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RESEARCH ARTICLE - ENGINEERING

Corrosion Behavior in Different Media of Dissimilar Super Duplex Stainless Steel 2507 and Austenitic Stainless Steel 316 Welding by Using GTAW Process with Filler Type 316L

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Abstract

The Super duplex stainless steel is the best of the stainless steel types because duplex stainless steel contains two phases, ferritic and austenitic, which promote this alloy's mechanical and corrosion properties compared to other types. This study will investigate the corrosion behaviour of weld metal and base metals in acidic and salty media. At 20 C, hydrochloric acid (1M, 3M, and 5M) was studied beside sodium chloride NaCl (1 wt%, 3.5 wt%, and 5 wt%). The potentiostat test results show that the effect of HCl is more aggressive than NaCl in all cases, as HCl is a strong acid. The results showed the 316 base metal being the weakest area compared with others (2507 BM and W.M.). The microstructure has been checked before and after the corrosion test and pitting corrosion has been found in the 316 base metal only, while the weld metal and 2507 base metal surfaces were free of pitting influence. Due to the welding technique and using a cooper back strip, the microstructure shows minor grain growth in the heat-affected zones (HAZ) on both weld sides. The micro-hardness test revealed that the duplex stainless steel had a higher value than the weld metal and the 316-base metal. The weld metal had a minor increase over the base metal because of the migration of the elements like chromium and nickel.

Publisher: Middle Technical University

Keywords: Dissimilar Welding; Super Duplex Stainless Steel Welding; Corrosion Behaviour.

1. Introduction

The dissimilar metal weld is as demanding as the similar weld; however, the dissimilar weld is more complex than the similar weld due to the requirement of being applied in zones where some properties must be improved [1]. Ferritic-austenitic duplex stainless steel is one of the stainless steel types with a mixed microstructure that contains about equal amounts of ferrite and austenite. The duplex stainless steel microstructure combines properties of both phases that the combination of the two phases may even enhance; the ferrite provides high strength and resistance to stress corrosion cracking, while the austenite provides excellent ductility and general corrosion resistance. The significant advantage of duplex stainless steel is pitting and erosion resistance [2]. An alloy such as AISI 2507 (UNS S32750) is primarily used in aggressive corrosion environments where service temperatures are about or less than 350 C [3]. Super duplex stainless steels (SDSS) are steels with a pitting resistance equivalent number higher than (PREN = wt.%Cr+3.3 wt.%Mo+20 wt.%N) than 40. This has been made possible by high levels of chromium (25-27%), molybdenum (3-4.5%), and intermediate nitrogen mass fractions (0.25-0.28%). Super duplex stainless steels outperform ordinary duplex stainless steels in terms of strength and corrosion resistance, particularly local pitting resistance and stress corrosion cracking in high chloride environments [4]. The austenitic stainless-steel groups provide good oxidation and general corrosion resistance at temperatures up to 650 C. These types also provide good ductility and toughness in this temperature range. Corrosion and oxidation resistance is provided primarily by a high chromium content, generally higher than 16 wt% [5]. It is found that welding parameters (such as heat input) play an important role in retaining the microstructure and high corrosion resistance of weld metal and suggested an allowable range of heat input for super duplex stainless steel to maintain the phase ratio in the weld [6]. The GTAW is the standard process for welding super duplex stainless steel and austenitic stainless steel [2]. GTAW welding (Gas Tungsten Arc Welding) is a type of shielded metal arc welding. In gas tungsten arc welding, however, the electrode is only used to create the arc. Compared to the shielded metal-arc process, the electrode is not consumed during the welding. An intense arc is formed between the base metal and a tungsten electrode in the basic GTAW process [7] This welding provides a high-quality weld for stainless steel and non-ferrous alloys.

Compared with gas metal arc welding (GMAW), the many limitations of the GTAW process embody its inferior joint penetration. Its limitation to welding thick materials in a single pass and has poor tolerance to several material compositions together with cast-to-cast variations within the composition of certain impurities described [8]. Sodium chloride (NaCl) solution is one of the typical types of electro-conductive media, which may destroy the dense oxide layer formed by chromium (Cr) and nickel (Ni) in stainless steel (S.S.), which contains these elements. The Sodium chloride (NaCl) solution can also cause pitting corrosion and stress corrosion cracking (SCC). Wear corrosion behaviour was observed by the mutual effect of wear and metal corrosion behaviour under specific conditions. In general, wear could reduce the pitting potential of

Nomenclature & Symbols			
GTAW	Gas Tungsten Arc Welding	W.M.	Weld Metal
SDSS	Super Duplex Stainless Steel	HAZ	Heat-Affected Zone
ASS	Austenitic Stainless Steel	HCL	Hydrochloric Acid
B.M.	Base Metal	NACL	Sodium Chloride

metals and accelerate the corrosion rate [9]. Hydrochloric acid (HCl), is used in cleaning, pickling of steel structures, and descaling operations. These processes are generally accompanied by the actual loss of the metal to corrosion reaction. Hydrochloric acid (HCl), besides seawater, consider the most source of aggressive chloride ions and can donate free chloride ions (Cl^-) in an aqueous solution which causes material failure as a result of its attack on metals by corrosion. Chloride ions are strongly electronegative, therefore, very reactive with certain compounds and elements. This reactivity is part of its advantage, which is undermined by befouling where stainless steel is concerned. Although chloride is known to be the primary agent of pitting attack, it is impossible to establish a single critical chloride value for metals and alloys [10]. The aims of the research are, to study the corrosion bevahiour of each of the base and weld metals, compare the corrosion resistance between the base and weld metals, and evaluate the corrosion level according to the national associated for corrosion engineers (NACE), and study the effect of chemical composition on the corrosion resistance and forming of solidification mode.

2. Materials and Method

2.1. Material selection

Two plates have been welded together, AISI 2507 super duplex stainless steel and AISI 316 austenitic stainless steel, which has (a 10 mm) thickness. Low-carbon austenitic stainless steel filler types have been used ER316L. The chemical composition of both base and filler metals has been verified, and the results are shown in Table 1.

Table 1. Shows the chemical composition of the B.M.s and filler metal

Element Material	C%	Si%	Ni%	Cr%	P%	S%	Mo%	Mn%	N%	Cu%	Fe%
Nominal Chemical Composition of AISI 316	0.08	0.75	10-14	16-18	0.045	0.03	2-3	2.00	0.10		
Actual	0.04	0.60	10.29	17.01	0.026	0.018	2.05	1.53	0.04		BN
Nominal Chemical composition of AISI 2507	0.03	0.8	6-8	24-26	0.035	0.02	3-5	1.2	0.24-0.32	0.50	-
Actual	0.013	0.38	6.91	25.17	0.026	0.001	3.80	0.86	0.27	0.29	BN
ER316L Nominal	0.03	0.3-0.65	11-14	18-20	0.03	0.03	2.50	1-2.5		0.75	
ER316L Actual	0.015	0.92	10.04	18.4	0.029	0.026	2.13	1.36		0.72	BN

2.2. Welding procedure

Two (10 mm) plates (10 x 20 cm) were bevelled along with the length and aligned together, the fit-up details as mentioned in Fig. 1. An (8 mm) copper back strip was used. The mechanical fixtures had been used to minimize the distortion which may cause during welding. The welder was qualified according to ASE IX Ed.19, and the position of the weld was 1G. The cleaning methods between the welding passes were the stainless steel wire brush and minor grinding. The welding parameters have been mentioned in Table 2. And the below notes have been followed during welding:

- The maximum inter-pass temperature was 95 °C.
- The shielding gas flow rate was 14-16 L/Min.
- The cold pass (Second pass) heat input is less than the first pass by 20%.
- The back weld technique has been used to avoid the purging process.
- Whenever the welder stops welding, the welding current shall gradually decrease using the remote current control. The torch shall be held close to the welding pool until the molten metal is solidified and shielded.
- Post gas flow for 3 seconds before starting each pass or/and stop-start point.

Fig. 1. Beveling of plates before welding

Table 2. Welding parameters

No.	Pass Name	Inter pass temp. °C	Speed (cm/min)	Current (Amp.)	Voltage (Volt)	Heat Input K.J./cm	Shielding Gas
1	Root	88	7	85	12	8.7	Argon99.999%
2	Cold pass	78	9.2	85	10	5.55	Argon99.999%
3	Filling 1	87	10	87	12	6.26	Argon99.999%
4	Filling 2	90	11.2	88	12	5.62	Argon99.999%
5	Cap 1	89	6.2	82	10	7.9	Argon 9.999%
6	Cap 2	92	6.13	85	12	9.9	Argon99.999%
7	Cap 3	86	7	82	10	7	Argon 99.99%
9	Back weld	76	6.6	78	10	7	Argon 99.99%

2.3. Radiographic test

After the welding is completed, an X-Ray test is performed to verify the weld soundness before moving on to the mechanical tests. The film/structure type is D7, and the brand is AGFA. The exposure time / IQI type (B) / Voltage (180V) / Amp. and Technique (SWSA) were all done by ASME V - Article II

2.4. Tensile Test

The tensile test has been performed for the welding coupon to ensure the strength of the weld and base metals. The test was carried out according to ASME IX - (QW-621.1).

2.5. Microhardness test

For the cross-section of the macro-etched specimen, the Vickers microhardness test was performed by ASTM E92. As shown in Fig. 2, the hardness was measured every 1 mm from the base metal to the base metal, including the base metals, welds, and HAZs. The applied load was 300 g, and the indentation time was 15 seconds. The device brand is HTMV 2000M as shown in Fig. 3.

Fig. 2. Microhardness map of the cross-section weldment

Fig. 3. Vicker microhardness device used in the test

2.6. Microstructure preparation and evaluation

By using a wire-cutting machine, the specimens were prepared. Then prepared by a cold mounting, grinding the cross-section face with different emery paper grades, ASTM grit (180, 320, 400, 600, 800, 1000, 1200, and 1500), and polished with special cloth with various alumina suspensions (0.3 and 0.05 μm). Then the samples were cleaned with water and alcohol then dried by dry air. After polishing, the specimen shall become like a mirror and free from any minor scratch. The microstructure was evaluated in a cross-section of base metals and weld metal specimens of dissimilar welding using a "MEIJI" optical Microscope provided with a digital camera Fig. 4. The etching was done for SDSS and Austenitic stainless steel with a Tri-mixing solution (3 parts HCl + 2 parts HNO3+ 2 parts acetic acid). The macroscopic interpretation was made to reveal the fusion line and Heat Affected Zone (HAZ) and the weld metal.

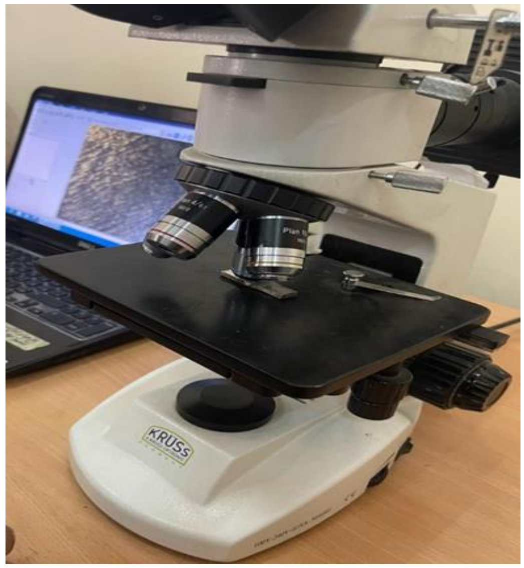

Fig. 4. The optical microscope used for microstructure assessment (KRUSS Brand)

3. Result and Discussion

3.1. Radiographic Test

The most common types of weld defects in the GTAW process are lack of fusion, porosity, cluster porosity, and tungsten inclusion; all of these defects are caused by insufficient welding techniques and poor weld shielding during the welding operation. The weld test was carried out by ASME V [11]. The film was AGFA, the RT technique was single shoot a single image, the film density was 2.2 when the requirement was (1.6-4), and the IQI type was SET-B because the plate thickness was greater than 10 mm. The test results showed that the weld was defect-free and acceptable, as shown in Fig. 5.

3.2. Microhardness

As shown in Fig. 6, microhardness tests were performed over the cross-section face of dissimilar weldments (316 BM, 316 HAZ, W.M. 316L, 2507 HAZ, and 2507 BM) for the welded plate. The unaffected B.M. of both materials recorded a microhardness of 275 HV for 2507 and 167 HV for 316. It was noticeable from the microhardness profile data that the microhardness results of the weld zone varied (average values of 175 HV for ER316L weld metal). This increase in weld hardness might be related to the solidification mechanism, morphology, and distribution of microconstituents in the resulting W.M. due to the dilution of the elements during the welding operation.

3.3. Tensile test

Fig. 7 depicts the results of a tensile test on the dissimilar weldment. The tensile specimen was fractured on the 316 BM side. Because the dissimilar weld joint was not to be less than the minimum tensile strength of the weaker base metal (AISI 316 austenitic stainless steel), and the fracture occurred on the 316 BM side, it was determined that the weld joint possessed adequate strength due to the migrated elements that come from the SDSS during welding, such as chromium and molybdenum. The fracture mode was ductile. The tensile strength of the specimen was 718. The minimum required tensile strength for 316 and 316L stainless steel is 515 and 485MPa, respectively. A bending test was also performed on the welding coupon.

3.4. Microstructure analysis

The microstructure examination was performed by using optical microscopy. The main aim of this examination was to verify the changes that occurred in the weld metal and HAZ microstructures and compare them with the base metals to discuss the filler material's role in the microstructure evolution. The examination was performed on the cross-section face of the welding joint. Figure 5. shows the optical microscope and macrographs of weld beads taken at suitable magnification; the examination covered the weld metal and HAZ and compared them to the unaffected B.M.; no defects were observed in either weld.

Low heat input and the inter-pass temperature has been used, as mentioned in Table 2. As well as a back copper strip with dimensions (40 x 20 x 8 mm) was used, which prevents severe grain growth in HAZ on both sides of the weld metal, as clearly shown in the below optical microstructure Fig. 8. As well as the microhardness reading which gave reading close to base metals reading in each side (super duplex and austenitic stainless steel). The concerns behind using back copper strips were to provide a suitable cooling rate and avoid the slow cooling cycle, dispersing the heat caused by welding and distributing the heat along the welding zone. And to minimize or avoid heat distortion, which is the major concern for stainless steel welding, especially duplex stainless steel, mechanical fixtures are used to fix the welding coupon as aligned. That caused minor distortion (as mentioned in ASME IX [12], only five degrees are accepted after welding of coupon).

Fig. 5. Radiographic test results of the welding coupon

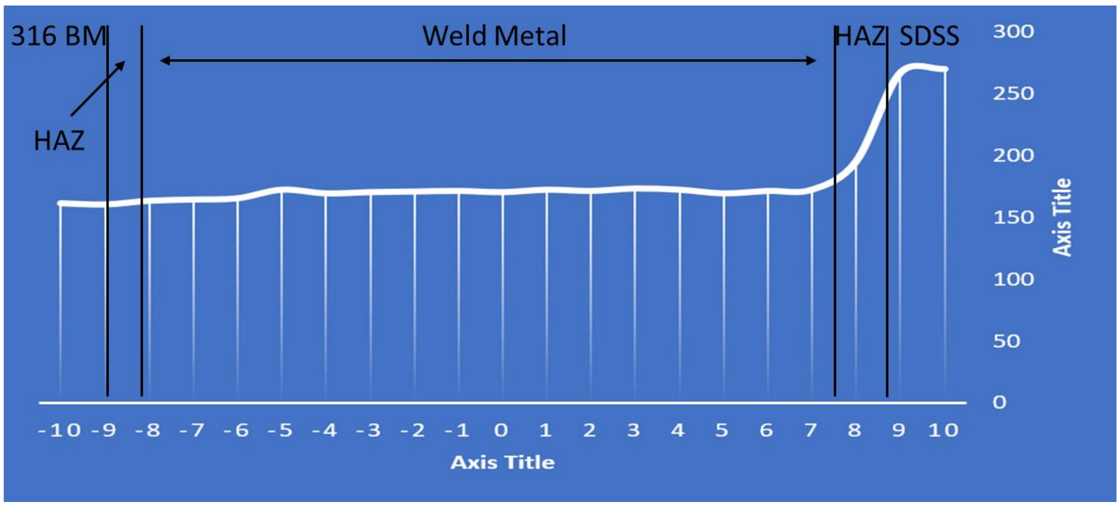

Fig. 6. Vickers microhardness reading

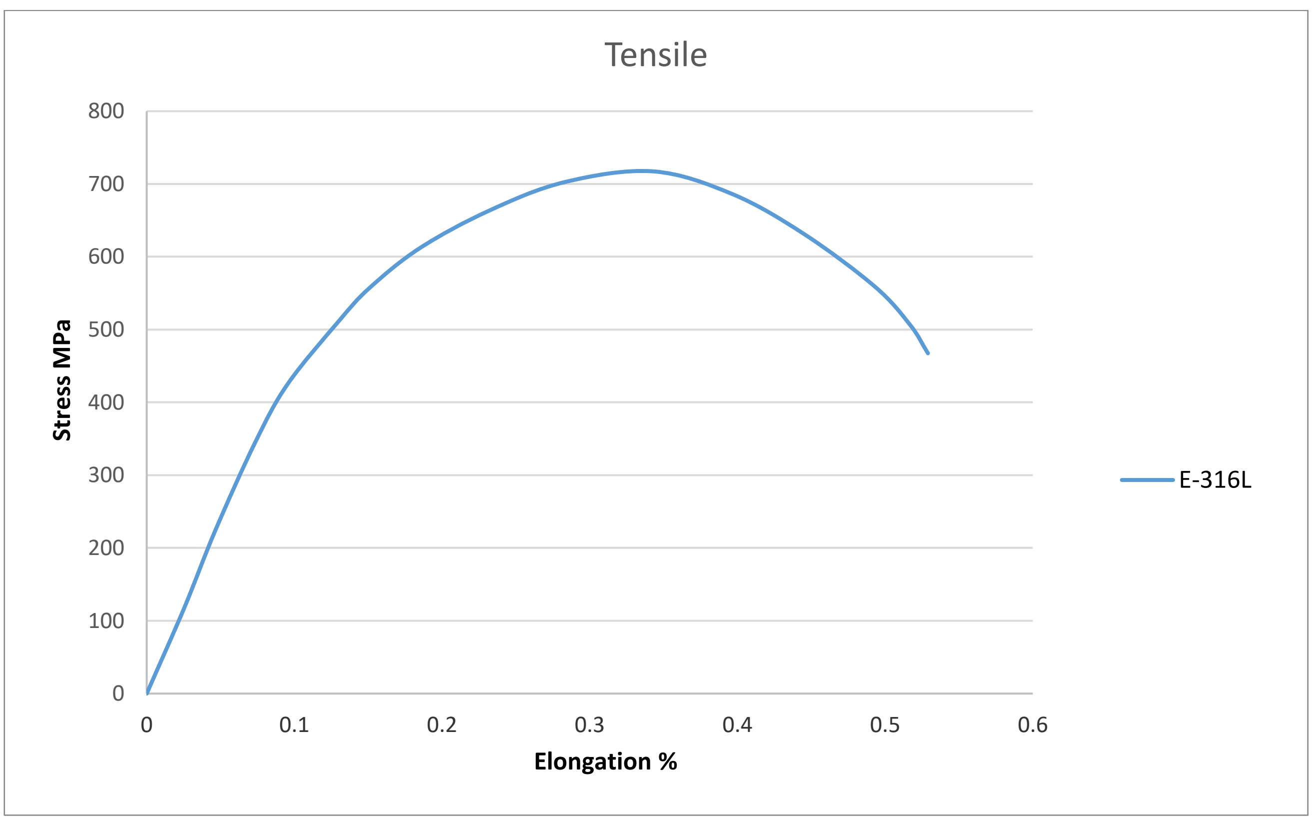

Fig. 7. The result of the tensile test

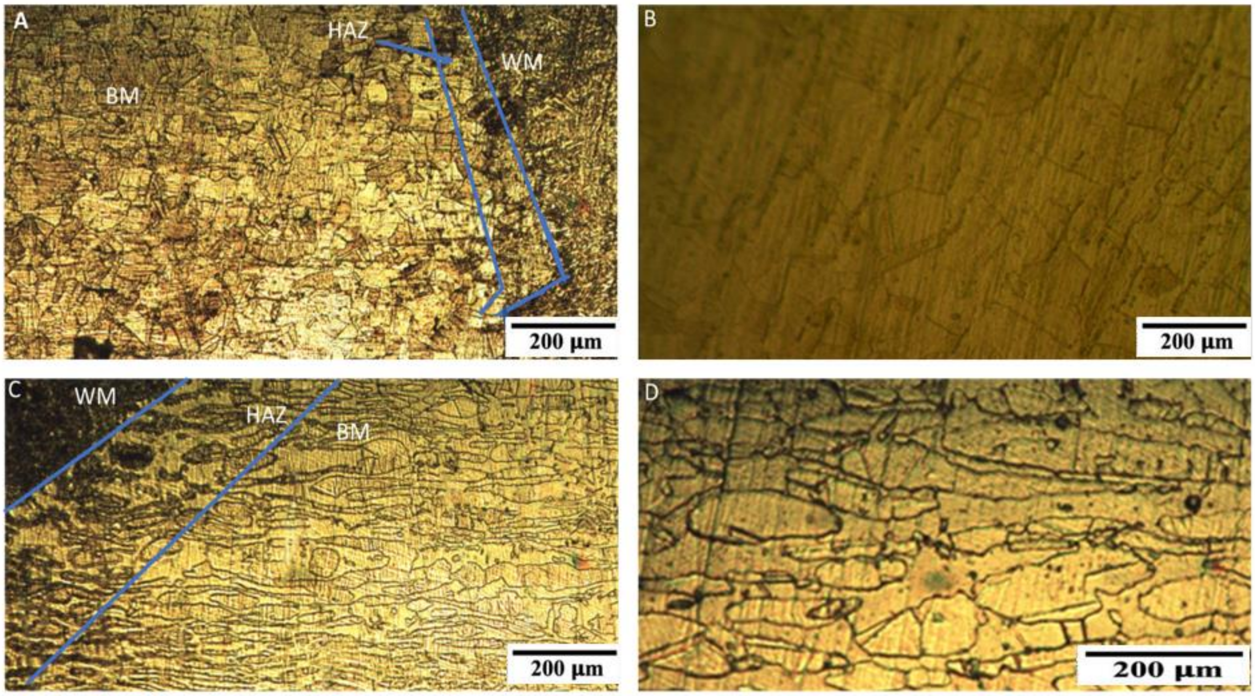

Fig. 8. Shows the microstructure photos; (A) Shows the weld W.M. and 316 BM included HAZ, (B) 316 BM, (C) Shows the W.M. and 2507 BM included HAZ, (D) 2507 SDSS BM

3.5. Corrosion performance

The potentiostat tests were conducted on the W.M.s and the B.M.s to compare the corrosion resistance ability between the weld zones on the one hand and between the weld area and the base metal on the other hand. The tests were performed by selecting several mediums and concentrations of salt and acid to monitor and analyze the behaviour of the W.M.s and B.M.s' corrosion resistance in each medium and concentration. The solutions used were NaCl with different concentrations (2, 3.5, 5 wt%) and HCl with different concentrations (1, 3, and 5 M). The tests were implemented in the following areas (2507 BM, 316 BM, and ER316L WM).

The test results showed a clear variation in the corrosion resistance in all corrosive media and concentrations. As a result, the corrosion rates were different. The weakest corrosion resistance region in all conditions was 316 BM, followed by ER316L WM. It is believed that this difference in corrosion resistance is due to the variation in the chemical composition between the base metals and filler metal, as shown in the chemical analysis in Table 3.

The ER316L weld metal contains a higher percentage of chromium than the 316 BM due to the dilution phenomenon and migration of Cr from SDSS BM to the W.M. area, which leads to higher resistance to corrosion in all media. As well as the presence of nitrogen and molybdenum alloying elements, which in turn give stability and help resist corrosion [13]. The corrosion resistance of the 2507 BM was the highest in all media and concentrations due to the chemical composition and the microstructure of the SDSS. All that has been shown in Figs. 9 and 10. below between media concentration and corrosion rates showed that the 316 BM resistance broke down while the SDSS was the best one in the carve stability. Furthermore, by comparing the corrosion resistance between the corrosive media, all the test regions showed higher resistance to NaCl than to HCl due to the difference in chloride concentration since the amount of chloride is higher in HCl than in NaCl. This is because of two reasons; the first is that HCl is a typical non-oxidizing strong acid, which can be completely dissociated into H+ and Cl [10] [14]. The other reason appears clearly by unifying the unit concentrations and converting them all by molarity ratio as shown below:

NaCl 2 wt% = 0.34 M
NaCl 3.5 wt% = 0.6 M
NaCl 5 wt% = 0.855 M

Table 3. Chemical composition of the weld metal and base metal

316 (B.M.)	Weld metal	2507 (B.M.)	Elements %
0.06	0.06	0.013	C
17.01	18	25.17	Cr
10.29	11	6.91	Ni
2.05	2.51	3.80	Mo
1.53	1.49	0.86	Mn
0.06	0.6	0.38	Si

The surfaces after corrosion were verified by the microscope, and it was found that only the 316 BM got pitting corrosion by all HCl concentrations and 5% NaCl, as shown in Fig. 11. And the Table 4. Demonstrate the corrosion rate of each zone in different concentrations.

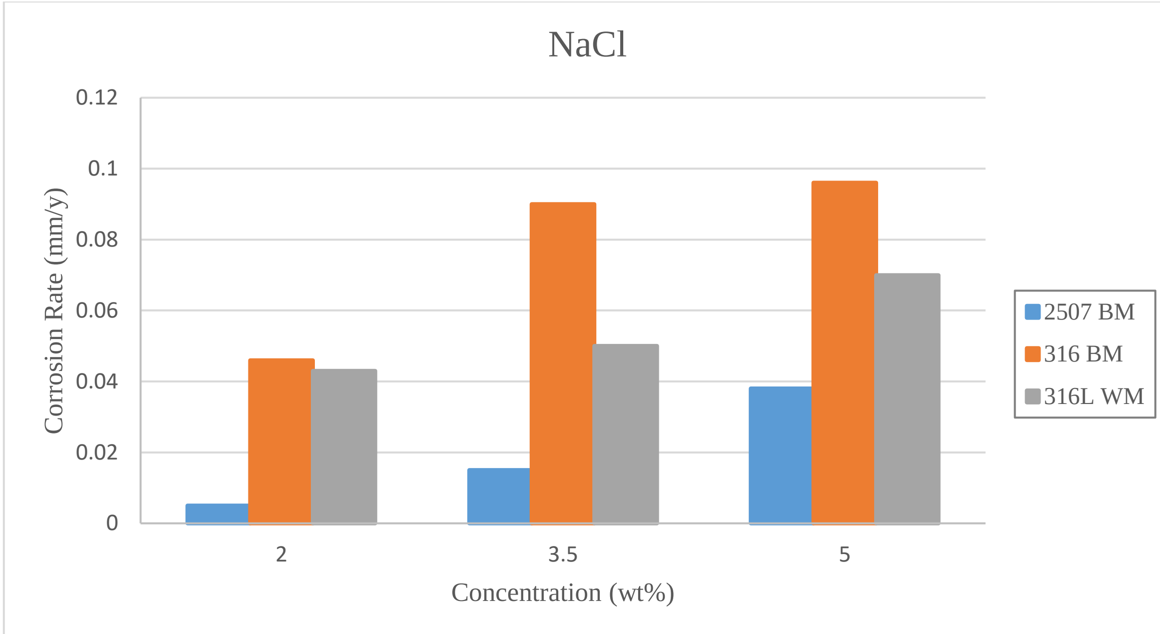

Fig. 9. The relation between the media concentrations and corrosion rates of NaCl

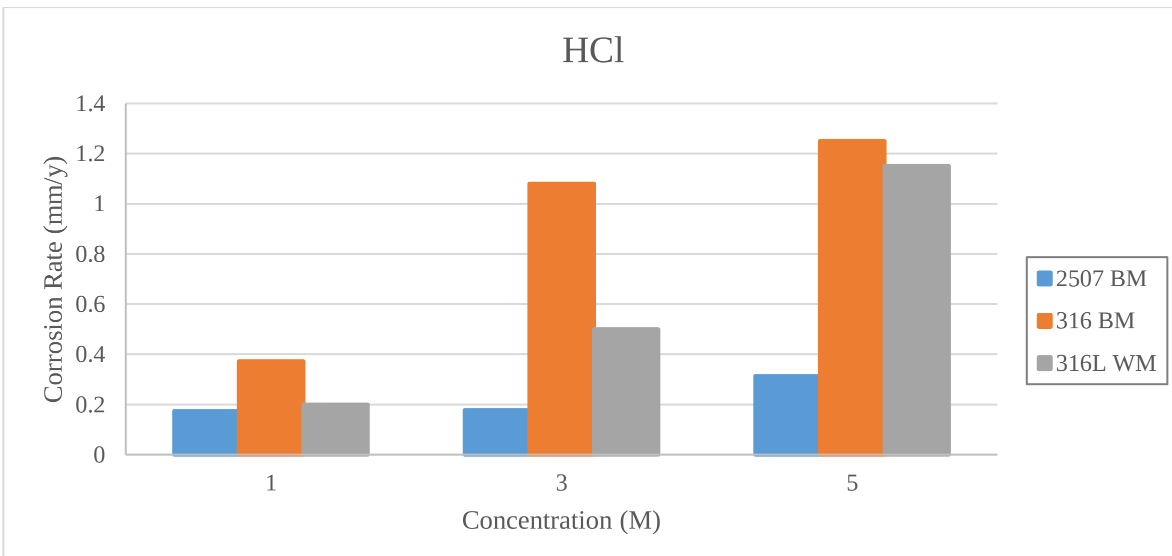

Fig. 10. The relation between the media concentrations and corrosion rates of HCl

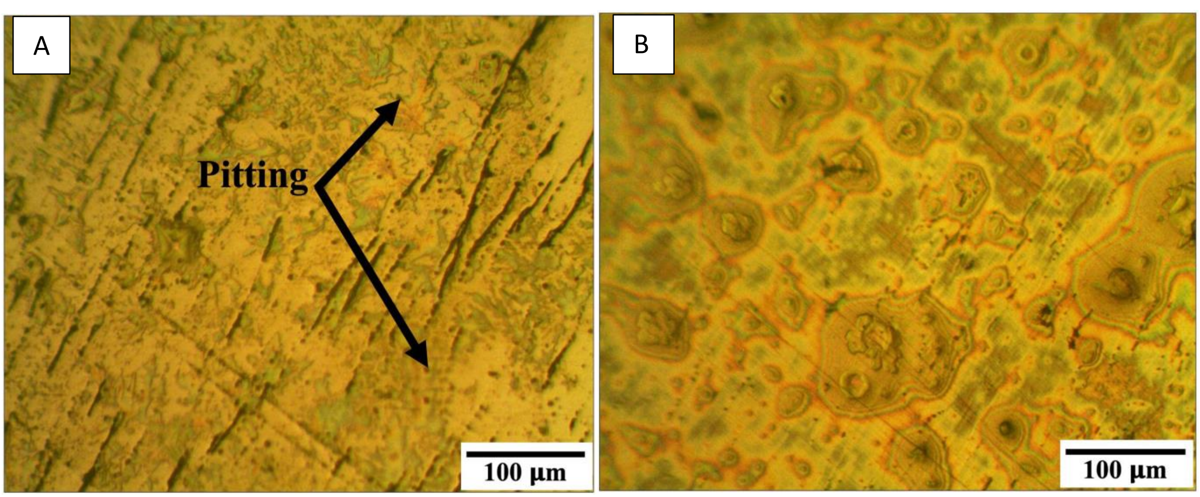

Fig. 11. (A) 316 BM after corrosion test of HCl 5M, (B) 316 BM after corrosion test of HCl 3M

Table 4. The results of potentiostat corrosion tests (A= 0.823 cm^2)

No.	Tested Area	Icor (mA./cm2)	Ecor (v)	Corrosion rate (mm/y)
			HCl 1M	
1	316 BM	33.8	-0.341	0.372
2	2507 BM	15.8	-0.313	0.174
3	316L WM	18.8	-0.363	0.2
			HCl 3M	
1	316 BM	98.4	-0.373	1.08
2	2507 BM	16.2	-0.369	0.178
3	316L WM	44.7	-0.381	0.5
			HCl 5M	
1	316 BM	107.2	-0.366	1.25
2	2507 BM	28.5	-0.346	0.313
3	316L WM	106	-0.326	1.15
			NaCLl2 wt%	
1	316 BM	4	-0.358	0.046
2	2507 BM	0.507	-0.267	0.005
3	316L WM	3.8	-0.393	0.043
			NaCl 3.5 wt%	
1	316 BM	8.21	-0.393	0.09
2	2507 BM	1.43	-0.368	0.015
3	316L WM	4.8	-0.528	0.05
			NaCl 5 wt%	
1	316 BM	8.7	-0.568	0.096
2	2507 BM	3.9	-0.387	0.038
3	316L W.M.	6	-0.409	0.07

4. Conclusion

- The filler metal ER316L is suitable for welding dissimilar metals SDSS AISI 2507 And ASS AISI 316.
- The hardness property is promoted in the weld metal than the nominal of the filler metal. That referred to the welding technique used during welding and element migration from duplex stainless steel to weld metal like chromium and molybdenum.
- The minimized heat input reduces or prevents grain growth in HAZ on both sides, as the low heat input did not give enough time for grain growth.
- Using a back copper strip minimizes the heat distortion caused by welding due the heat dispersion.
- The weld metal has given corrosion resistance better than the 316 base metal.
- The super duplex stainless steel was higher in corrosion resistance in all media.

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