

Influence of solution annealing time on the hydrostatic integrity of super duplex steel 3D hot induction bends

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ARTICLE HISTORY

Received : 4 November 2025

Accepted : 15 February 2026

Online : 30 September 2026

KEYWORDS

hot induction bends,
intermetallic phase,
hydrostatic pressure,
solution annealing

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ABSTRACT

UNS stainless steel S32760 is commonly used in the petrochemical and gas industries for its superior mechanical properties and corrosion resistance. Its primary applications in offshore systems are predominantly in topside process piping. It consists of extensive network of pipes located on the deck of offshore oil and gas platforms. These high-temperature pipes transport hydrocarbons and chemicals for processing, drilling, and utility services, exposing them to highly corrosive processed fluids and saltwater. Despite its superior performance, both austenitic (γ) and ferritic (α) phases could be altered by shifts in the microstructure, by excessive heat input during welding, potentially affecting their mechanical properties and corrosion resistance. The research investigates the impact of hot induction bending on stainless steel S32760 by examining its post-bending effects at recommended temperatures of 850 to 1150 °C. Metallurgical analysis was performed to evaluate the austenite (γ) and ferrite (α) contents in the base metal (BM), heat-affected zone (HAZ) and weld metal (WM) followed by positive material identification (PMI). The results observed an increase in chromium content by 25% reflect microstructural phase distribution and elemental partitioning rather than direct evidence of intermetallic phase formation. Mechanical properties and corrosion resistance were tested after the bending process through hardness and pitting resistance equivalent number (PREN). Higher hardness measurements and corrosion resistance demonstrated robust structural integrity of samples tested. Further hydrostatic pressure test and radiography examination were performed to evaluate the integrity of the welded materials in multiple solution annealing treatments at 1120 °C and 1110 °C. The data suggests multiple heat treatments during solution annealing revealed well-distributed mixture of ferrite and austenite indicated by 381 MPa. Yet, lower ferrite content demonstrated failure at 266 MPa due to the brittleness. This research suggested that multiple heat treatments and solution annealing above 1000 °C are effective to prevent formation of intermetallic phase and enhance materials' structural integrity.

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1. INTRODUCTION

Super duplex stainless steel (SDSS), specifically UNS S32760 is widely used in the fabrication of topside piping due to its excellent mechanical strength, high-pressure tolerance and corrosion resistance in marine environments and transporting processed fluids of hydrocarbon and chemicals (Chagas de Souza et al., 2016). In offshore facilities, hot induction bending is widely employed to form pipe elbows, while preserving wall thickness, maintaining smooth laminar flow, and ensuring dimensional accuracy (Collie & Black, 2009). This ensures the precise shaping of 3D bends, such as 45° and 90° elbows, with a bend radius typically three times of the pipe diameter. Maintaining this geometry is crucial for pigging operations, as it enables inspection and cleaning pigs to pass through bends without obstruction. Reliable pigging capability ensures continuous

pipeline operation, facilitates maintenance, prevents blockages, and allows effective inspection of high-temperature and corrosive offshore topside flowlines, transporting liquids and gases (Cordell & Vanzant, 2003).

Fabrication of topside piping generally follows ASME B31.3, which provides safety and design requirements for offshore oil and gas systems (Byrne et al., 2016). Hydrostatic testing is mandated prior to commissioning to ensure leak tightness (ASME, 2020). For sour-service environments containing H₂S and high CO₂, super duplex stainless steels such as UNS S32760 required NACE MR0175 and ISO 1516 to ensure resistance to sulfide stress cracking. However, although these standards define acceptable materials and design requirements, they provide limited guidance specific to induction-bent SDSS components (Byrne et al., 2016; Sherar et al., 2022). Existing codes such as ASME B16.49 and ISO 15590-1 outline testing procedures for induction-bent carbon

and low-alloy steels, but they do not explicitly address super SDSS (ASME, 2017; 2020). Furthermore, the post-heat treatment requirements for super duplex alloys differ significantly from those of carbon steels, since SDSS must undergo solution annealing and rapid water quenching to avoid detrimental phase formation, especially when the components to be heat-treated includes base material (BM), heat-affected zone (HAZ), and weld metal (WM) (Elsabbagh et al., 2015; Juraga et al., 2014).

During induction bending and subsequent heat treatment, at different regions of BM, HAZ and WM may experience microstructural changes that influence corrosion resistance, hardness, and mechanical performance. One of the key metallurgical concerns during heat treatment of SDSS is sigma phase precipitation (Quadros et al., 2024), which is favored at intermediate cooling rates and elevated temperatures. particularly evident during cooling after solidification and heat treatment (Fonseca et al., 2014). Excessive sigma phase formation increases hardness and brittleness, contributing to failure risks during hydrostatic testing (Salvetr et al., 2024). Nevertheless, hardness variations may also be associated with ferrite–austenite phase imbalance or residual stresses induced during welding and heat treatment processes, rather than direct evidence of sigma phase formation. Although prior studies have shown that sigma phases can be dissolved at solution treatment temperatures between 1065 °C and 1200 °C (Fellicia et al., 2017), and that induction bending affects ferrite content in duplex grades such as UNS S31803 (Jiang et al., 2014) (Garcia et al., 2022). Despite the availability of industrial standards such as ASME, ASTM International, and NACE International, limited studies have addressed the microstructural stability and corrosion performance of longitudinally welded super duplex stainless steel (SDSS) subjected to multiple solution annealing cycles during 3D induction bending processes, particularly in hydrostatic qualification requirements. Therefore, this study investigates the potential formation of sigma (σ) and other intermetallic phases in the base metal (BM), heat-affected zone (HAZ), and weld metal (WM) of UNS S32760 super duplex stainless steel subjected to different post-heat treatment conditions. The material was exposed to varying heating rates during solution annealing followed by water quenching prior to the hot induction bending process.

2. MATERIALS AND METHODS

2.1. Welding of super duplex stainless steel

The raw material used in this study was a super duplex stainless steel (SDSS) rolling plate, specifically UNS S32760 in compliance to the requirements of ASTM A928 standard. The raw material with a thickness of 25 mm was

initially heat treated (1st heat cycle) by solution annealing and water quenching at 1100 °C to achieve the desired mechanical properties and microstructure. Prior to welding, the SDSS rolling plate was butt-welded on the two types of duplex and SDSS plates (20 mm to 50 mm in thickness, and V-edge prepared), to form into mother tube by longitudinal-seam Submerged Arc Welded (LSAW). The formed mother tube was then heat treated (2nd heat cycle) by solution-annealed and water quenched at 1120 °C with a heating rate of 353 °C hr⁻¹ for 15 minutes to ensure the integrity and uniformity of the welded and base materials. The chemical compositions (wt%) of the mother tube, both base metal and weld metal are listed in Table 1. The mechanical properties of the mother pipe are as the following: tensile strength (838 N mm⁻²) and yield strength (605 N mm⁻²). For SAW, the arc energy, interpass temperature and the welding parameters settings (Table 2) were set according to those recommended by guidelines and practices (16).

Table 1: Chemical composition of the base metal and weld metal

Element (wt%)	Base Metal	Weld Metal
Carbon	0.013	0.014
Sulphur	0.001	0.001
Phosphate	0.027	0.017
Manganese	0.64	0.50
Silicon	0.30	0.32
Nickel	6.82	7.94
Chromium	25.45	25.59
Molybdenum	3.49	3.64
Tungsten	0.54	0.40
Copper	0.55	0.40
Nitrogen	0.280	0.218

Table 2: Welding parameters settings of LSAW

Condition	Longitudinal seam welding of SDSS
Material	ASTM 1928 Class 1 UNS S32760 (welded)
Dimension	18" x 25mm (WT) x 4500mm (L)
Joint Configuration	Double Vee Butt Joint
Welding Position	1G
Welding Process	SAW
Welding Polarity	DCEP
Welding Comable	Wire (Sandvik W25.10.4.L – ER2594) & Flux (Bohler nsuRecord Ind24)
Welding Parameters	1st Pass – 2.4mm Ø: 350 - 370 (A), 28 – 29 (V), 500 mm min ⁻¹
	2nd to 3rd Pass – 2.4mm Ø: 380 - 400 (A), 29 – 30 (V), 390 - 400 mm min ⁻¹
	4th to 11th – 2.4mm Ø: 435 - 440 (A), 29 – 30 (V), 340 - 350 mm min ⁻¹
	2nd Side – 12th Pass – 2.4mm Ø: 570 - 580 (A), 35 – 36 (V), 390 - 400 mm min ⁻¹
Target Heat Input	1.2 to 3.2 kJ mm ⁻¹
Preheat Temperature	32 °C (ambient)
Interpass Temperature	150 °C
Bevel Preparation Method	Plasma Cutting and Grinding
Welding Technique	Stringer Bead with no oscillation
Interpass Cleaning	Grinding, Wire Brush and Chipping

2.2. Fabrication of hot induction bend and post-hot induction bend condition

For hot induction process, the welded mother tubes were further heat treated to 1120 °C in the 3rd heat cycle prior to 3D bending formation. Once bent, the formed and welded

tubes were subjected to the 4th heat cycle of multiple heat treatments in the post-hot induction bending at two different temperatures processing and heating rates with a constant holding time of 90 minutes to reduce residual stresses and enhance the material's mechanical and corrosion-resistant properties. Table 3 shows the control range and tolerance parameters during the hot induction bending formation in the 3rd heat cycle. For post-hot induction bend, the two fabricated main samples, Test Bend 1 and Test Bend 2 conditions in the present study are tabulated in Table 4.

Table 3: Hot induction bend parameters

Parameter	Control Range and Tolerance
Temperature	1120 ± 50 °C
Production Speed (mm min ⁻¹)	15 ± 2.5 °C
Coolant (Water) Temperature	30 ± 15 °C
Coolant Flow Rate (%)	+ 10%
Induction Heating Frequency (Hz)	+ 20%

Table 4: Post-induction bend conditions

Condition	Test Bend 1	Test Bend 2
Solution Annealing	1110 °C	1120 °C
Water Quenching + Heating Rate	141 °C hr ⁻¹	154 °C hr ⁻¹
Holding Time	90 min	90 min

2.3. Non-destructive test by metallurgical and chemical analyses

Metallurgical austenite (γ) and ferrite (δ) contents were measured in the weld metal (WM), heat-affected zone (HAZ) and base metal (BM) regions of longitudinal seam in the as-welded condition using in-situ metallographic and ferrite scope techniques. Metallographic in-situ test was performed according to ASTM standard E3 (ASTM, 2017) by polishing (MINIPOL B, S/N: MPL-190621 Model) and the results were interpreted according to ASTM A923 Method A (ASTM, 2013). Further austenite and ferrite counts were evaluated according to the ASTM standard E562 (ASTM, 2019) by using an optical microscopy examination (UHL, S/N: TR7 Model) at 400X magnification. For ferrite scope, samples were tested using a Fischer Ferrite Scope (Model FMP30C), calibrated to AWS standard A4.2 (ASTM, 2006). The evaluation of chemical analysis of the alloy in WM, HAZ and BM regions after subjected to multiple heat treatments were conducted by Positive Material Identification (PMI) using X-ray fluorescence technique prior to measurements of the Chromium (Cr), Nickel (Ni) and Molybdenum (Mo) compositions.

2.4. Mechanical test and pitting resistance equivalent number (PREN)

Hardness test was measured by using Portable Hardness Tester (AlphaDur Mini, S/N: Adm-1922 Model) in the weld metal (WM), heat-affected zone (HAZ) and base metal (BM) regions. The samples were cut to dimension of 30 mm x 6 mm x 6mm and the hardness measurements at selected location of the samples were obtained in Vickers (HV)

(Figure 1).

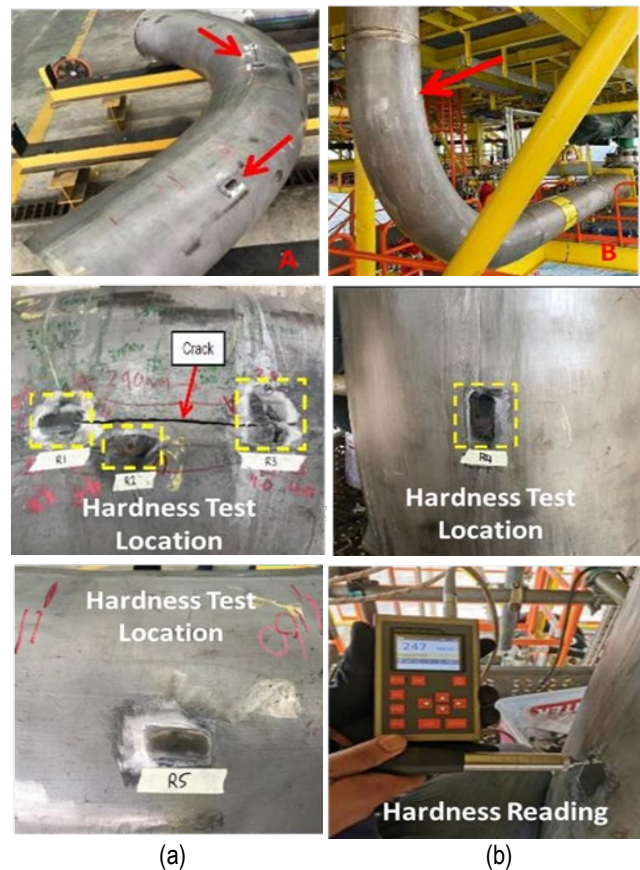


Figure 1: Selected location of hardness test of SDSS (a) Test Bend 1; (b) Test Bend 2

2.5. Hydrostatic test and radiography examination

For hydrostatic test, the samples were filled with water and pressurised to 1.5 times above the maximum operating pressure. The pressure was held for hours to detect any leaks or pressure drops. Prior to post-test inspection, samples were allowed to drain and inspected for any signs of damage or deformation. Table 5 shows the details of hydrostatic test prior to bend inspection. The two sample bends as in welded were further tested for radiography examination after subjected to multiple heat treatments to evaluate the weld quality by generating an image using gamma rays as previously described by Sherar et al. (2022).

Table 5: Hydrostatic pressure test main settings

Description	Test Data	Unit
Bend Diameter	18	inches
Thickness before Hot Induction	25	mm
ASME Rating Class	1500	Pressure Class
Design Pressure (DP)	253.7	MPa
Hydrostatic Test Pressure (1.5 x DP)	380.55	MPa
Hydrostatic Test Medium	Water	-
Design Code	ASME B31.1	2020 Edition
Holding Time	4	hours

Figure 2 depicts a radiographic film was positioned on one side of the welded joint, and gamma rays were aimed at the other side using the panoramic single wall single image

(SWSI) technique per ASME Section V (ASME, 2019).

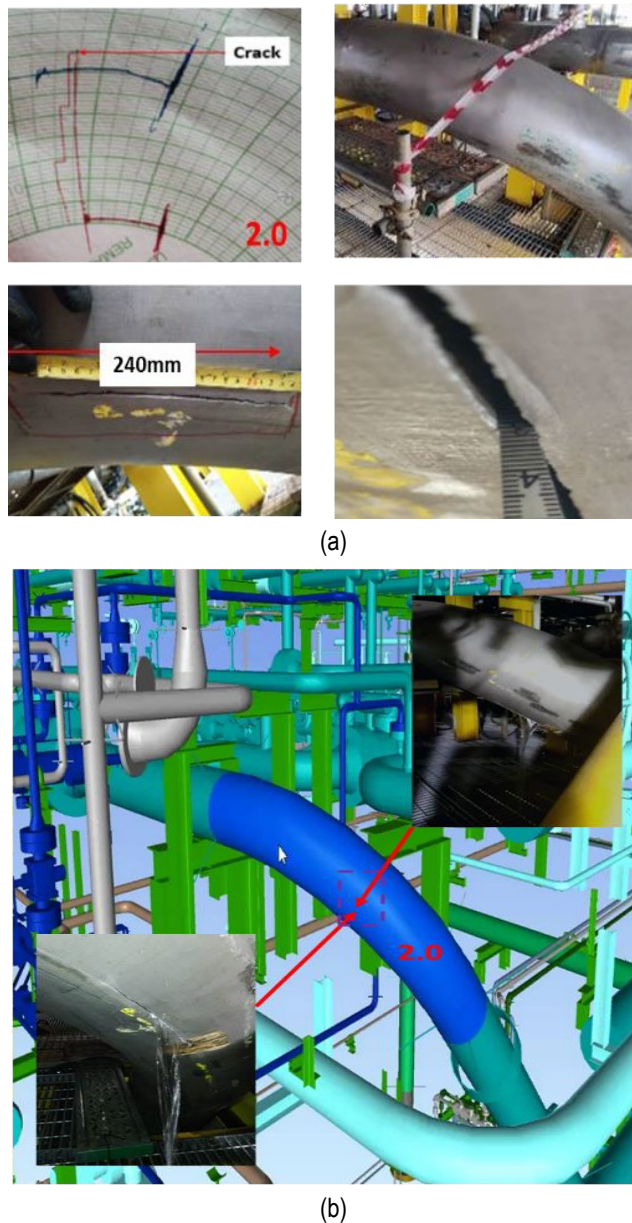


Figure 2: Sample of Test Bends (a) as in welded; (b) Radiographic examination using the panoramic single wall single image (SWSI) technique per ASME section V

3. RESULTS

3.1. Metallurgical analysis of austenite (γ) and ferrite (δ) contents

Distribution of austenite (γ) and ferrite (δ) was evaluated to determine the mechanical strength and corrosion resistance of super duplex stainless steel (SDSS). The microstructural composition of SDSS in the base metal (BM), heat-affected zone (HAZ) and weld metal (WM) was remarkably influenced by thermal and mechanical processes during welding and multiple heat treatments in the hot induction process for bend formation (Figure 3, Table 6). In the 1st heat cycle of SDSS raw material, the microstructure of base metal at the initial 1100 °C heat treatment exhibited ferrite and austenite contents of 44.00% and 57.00%, respectively. When SAW

welding was performed on the SDSS raw material at 1120 °C, the ferrite content was increased to 49.77%. Result indicates that higher temperature, such as 1120 °C, facilitate the formation of ferrite in the SDSS. Subsequent multiple heat treatments for Test Bend 1 at 1110 °C and Test Bend 2 at 1120 °C reduced the ferrite content to 44.90% and 41.10%, respectively, demonstrating the impact of specific heat treatments on phase stability.

Table 6: Metallurgical analysis of ferrite (δ) and austenite (γ) contents in different regions and conditions of SDSS. The analysis includes measurement taken at different post-processing in BM, HAZ and WM

Metallurgical Analysis			Raw Material	Hot Induction Bend	Test Bend 1	Test Bend 2
BM	Ferrite Content (%)	δ % - BM	44.00	46.00	44.90	41.10
	Austenite Content (%)	γ % - BM	57.00	54.00	55.10	58.90
HAZ	Ferrite Content (%)	δ % - HAZ	0.00	53.87	45.30	38.07
	Austenite Content (%)	γ % - HAZ	0.00	46.13	54.70	61.93
WM	Ferrite Content (%)	δ % - WM	0.00	44.50	48.70	34.47
	Austenite Content (%)	γ % - WM	0.00	55.50	51.30	65.53

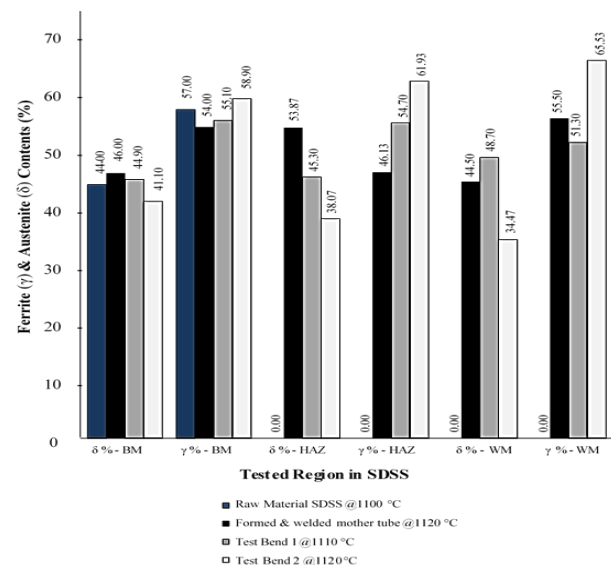


Figure 3: Comparison of ferrite (δ) and austenite (γ) contents in BM, HAZ and WM regions of SDSS

The heat-affected zone (HAZ) in the 1st heat cycle of 1100 °C, revealed no measurable ferrite or austenite content yet, during the post-hot induction in the 3rd heat cycle of 1120 °C, the ferrite content increased to 53.87% with austenite, 46.13%. Results indicated the microstructure of the SDSS raw material was attributed to thermal cycles associated with welding, causing a pronounced shift in phase balance. For both Test Bend 1 and Test Bend 2 that were heat treated at 1110 °C and 1120 °C, respectively, reduced ferrite content the lowest at 38.07% in the latter process. These changes

highlight the sensitivity of HAZ microstructure to thermal cycles and cooling rates, which are crucial for controlling the mechanical properties and corrosion resistance of SDSS.

For the weld metal (WM), the initial ferrite and austenite contents were not detectable in the 1st heat cycle at 1100 °C. After welding and heat treated at 1120 °C, the ferrite content was 44.50% and the austenite content was 55.50%. Test Bend 1 sample at 1110°C showed decrement in ferrite content to 36.80% and increment in austenite content to 63.20%. While Test Bend 2 processing at 1120 °C further reduced the ferrite content to 34.47%, whereas, the austenite content reached the highest at 65.53%.

3.2. Positive Material Identification (PMI) using X-ray Fluorescence (XRF)

Chemical composition by PMI using XRF method was carried out in three common alloying elements including, Chromium (Cr), Nickel (Ni), and Molybdenum (Mo) of SDSS (Figure 4). Measured elemental compositions of each material samples were evaluated and data indicated that Chromium (Cr) had consistent composition between 25.45% and 25.68% across various samples and conditions, suggesting presence of stainless steel or high-chromium alloys. The raw material of SDSS subjected to heat treatment at 1100 °C in the 1st heat cycle, had the lowest Nickel (Ni) composition, 6.82% compared to Test Bend 1 and Test Bend 2. This raw material is possibly austenitic stainless steel, which require higher Ni content to maintain its austenitic structure. Molybdenum (Mo) composition was almost the same, ranging in between 3.25% and 3.64% among all samples and conditions, indicating its role in enhancing corrosion resistance and strength.

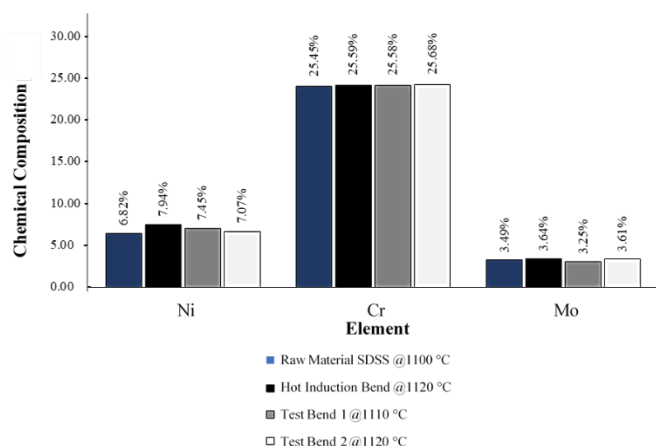


Figure 4: Chemical compositions via PMI technique. The key elements measured in this analysis include Chromium (Cr), Nickel (Ni) and Molybdenum (Mo)

3.3. Hardness analysis and Pitting Resistance Equivalent Number (PREN) by localized corrosion

Hardness analysis of super duplex stainless steel (SDSS) revealed distinct variations across the base material

(BM), heat-affected zone (HAZ), and weld metal (WM) under different processing conditions (Figure 5). The BM exhibited a hardness of 281 HV in the raw state after heat treatment at 1100 °C. For hot induction bends, Test Bend 1 processed at 1110 °C showed a hardness of 256 HV, while Test Bend 2 processed at 1120 °C recorded 295 HV. The HAZ displayed variable hardness values of 305 HV, 250 HV, and 294 HV, whereas the WM measured 298 HV, 223 HV, and 285 HV. These findings demonstrate that processing temperature has a significant influence on the hardness of SDSS, which is critical for ensuring its mechanical performance and corrosion resistance in demanding applications.

The pitting resistance equivalent number (PREN) was evaluated based on the chemical composition of SDSS processed at different temperatures (Table 7). The raw material processed at 1100 °C exhibited a PREN value of 41.4, indicating high pitting corrosion resistance. The hot induction bend processed at 1120 °C showed a slightly lower PREN value of 41.1. Meanwhile, Test Bend 1 processed at 1110 °C and Test Bend 2 processed at 1120 °C exhibited PREN values of 39.5 and 39.6, respectively. The relatively small variation in PREN values (39.5 – 41.4) indicates that the overall chemical composition of the SDSS remained stable during the processing conditions. Since PREN is primarily determined by alloying elements such as Cr, Mo, and N, the minor differences observed are more likely attributed to compositional variation rather than the direct influence of processing temperature.

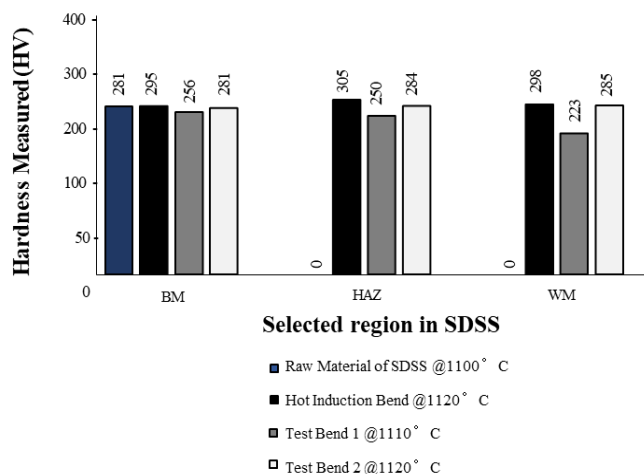


Figure 5: Hardness of SDSS tested at different regions of BM, HAZ and WM

Table 7: Pitting resistance equivalent number (PREN) at different temperature processing

Samples	Temperature (°C)	Processing / Heat Cycle	PREN
Raw Material SDSS	1110		41.4
Hot Induction Bend	1120		41.1
Test Bend 1	1110		39.5
Test Bend 2	1120		39.6

3.4. Microstructural changes at different temperature processing

To examine the microstructural changes in the BM, HAZ and WM under multiple heat cycle treatments and temperature processing, such ferrite (F) and austenite (A) phases were evaluated to investigate the effects of thermal and mechanical treatments of material properties in SDSS. The examination of micrographs labelled A observed distinct ferrite and austenite regions at 1100 °C in the raw material SDSS (Figure 6). Upon hot induction bend formation processed at 1120 °C observed a well-defined mixture of ferrite and austenite phases across BM, HAZ, and WM in the micrographs labelled B, B1 and B2. This can be explained by intricate intermixing patterns due to heat and mechanical work. Further effects of heat cycle treatments were tested on Test Bend 1 processed at 1110 °C with heating rates, 154 °C h⁻¹, exhibited refined microstructures with complex ferrite and austenite patterns in the micrographs C, C1 and C2 in the BM, HAZ and WM of SDSS. This demonstrates remarkable phase interaction thus, enhancing its mechanical properties due to the combined thermal and mechanical processing. For Test Bend 2 processed at 1120 °C, the micrographs labelled D, D1 and D2 showed a highly refined and patterned microstructure, with distinct regions of ferrite and austenite in the BM, HAZ and WM, highlighting the influence of thermal treatments on microstructural properties.

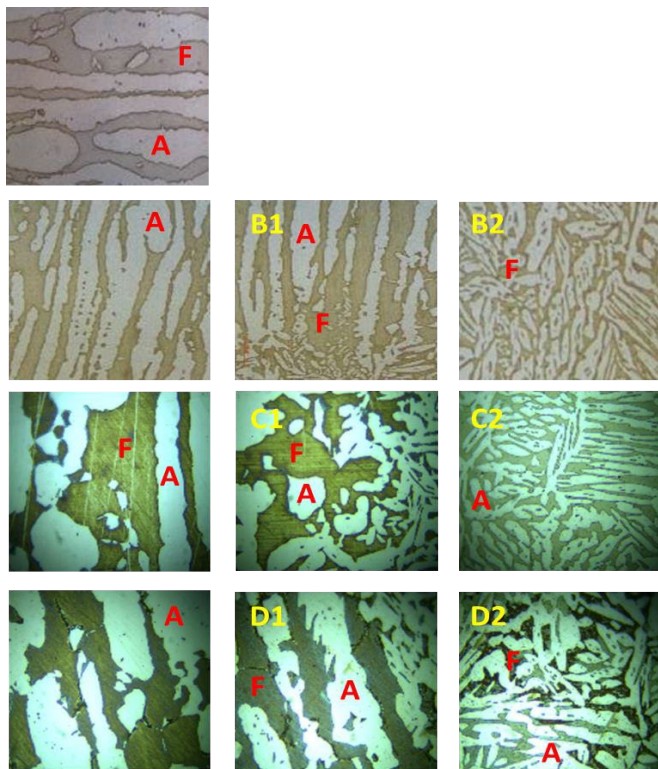


Figure 6: Microstructure of austenite (A) and ferrite (F) examined on SDSS exposed surface. Micrograph A refers to raw material of SDSS heat treated at 1100 °C; micrographs B, B1 and B2 refers to hot induction sample heat treated at 1120 °C; micrographs C, C1 and C2 refer to post-hot induction Test Bend 1 sample heat treated at 1110 °C; micrographs D, D1 and D2 refer to post-hot induction Test Bend 2 sample heat treated at 1120 °C

3.5. Hydrostatic test and radiography examination

Analysis of hydrostatic test followed by radiography examination conducted on two sample material bends, Test Bend 1 and Test Bend 2 made of ASTM A790/A928 UNS S32760 Class 1. Test Bend 1 was heat treated to 1110 °C with heating rate 154 °C h⁻¹ passed the pressure test at 381 MPa compared to the Test Bend 2 that was heat treated to 1120 °C with 141 °C h⁻¹ failed at 266 MPa or 75 of its maximum pressure. The results showed in Table 8 demonstrated Test Bend 1 performed well under high conditions than that Test Bend 2 due insufficient heat treatment thus, resulting to brittle fracture.

Table 8: Samples of post-hot induction bends tested for hydrostatic pressure and radiography examination

Material Selection	Samples	Hydrostatic Test	Failed Pressure	Type of Failure
ASTM A790/A928 UNS S32760 Class 1, NACE MR0175	Test Bend 1	Passed (381 MPa)	-	-
	Test Bend 2	Failed	266 MPa @ 75% pressure	Brittle fracture

The radiography examination performed after hydrostatic tests highlights the impact of different heat treatments on the integrity of welded components in the hot induction process for detection of inadequate or excessive heat treatment that potentially leading to defects and rejection (Figure 7). For Test Bend 1, processed at 1110 °C with heating rate of 154 °C h⁻¹ was accepted for inspection on welding quality after heat treatment, as indicated by the clear radiograph image. Conversely, for Test Bend 2, processed at 1120 °C with heating rate of 141 °C h⁻¹ initially showed a clear radiograph (see image A) yet, significant defects like crack was examined in the radiograph (see image B), leading to rejection for welding quality inspection after heat treatment.

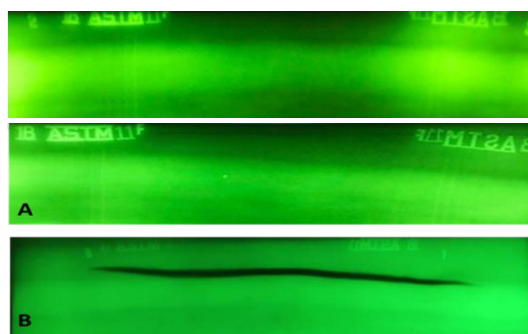


Figure 7: Radiography examination performed after hydrostatic test for Test Bend 1 and Test Bend 2 of A) before heat treatment and B) after heat treatment.

4. DISCUSSION

4.1. Examining the presence of intermetallic or sigma phases in the HAZ, BM, and WM after heat treatment

The examination of intermetallic or sigma (σ) phase in the heat-affected zone (HAZ), base material (BM), and weld metal (WM) regions after heat treatment for Test Bend 1 and Test Bend 2 is crucial to fully understand the integrity and performance of these components under operational conditions. Microstructural observations reveal the presence of ferrite (F) and austenite (A) phases, which are typically found in duplex stainless steel (SDSS), with no evidence of sigma (σ) phases (Figure 6) (Dubiel & Jakub, 2011).. This balanced mixture of austenite and ferrite, offering both mechanical strength and corrosion resistance (Lippold & Kotecki, 2005). The absence of sigma phase can be explained by the phase diagram in Fe-Cr system (Figure 8), which shows that sigma phase stability increases with chromium content and typically occurs below 800 °C (Khatak & Raj, 2002). If present, sigma phase would reduce toughness and corrosion resistance, leading to premature failure (Charles, 2008). Since Test Bend 1 and Test Bend 2 were heat treated at, 1110 °C and 1120 °C, respectively, the high temperatures applied during hot induction process are suppressing its formation in the HAZ, BM, and WM. This aligns with the previous study shown that solution annealing and quenching dissolve any sigma phase present, and rapid quenching prevents re-precipitation during cooling (Zhang et al., 2019). Thus, Figure 6 shows the applied heat treatments successfully maintained the duplex microstructure of ferrite and austenite, ensuring mechanical integrity and corrosion resistance without sigma phase formation. Nevertheless, further phase verification using advanced characterization techniques such as scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS) mapping and X-ray diffraction will be conducted in our future work to provide more confirmation of the phase constituents.

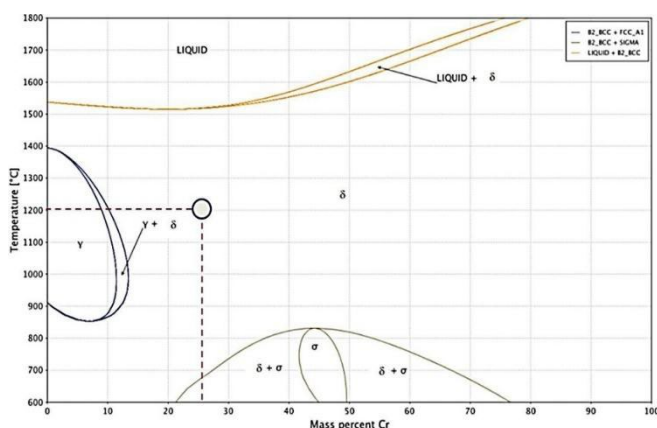


Figure 8: Phase diagram of Fe-Cr system (Dubiel & Jakub, 2011).

4.2. Impact of ferrite and sigma phase evolution during solution annealing on hot induction bending under hydrostatic test conditions

Multiple cycles of solution annealing during the hot induction process demonstrated the stabilization and distribution of delta ferrite (δ) in duplex stainless steel (SDSS). Delta ferrite (δ -) is a crucial phase in SDSS, contributing to mechanical strength and resistance to stress corrosion cracking. Microstructural analysis of Test Bend 1 and Test Bend 2 confirmed the presence of ferrite (F) and austenite (A) across the BM, HAZ, and WM regions (Figure 7). At 1110 °C, Test Bend 1 exhibited a well-distributed mixture of ferrite and austenite, resulting in superior mechanical performance. This was validated by the hydrostatic pressure test, where Test Bend 1 maintained structural integrity at 381 MPa (Table 8). In contrast, Test Bend 2, processed at 1120 °C, showed signs of brittleness in hardness testing and failed at 266 MPa.

The hydrostatic test results highlight the critical impact of expected ferrite phase imbalance or residual stresses induced during welding and heat treatment processes or possible formation of sigma phases on the structural integrity of SDSS. Test Bend 1, with higher delta ferrite (δ -) content and a sigma-free microstructure, demonstrated robust performance, while Test Bend 2, failed under pressure due to lower ferrite content probably, susceptible to residual stress during welding or possible formation of sigma phase. Nevertheless, further phase verification using advanced characterization techniques such as scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS) mapping, and X-ray diffraction (XRD) would provide confirmation to this intermetallic precipitation. These results highlight the importance of optimizing heat treatment parameters.

Higher annealing temperatures promote a more uniform distribution of delta ferrite (δ -), improving toughness and ductility, while insufficient heat treatment can lead to uneven ferrite distribution, reduced mechanical properties, and susceptibility to failure (Charles, 2008; Khatak & Raj, 2002). Furthermore, rapid cooling (quenching) followed by high-temperature annealing helps preserve the favorable ferrite distribution and prevents the formation of unwanted phases such as sigma or other intermetallics phase (Lippold & Kotecki, 2005). Thus, the superior performance of Test Bend 1 demonstrates that effective stabilization of delta ferrite (δ -) through optimized solution annealing directly enhances hydrostatic strength and resistance to brittle fracture in SDSS components.

5. CONCLUSION

In conclusion, the comparative evaluation of Test Bend 1 and Test Bend 2 demonstrates that optimized solution

annealing directly links ferrite content to hydrostatic performance in super duplex stainless steel (SDSS). Test Bend 1, processed at 1110 °C, achieved a uniform ferrite–austenite distribution with a sigma-free microstructure, enabling superior toughness and ductility and maintaining structural integrity at 381 MPa. In contrast, Test Bend 2, processed at 1120 °C, exhibited reduced ferrite content and susceptibility to sigma phase formation, resulting in brittleness and failure at 266 MPa. Overall, these findings confirm that higher annealing temperatures and controlled cooling stabilize delta ferrite (δ -), prevent sigma phase precipitation, and significantly enhance the mechanical reliability of SDSS components subjected to hot induction bending.

ACKNOWLEDGEMENT

This work is part of a research project supported by Faculty of Bioengineering and Technology, Universiti Malaysia Kelantan.

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