Investigations on dissimilar metal welding for marine applications

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CONCLUSION AND SCOPE OF FUTURE WORK

This study investigates structural integrity and structure-property relationships in marine dissimilar metal welding. The investigation involves selecting filler metals and welding parameters for fabricating weld joints (sDSS 2507/IN-625, sDSS 2507/N50, and sDSS 2507/X-70) using the gas tungsten arc welding (GTAW) process. Previous literature reviews have identified instances of failure in each of these dissimilar weld joints that have been subjected to harsh marine environments. The detailed results obtained from these experiments have been thoroughly discussed in Chapter 5. This chapter encapsulates the conclusions drawn from the experiments that were conducted. Despite the extensive experimentation and characterization of these dissimilar weld joints, certain areas of investigation remain unexplored, as highlighted in the scope for future research.

6.1 CONCLUSION

6.1.1 DISSIMILAR METAL WELD OF SUPER DUPLEX STAINLESS STEEL AND INCONEL 625

This study examined the structure-property relationship and structural integrity of sDSS 2507/IN-625 dissimilar weld joints (DWJs) welded with ER2594 and ERNiCrMo-3 filler and different heat input parameters employing a multi-pass GTAW method. Notable findings from this investigation on microstructural characterization, solidification mechanism, mechanical properties, residual stresses, wear, and corrosion behavior are highlighted below:

- Macroscopic and microscopic inspection of the resulting sDSS 2507/IN-625 DWJs revealed no signs of defects such as porosity, cracks, or incomplete weld fusion, and the macrostructure analysis confirmed this. Both the radiographic analysis and the macrostructure analysis indicate that the quality of the weld joint is satisfactory. There was no evidence of solidification cracking or liquation cracking in the weld or heat-affected zone (HAZ).

- The ER2594 weld interface displayed microstructural heterogeneity, featuring a diffused sDSS 2507 weld interface and sharp IN-625 interfaces with partially mixed zone (PMZ) and island formation. The similarity in composition between IN-625 and ERNiCrMo-3 filler metal eliminated macrosegregation at the interface. However, significant macrosegregation occurred at the sDSS 2507 base metal (BM) and weld metal (WM) interface, manifesting as islands, PMZ, unmixed zone (UMZ), peninsulas, and banding. Energy dispersive spectroscopy (EDS), elemental line mapping, and electron probe microanalysis (EPMA) confirmed elemental variations across the island and peninsula. The weld zone (WZ) with ERNiCrMo-3 filler exhibited an austenitic solidification with columnar and cellular dendrites containing Nb and Mo-laves phase. Conversely, the weld zone with ER2594 filler showcased a ferritic solidification mode with various reformed austenite types, including widmanstätten austenite (WA), intergranular austenite (IGA), partially transformed austenite (PTA), grain boundary austenite (GBA), and dominant precipitation of Laves phase (Fe_2Nb type) in the ferrite matrix.

- ER2594 filler weld joint resulted in a heterogeneous microstructure due to heat input, displaying peninsulas and islands at the interface. Microstructure varied with heat input,

exhibiting finer dendritic structure at low heat and multi-directional grain growth at high heat. Increased heat input led to elevated Ni content in the weld metal. Nb-rich Laves phases were dispersed unevenly, and segregation occurred at the weld interface. Mo and Nb-rich phases are segregated in the inter-dendritic region, particularly in high heat input weldment. The sDSS 2507 HAZ showed secondary phases and ferrite grain growth, while the IN-625 HAZ exhibited austenite grain coarsening. Overall, the ER2594 filler demonstrated significant sensitivity to heat input, which influenced its microstructural characteristics.

- ERNiCrMo-3 filler welding induced microstructural heterogeneity in the weldment, particularly in lower heat input (LHI) and higher heat input (HHI) zones and sDSS 2507 BM near the interface. The weld interface displayed peninsulas and islands as unmixed zones due to the filler's higher liquidus temperature. Elemental line mapping and EDS confirmed elemental variation across the peninsula. Microstructure analysis showed an austenitic structure with dendrites in the weld metal. Optical microscopy (OM) and scanning electron microscope (SEM) images verified secondary phases rich in Nb and Mo in the inter-dendritic areas, attributed to segregation during solidification. Both weldments featured NbC and Laves phases, which are prevalent in interdendritic regions. The chemical analysis highlighted dense Laves phases with higher Mo concentration in the HHI weld zone.

- The microhardness map and profile clearly show the heterogeneity of both fillers' weld zones. The ER2594 and ERNiCrMo-3 filler weldments had average hardness values of 304 ± 7 $HV_{0.5}$ and 290 ± 3 $HV_{0.5}$ in the sDSS 2507 HAZ and 282 ± 5 $HV_{0.5}$ and 280 ± 3 $HV_{0.5}$ in the IN-625 HAZ, respectively. ER2594 and ERNiCrMo-3 weld zones have average hardness values of 310 ± 7 $HV_{0.5}$ and 270 ± 10 $HV_{0.5}$, respectively. The austenitic microstructure of the WZ accounts for the ERNiCrMo-3 filler's lower microhardness value. ER2594 filler LHI/HHI weldment showed increased microhardness with lower heat input, characterized by thinner dendritic grains and smaller arm spacing. HAZ softening was confirmed in LHI's IN-625 HAZ through microhardness mapping. Microhardness maps for ERNiCrMo3-LHI/HHI revealed heat input-dependent variations in weld zones, with increased hardness at higher heat inputs.

- The ER2594 and ERNiCrMo-3 filler weldment tensile specimens failed from the weld center with an ultimate tensile strength (UTS) of 750 ± 6 MPa and 790 ± 7 MPa, respectively, were inferior to both BMs. ERNiCrMo-3 filler weldment outperforms ER2594 weldment in terms of ductility. In SEM fractography, dimples, micro-voids, and cleavage facets indicated a hybrid (ducltile+brittle) fracture mode. Tensile testing indicated fractures at the weld zone for both LHI and HHI weldments, suggesting reduced mechanical performance due to Nb-rich phases in the inter-dendritic regions for ER2594 filler LHI/HHI weldment. Whereas, ultimate tensile strength and yield strength also increased with higher heat inputs, and the tensile experiments showed a ductile fracture mode for ERNiCrMo3-LHI/HHI weldments.

- ER2594 filler weldment's impact toughness for the V-notch in the cap and root region was 100 ± 3 J and 110 ± 6 J, respectively, compared to ERNiCrMo-3's 165 ± 5 J and 180 ± 3 J. Due to Laves phase precipitation in the weld zone, filler weldments have lower impact toughness than base metals. Fractographic analysis of the impact test reveals the brittle fracture mode of the ER2594 filler and the ductile fracture mode of the ERNiCrMo-3. The impact toughness of the ERNiCrMo3-LHI weldment was inferior to the ERNiCrMo3-HHI weldment, as indicated by SEM fractography exhibiting ductile fracture modes. Similarly, ER2594-LHI weldment also exhibited inferior impact toughness compared to HHI, attributed to Nb-rich Laves phases and other inclusions.

- ERNiCrMo-3 and ER2594 exhibited compressive residual stresses of 168 MPa and 33 MPa at the filler pass and tensile residual stresses of 591 MPa and 481 MPa at the weld cap at 3 mm, respectively. At the root pass, the ERNiCrMo-3 filler had 560 MPa, while the ER2594 filler

had 250 MPa. The backing pass of the weld zone shifted compression transverse residual stress from 88 MPa to tensile at 7 mm. In ERNiCrMo-3 filler weldments, the increased heat input led to a 23% increase in longitudinal residual stress and a 21% increase in transverse residual stress. For ER2594 filler weldment, high heat input increased longitudinal and transverse residual stress by 16% and 19%.

- In slurry erosion tests, increasing slurry concentration led to cumulative weight loss in all specimens. The erosion rate decreased due to reduced impact efficiency, the blanketing effect, and particle rotation. Microstructure and microhardness influenced slurry erosion, with ER2594 filler weldments exhibiting higher post-erosion microhardness than ERNiCrMo-3 weldments. Higher slurry concentrations caused significant weight loss, particularly with ERNiCrMo-3-LHI losing 77% more and ER2594-LHI losing 72% more as slurry concentration increased. Erosion rates were correlated with base metal hardness and microstructural changes, with sDSS 2507 BM and IN-625 BM eroding 1.8 and 1.45 times faster, respectively, at higher slurry concentrations. Slurry erosion rates were lower in ERNiCrMo-3 and ER2594 weldments compared to the base metal, and ER2594-LHI and ERNiCrMo-3-LHI eroded 0.85 and 1.2 times faster, respectively. Material removal mechanisms involved mixed cutting-ploughing modes, craters formation, plastic deformation, and the development of frontal and lateral lips.

- A 60-day complete immersion corrosion study of sDSS 2507/IN-625 DWJs was conducted in 3.5 wt.% NaCl solution. The results of the weight loss analysis and corrosion rates indicate that pitting corrosion is more likely to occur in the overmatching ER2594 filler weldments and base metal sDSS 2507 than in the matching IN-625 base metal and ERNiCrMo-3 filler weldments. On the other hand, in the process of investigating electrochemical corrosion, the corrosion rate (mm/year) is ranked from high to low, where a higher rating indicates less corrosion resistance: sDSS 2507 BM (0.02245) > ER2594-LHI (0.01040) > IN-625 BM (0.00673) > ERNiCrMo-3-LHI (0.002760) > ER2594-HHI (0.002552) > ERNiCrMo-3-HHI (+0.00075). sDSS 2507 BM has lower corrosion resistance than IN-625 BM and other weldments. ERNiCrMo-3 weldment outperforms ER2594 in electrochemical corrosion.

6.1.2 DISSIMILAR METAL WELD OF SUPER DUPLEX STAINLESS STEEL AND NITRONIC STEEL

This study investigated the structure-property relationship and structural integrity of multi-pass GTAW-welded sDSS 2507/N50 DWJs with ER2594 and ER70S-2 fillers and varied heat input parameters. The study suggests that sDSS 2507/N50 DWJs are suitable for high-pressure tubing in remote deep-water environments, which is crucial for tubing-coupler assembly and design. Key study findings on microstructural characterization, solidification mechanism, mechanical properties, sliding wear behavior, and corrosion behavior are highlighted below:

- Macroscopic examination of sDSS 2507/N50 DWJs with ER2594/ER70S-2 filler metals and heat inputs weldments showed no cracks, porosity, incomplete fusion, or discontinuity at the interface or in the weld zone. The weld zone and HAZ zones in both LHI and HHI weldments exhibited no signs of solidification or liquation cracking.

- ER2594 filler weldment displays reformed austenites like WA, IGA, and GBA within a ferrite matrix. Conversely, the ER70S-2 filler weld joint's microstructure consists of ferrite and long martensite laths. An unmixed zone, characterized by peninsula, beach, and island formations, results from the liquidus temperature difference between the base metal and filler metal. The ER70S-2 weldment shows a type II boundary near the fusion boundary on both N50's and sDSS 2507's sides. Furthermore, variations in Cr and Ni concentration gradients are evident in the line scan across the fusion boundary and ER70S-2 weldment but are absent with the ER2594 filler metal.

- Increased heat input during the GTAW process influences microstructure evolution in ER2594 filler weldments, leading to significant changes in grain size, austenite precipitation, and phase balance. The higher heat input results in increased grain growth, extensive grain coarsening, and the appearance of secondary austenites (γ_2) and possibly sigma phase in the HHI weldment. Additionally, epitaxial growth occurs at the sDSS 2507 interfaces. The weld zone undergoes shifts in austenite morphology, with decreased GBA and reformed austenite and increased IGA and WA, achieving a 50/50 phase balance. Ferrite content in the root of the weld zone increases with higher heat input. Macrosegregation, including islands, peninsulas, beaches, and banding, is observed in the interface and weld zone of both weldments.

- The microstructure of weld joints with ER70S-2 filler, under different heat inputs, consists of ferrite with long martensite laths. No intermetallic phases were detected. Higher heat input leads to larger heat-affected zones and fusion boundaries, causing notable grain growth. Concentration gradients of major alloying elements are observed, and macrosegregation is evident in various forms at the interface and within the weld joint.

- The average hardness of sDSS 2507 is 290.17 ± 10 $HV_{0.5}$, and N50 is approximately 317.86 ± 10 $HV_{0.5}$. In the weld zone, ER2594 filler exhibits an average hardness of 287.34 ± 10 $HV_{0.5}$, while ER70S-2 shows a higher hardness of 372.36 ± 10 $HV_{0.5}$. The microhardness study indicates that ER70S-2 filler has a greater hardness than ER2594 due to the presence of long martensite laths within the ferrite matrix, compared to the softer reformed austenite in the ER2594 filler's weld zone. The mechanical assessments for ER70S-2 filler indicate that hardness exhibits no significant variation with varying heat input. However, an increase in heat input results in a decrease in hardness, attributed to the changing ferrite/austenite ratio in the HAZ and weld zone. For LHI and HHI weldment, the weld zone's average hardness is 280 ± 4 $HV_{0.5}$ and 270 ± 3 $HV_{0.5}$, respectively. The higher hardness in the weld root of the HHI weldment is attributed to the formation of hard and brittle secondary phases and varying thermal cycles during welding. Lower heat input for ER70S-2 weldment results in higher hardness in the weld, while other zones, like the heat-affected zone and interface, show no significant hardness variations.

- Tensile fractures occurred in the base metal of sDSS 2507 in all trials. The ER2594 filler weldment displayed a tensile strength of 890±10 MPa, while the ER70S-2 filler weldment had a slightly lower strength of 870±10 MPa. Despite lower strength, ER70S-2 filler exhibited nearly 10% better ductility than ER2594 filler, making it a preferred choice for improved tensile properties. ER2594-LHI weldment exhibits superior ductility and tensile strength compared to the HHI weldment. Tensile fractures in the ER2594-HHI weldment are identified in the weld zone due to the presence of γ_2 precipitate particles. LHI and HHI weldments demonstrate nearly identical tensile strength, specifically 895 ± 4 MPa and 900 ± 5 MPa, respectively. Fractography analysis of both weldments reveals a ductile fracture mode in all trials. The weld joints produced with an ER70S2-LHI exhibits superior ductility and tensile strength compared to the ER70S2-HHI weldment. Tensile test failures occurred in the sDSS 2507 BM, with fractography indicating a ductile fracture mode in both heat input conditions for all trials.

- ER2594 filler weldment demonstrated superior impact toughness at 165 ± 5 J compared to ER70S-2 filler with an impact toughness of 110 ± 8 J. Charpy impact tests revealed a ductile fracture mode for ER2594 filler, while ER70S-2 exhibited a mixed fracture mode (ductile-brittle). Higher heat input led to decreased impact toughness due to secondary austenite phase formation and increased grain size. ER2594-LHI weldment exhibited superior impact toughness at 165 ± 5 J compared to ER2594-HHI weldment at 145 ± 3 J. Fractographs revealed a prevalent ductile mode fracture in all specimens. Impact

toughness increases with heat input for ER70S2-LHI/HHI weldment, with fractographs showing a dominant brittle fracture mode in the weld zone for both heat input conditions.

- The wear performance varied among different materials and weld conditions. N50BM exhibited higher weight loss, while ER70S2 and ER2594 fillers had lower weight loss. In particular, ER70S2-LHI weldments showed an 88% reduction in volume loss compared to N50 BM. For both LHI and HHI weldment conditions, ER70S-2 filler outperformed ER2594 filler, with volume loss reductions of 85% and 60% and wear rate reductions of 81% and 48%, respectively. Microstructure and microhardness significantly influenced wear behavior, with ER70S2-LHI and ER70S2-HHI weld zones displaying the lowest cumulative volume loss and wear coefficients due to their martensitic structure. Analyzing worn pin surface profiles and weight loss-sliding distance correlations helped to understand the progressive wear mechanism, highlighting ER70S2-LHI weldments as having the least wear progression. The wear process predominantly exhibited a mixed mode, including adhesive, abrasive, and fatigue wear, with N50 BM experiencing significant material loss through the micro-cutting mechanism.

- The pitting corrosion resistance is superior in ER2594 filler weldments compared to ER70S-2, primarily due to a significant difference in pitting resistance equivalent number (PREN). The HAZ on the N50/sDSS 2507 BM side is prone to pitting initiation, indicating potential galvanic coupling-induced general corrosion. The proposed cooperative precipitation mechanism sheds light on corrosion initiation and propagation. Weight-loss measurement relates to corrosion rate with dissolved oxygen diffusion inhibited by corrosion products over prolonged immersion. The inner rust layer with high electrochemical activity, rich in β-FeOOH, restricts oxygen transport. In electrochemical tests, the cathodic reduction reaction incorporates oxygen. Complete immersion corrosion led to the formation of primary products such as β-FeO(OH), γ-FeO(OH), Fe_3O_4, and Fe_2O_3. The corrosion model highlighted Cl^-, O_2, and rust layer interactions, revealing an oxygen-absorbing mechanism with non-protective rust layers and O_2 diffusion control.

6.1.3 DISSIMILAR METAL WELD OF SUPER DUPLEX STAINLESS STEEL AND PIPELINE STEEL

This study investigated the structure-property relationship and structural integrity of multi-pass GTAW-welded sDSS 2507/X-70 DWJs with ER2594 and ER309L fillers and varied heat input parameters. The study suggests that sDSS 2507/X-70 DWJs are employed in marine applications for hydrocarbon drilling risers in the splash zone. Key study findings on microstructural characterization, solidification mechanism, mechanical properties, sliding wear behavior, and corrosion behavior are highlighted below:

- The sDSS 2507/X-70 DWJs' macrostructure demonstrated no porosity, fractures, or partial weld fusion. The welding passes' heating generated microstructure heterogeneity along X-70 and sDSS 2507 BM HAZ. The X-70 BM has a coarse grain, fine grain, and intercritical HAZs, and the sDSS has HT-HAZ and LT-HAZ.

- Welded joints have Cr_{eq}/Ni_{eq} ratios of 2.3 for ER2594-LHI and 1.78 for ER2594-HHI. ER2594-LHI and HHI weldments have 80% and 35% ferrite in the Schaeffler diagram prediction. Ferritic-austenitic (FA) solidification in ER2594-HHI weldments is more prone to cracking than ferritic solidification in ER2594-LHI weldments. Duplex microstructures like GBA, WA, and IGA dominate the cap and filler pass of the ER2594-LHI and HHI weld zone. In the ER2594-HHI weld zone's root pass, the skeletal ferrite structure dominates and becomes duplex microstructure in the backing pass. Peninsulas and islands appeared as unmixed zones, Type II boundaries in both heat input weldments at the X-70 weld interface. EDS spectra, EPMA, and line mapping analysis confirmed elemental variation along the weld interface's macro segregation.

- The Cr_{eq}/Ni_{eq} ratios of weld joints are 1.81 and 1.76, respectively, under both heat input conditions. The Schaeffler diagram shows 35% and 25% ferrite content for ER309L-LHI and HHI weldments. ER309L solidifies into a ferrite-austenite (FA) microstructure with a mix of skeletal and lathy ferrites and interdendritic austenite. The microstructure of the weld zone and HAZ was found to exhibit Type II boundaries and macro-segregation in both heat input weldments. Elemental variation across the macro segregation and Type II boundaries along the weld interface was confirmed by elemental line mapping and EDS spectra.

- The microhardness maps showed hardness variations across the weld zone for both filler weldments. Weld zone hardness ranged from 190 to 320 $HV_{0.5}$, with ER2594-HHI weldments averaging 285 ± 5 $HV_{0.5}$ and ER2594-LHI weldments 275 ± 7 $HV_{0.5}$. The sDSS 2507 HAZ had negligible hardness changes between ER309L-LHI and HHI weldments, 275 ± 6 $HV_{0.5}$ and 285 ± 4 $HV_{0.5}$, respectively. Hardness ranged from 190 to 290 $HV_{0.5}$, with ER309L-LHI averaging 205 ± 6 $HV_{0.5}$ and ER309L-HHI 225 ± 4 $HV_{0.5}$. The X-70 HAZ has 250 ± 6 $HV_{0.5}$ for ER309L-LHI and 275 ± 4 $HV_{0.5}$ for ER309L-HHI. Increased heat input resulted in an increased hardness value for both filler weldments.

- ER2594-LHI and HHI weldments had UTS of 600 ± 3 MPa and 610 ± 5 MPa, respectively. With ER2594-LHI and ER2594-HHI elongation percentages of 22% and 18%, respectively, the sample fractured at the weaker X70 BM side. ER309L-HHI samples had a tensile strength and elongation of 601.7 MPa and 30.8%, compared to the ER309L-LHI samples' 609.4 MPa and 25.3%. Weld ductility was found to increase with increased heat input. Fractographic analysis reveals the ductile fracture mode for both weldments.

- ER2594-LHI weldments (200 ± 7 J, 210 ± 4 J) and ER2594-HHI weldments (210 ± 5 J, 220 ± 8 J) perform worse than the sDSS 2507 BM (320 ± 3 J), and the X-70 BM (300 ± 6 J) in terms of average impact toughness in cap and root pass. ER309L-LHI weldment cap and root impact toughness were 195 ± 5 J and 185 ± 2 J, compared to 180 ± 4 J and 200 ± 3 J for ER309L-HHI. In SEM fractography, dimples, micro-voids, and cleavage facets indicate a ductile fracture mode for both filler weldments.

- ER2594 filler exhibited a peak tensile residual stress of 241 MPa at the weld cap, gradually decreasing towards the root, with predominant tensile residual stress throughout. In contrast, ER309L weldments had a maximum tensile residual stress of 175 MPa at the weld cap, and the highest compressive residual stress of 46 MPa was observed near the weld root.

- Increased slurry concentration caused higher weight loss in welded joints, impacting microstructure and hardness. X-70 BM's reduced hardness correlated with elevated erosion and weight loss. ER309L-LHI lost 55% more weight than ER2594-LHI, and ER309L-HHI lost 56% more than ER2594-HHI. Slurry concentration intensified X-70 and sDSS 2507 BM erosion by 1.8 and 1.4 times. ER2594-LHI and ER309L-LHI showed better erosion resistance, while ER2594-HHI and ER309L-HHI had higher erosion rates. Material removal mechanisms revealed features like micro-cutting, craters, and lip formation.

- Pitting corrosion is most pronounced in the X-70 regions of the sDSS 2507/X-70 dissimilar weld joint, attributed to a galvanic couple, leading to inferior overall corrosion resistance. In dry/wet cycles, rust layers exhibit distinct structures and are thicker compared to complete immersion corrosion. Pitting and intergranular corrosion

are observed, with different corrosion products in complete immersion and dry/wet conditions. Corrosion increases with dry/wet cycles but remains low in complete immersion. Primary corrosion products in complete immersion include α-FeOOH, γ-FeOOH, Fe_3O_4, and Fe_2O_3, while dry/wet cyclic conditions are dominated by γ-FeOOH and Fe_3O_4. Various models are proposed, emphasizing Cl^-, O_2, and rust layer effects. In complete immersion, an oxygen-absorbing corrosion mechanism prevails, lacking protective rust characteristics, controlled by O_2 diffusion.

6.2 SCOPE OF FUTURE WORK

- Explore more filler metals for all investigated dissimilar weld joints to obtain better structural integrity for marine applications.

- Investigating the application of a Ni-buttering layer on X-70 base metal to enhance structural integrity by minimizing the gradient at the X-70/weld interface for sDSS 2507/X-70 DWJs.

- Utilize modeling and simulation techniques to predict the residual stresses generated in dissimilar weld joints.

- Explore the complex tribo-corrosion synergy between mechanical wear and corrosion to understand how it accelerates material degradation, especially in corrosive conditions.