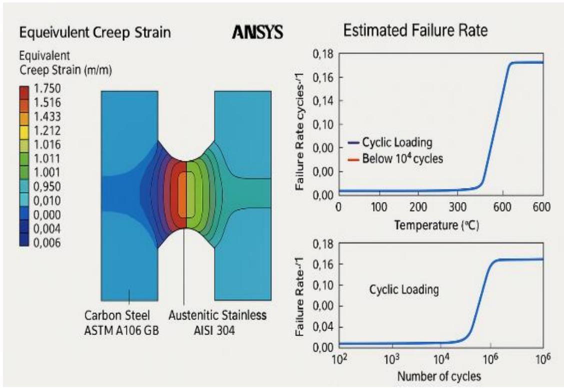

Figure 4.11 FEA-Based Fatigue and Creep Analysis under simulated temperature and pressure variations V-Groove Butt Welded Joint between Carbon Steel, ASTM A106 Gr. B using ER309L Filler Electrode

3.3 Reliability Assessment

Failure rate (λ) increased sharply beyond 450 °C. The Weibull shape parameter (β) rose from 1.1 at 300 °C to 2.3 at 500 °C, indicating a transition from random to wear-out failure behavior. Elevated pressures (15–40 MPa) amplified stress intensities in the fusion zone, accelerating creep and thermal fatigue

Temperature (°C)	**Mean Time to Failure (MTTF, h)**	**β (Weibull)**
300	26,000	1.1
400	19,000	1.6
500	12,500	2.3

3.4 Comparative Performance of Dissimilar Joints

A comparative evaluation was performed between CS–ASS, Cu–CS, Al–CS, and Br–Al welded joints. The CS–ASS configuration exhibited superior mechanical and corrosion performance (Table 2), validating its suitability for high-stress piping applications.

Table 2. Comparative performance of dissimilar metal welded joints.

Joint Type	**Tensile Strength (MPa)**	**Corrosion Resistance**	**Weldability**	**Structural Integrity**
CS–ASS	480–500	Moderate–High	Good	Excellent
Cu–CS	270–300	Low	Poor	Moderate
Al–CS	110–160	Low	Very Poor	Low
Br–Al	~130	Low–Moderate	Poor	Low

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3.5 Mitigation Strategies

1. **Filler Selection:** Nickel-based filler (ER309L) reduces carbon diffusion and enhances corrosion resistance.
2. **Low Heat Input Welding:** Techniques like GTAW and laser beam welding (LBW) minimize residual stress and intermetallic formation.
3. **Post-Weld Heat Treatment (PWHT):** Controlled PWHT (~650 °C, 1 h) reduced residual stress by 40–60%.
4. **Corrosion Control:** Protective coatings and cathodic protection decreased pitting depth by ~65%.
5. **Design Optimization:** Smooth joint transitions and buttering layers improved fatigue life by >30%.

4. CONCLUSIONS

The performance of dissimilar welded joints between carbon steel (ASTM A106) and stainless steel (AISI 304) using ER309L filler metal demonstrates superior strength, reliability, and metallurgical compatibility compared to other dissimilar combinations.
Key conclusions include:

- The **carbon steel HAZ** remains the critical failure region due to residual stress and carbon migration.
- **Residual stress peaks (~315 MPa)** correlate with localized cracking and reduced fatigue life.
- **Failure rates rise exponentially** beyond 450 °C, transitioning to wear-out failure behavior.
- **Nickel-based fillers, low heat input**, and **PWHT** effectively improve durability and performance.
- Compared with Cu–CS, Al–CS, and Br–Al joints, the **CS–ASS configuration** offers the best balance of mechanical strength, weldability, and corrosion resistance for high-pressure applications.

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