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Mechanical and corrosion behaviour of conventional and high-speed remote scanner laser welding for duplex stainless steel: A comparative study

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Abstract. High-speed remote scanner laser-welding is a relatively new technique that is being tried out at the Mittweida Laser institute to weld stainless steel sheets of high thicknesses; the material used was (1.4462) 8mm thick. For comparison, the material was welded also by gas tungsten arc welding (GTAW) or TIG. The welding processes were evaluated by several testing techniques; mechanical testing using (tensile testing and hardness). Optical microscopy was employed to investigate the phase changes and weld defects inside the material. Scanning electron Microscope investigated the grain size before and after weld with the precipitate. Electrochemical corrosion testing was used to evaluate the corrosion behaviour of the weld zone. For each experiment, base metal and heat affected zone (HAZ) have been selected. Microstructure investigation of HAZ revealed the formation of finer microstructures with different grain boundaries due to the melting and the resolidification of the base metal and extensive microstructure changes inside the materials. In comparison to TIG, many weld defects were observed and carbide precipitations formed at the grain boundaries. Hardness measurements revealed that hardness increases towards the centre of both laser and TIG. Tensile testing revealed that the weld has the potential to have very high strength approaching that of the original material, particularly for laser welding. Measuring corrosion rates shows that the welded material is more susceptible to corrosion and to pitting, the pitting potential was estimated reflecting higher pitting resistance for base metal than laser and TIG weld respectively, thus can be explained due to the formation of precipitates of carbide and ferrite particularly for TIG Weldament.

Keywords. Remote laser-welding, Duplex stainless steel 1.4462, corrosion behaviour of welded joints, HAZ, TIG welding, electrochemical corrosion, Scanning electron microscope (SEM), energy-dispersive X-ray (EDX), Open circuit potential (OCP)

1. Introduction

Some of Metals which has been being used for more than a decade's like Iron, Stainless steel is a relatively new to the materials science world, it has been first used for century. This may appear to be difficult to accept at first, given the omnipresence of the metal in every feature of present day life, yet this is essentially a demonstration of what is important about stainless steel. The metal has remarkable contribution which revolutionized the modern world, and has found applications in almost every



manufacturing sector, from healthcare and catering equipment, the automotive, construction industries to Oil and gas industry [1]

Duplex Stainless steel are the stainless steel with two-phase microstructure comprising of around half ferrite(BCC) and half austenite(FCC) and this phase balance is known to decide the corrosion opposition of this duplex stainless steel 1.4462.1 As in nature of this material[2], the balance among ferrite and austenite in Heat affected zone of the welds changes from that in the base metal because of welding heat distortion and gradually quick cooling and therefore HAZ will have high ferrite content which may be subjected to chloride pitting and chloride stress corrosion cracking. Henceforth, when this kind of steel is connected to welded segments, ferrite estimation is frequently required to welding system capability and the run of the indicated ferrite content territory is 30-65% . Furthermore, they are weldable as long as you take care to use the right **heat** input and welding consumables. Duplex stainless steel is also magnetic with moderate formability [3,4].

Remote scanner laser welding which is a high-speed system works as multiplier of laser stitch to make weld combined with very short un countable welding times like Tungsten Inert Gas (TIG). To get good remote welding system, the presence of high performance laser with power in excess of 3 Kw in addition to high beam quality is a must. This which makes the direction of auto-motive industry to use this type of welding in order to increase the productivity, strength and new designs to be implemented [5,6]. In the auto-motive industry the laser technology was implemented to increase the productivity, strength of constructions and new designs [8,9]. First applications with long welds on the vehicle body are currently trailed by replacement of resistive spot welds by short laser welded fastens with the benefit of shorter preparing times. [12,13].

Keyhole welding or deep penetration welding is a procedure in which the laser beam penetrates partially or completely through a specimen forming a keyhole; so as the laser beam progresses, molten metal fills in behind the hole to form the weld bead; which results in a homogenous weld. At the point when high laser beam power densities are accomplished, deep- penetration fusion welding is cultivated by a keyhole energy transfer mechanism. Laser beam welding gives Weldament less Heat affected zone(HAZ) and less distortion in contrasting with traditional tungsten inert gas (TIG) welding which gives an important solution for welding critical joints, and for the circumstances where quality and purity welds are required it creates a high-virtue weld contrasted, which is pivotal in huge number of applications. The cost of TIG welding is very moderate and affordable. However, the process has a low deposition rate and whenever performed inappropriately, continuations, inclusions, overheating of specimen can make products to become defective [13].

The main objective of dealing with the research mechanical properties and corrosion resistance of laser-welded stainless steels and conventional tungsten inert gas welded stainless steel that it may be deteriorated due to micro-segregation which attacked during the corrosion test due to the weld zone, presence of porosities, unfavorable phase content, micro-fissures, solidification cracking and loss of materials by vaporization. So, to see the effect of these microstructure changes on the material, these tests are performed:



Figure 1 Working area of the laser scanner system, (Courtesy of Trumpf Laser technique)

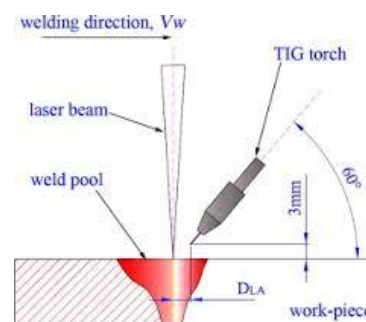


Figure 2 Key hole penetration between Laser and TIG weld

2. Experimental procedure

The chemical Composition of the material shown in the table1 1.4462 (318LN) Duplex stainless steel (D.S.S)[14].

Table1. Chemical composition (wt. %) of the stainless steel 1.4462 (318LN) used in this study.

Code		C	Si	Mn	P	S	Cr	Mo	Ni	Cu	N
EN(DIN)	AISI										
1.4462	318LN	≤0.03	≤1.0	≤2.0	≤0.035	≤0.015	21.0-23.0	2.50-3.50	4.50-6.50	-	0.10-0.22

2.1. Material preparation

The duplex stainless steel received as 400 mm x 100 mm plates; so to make work pieces of acceptable dimensions, they must be cut cautiously in order not to change the metallurgical structure of the material. A reasonable cut-off wheel (50A25) was utilized under water-cooling to prevent changes in metallurgical structure and the sheets were fixed mechanically précised to give a straight edge appropriate to welding. For the tensile test, 100 mm x 25 mm pieces were cut and the welding edges were set up by removing the rough edges to give us with reasonable edges which help in giving deep welding penetration and minimum distortion. Then after setting up these pieces, welding was done to give us pieces around 200 mm x 25 mm dimensions. For duplex stainless steel 1.4462 8mm thickness 4 welded specimens (2 remote scanner laser welding and 2 Tungsten inert gas welding) 2 un-welded specimens were tested for comparison.

The welding of duplex stainless steel 1.4462(318LN) sheets of such large thicknesses 8mm was a hard technique. Literature was not helpful in giving us precise weld speed to give out an especially strong weld. Therefore, we worked on recommended weld speeds from references, and after a few preliminaries, we used a weld speed that gave us a weld that is good upon visual investigation. The welding equipment used a high-power of about 3kW (Ytterbium Fibre Remote Scanner Laser); the shielding gas used was Argon. The materials were clamped in place mechanically to reduce thermal distortion of the material due to welding. No filler metals were used. Therefore, to guarantee that we obtain high-quality welds in high thicknesses, the welding is done by keyhole welding technique

For Tungsten inert gas welding (TIG) equipment was used a high power up to 3KW and direct current(DC) of 80 amperes with a shielding gas of pure Argon at pressure of 5 Bar which is flowed also to remove atmospheric contamination and protect the filler metal with the weld zone from impurities. There is only one type of weld used for the 1.4462(318LN) stainless steel with process of counter welding and inside with using a filler metal Microstructure: Austenite with 7-9% ferrite. Typical ferrite number is 6 Flux Color: White-Grey; with a chemical analysis table 2[13]

Table 2. TIG filler metal chemical analysis

C	Mn	Si	S	P	Cr	Ni	Mo	Cu	Fe
0.018	0.9	0.75	0.01	0.02	0.19	0.12	2.65	0.1	balance

The Welding speeds for Stainless Steel 1.4462(318LN) for Thickness 8mm as follow:

- i) Remote Scanner laser Parameters :2.5m/min
- ii) Tungsten inert gas (TIG) parameters :8mm/min

2.2. Microstructure investigation

The laser-welded and TIG welded specimens were sectioned, polished and etched. The microstructure and phases in the weld line were analysed by Zeiss Axioscope 7 optical microscopy. The weld defects inside the weld profile were also examined to determine if improvements can be made inside the weld in the future which will minimize weld defects, such as incomplete penetration, porosity and cracking. Also the size of the grains changed from the base metal to the heat affected zone (HAZ) to the weld zone which totally different for types of weld (Laser-TIG). Using EVO-MA15 and TESCAN-Mira 3

for Scanning electron microscope (SEM) to give more detailed information about grain size and behaviour in weld zone, energy-dispersive X-ray (EDX) to trace the important elements.,

2.3. Mechanical testing

i. Micro hardness test

The Vickers micro hardness was used to attain the hardness of the specimens across line path according to (ASTM E384-99)[14] standard done through the top and side surfaces of the specimen of the laser-welded specimens and the TIG welded specimens as shown in fig.3 The load applied was 300 g and the loading time was 15 s by equipment Buehler Micromet 5100 series. All the specimens were ground to provide a smooth surface for the test. In order to get the precise results; the sample has been handled around the weld line from extreme left to the extreme right passing by the weld line; as well as the heat affected zone HAZ, measurements are also taken from the top and the surface of the specimen as shown schematically on Figure 3

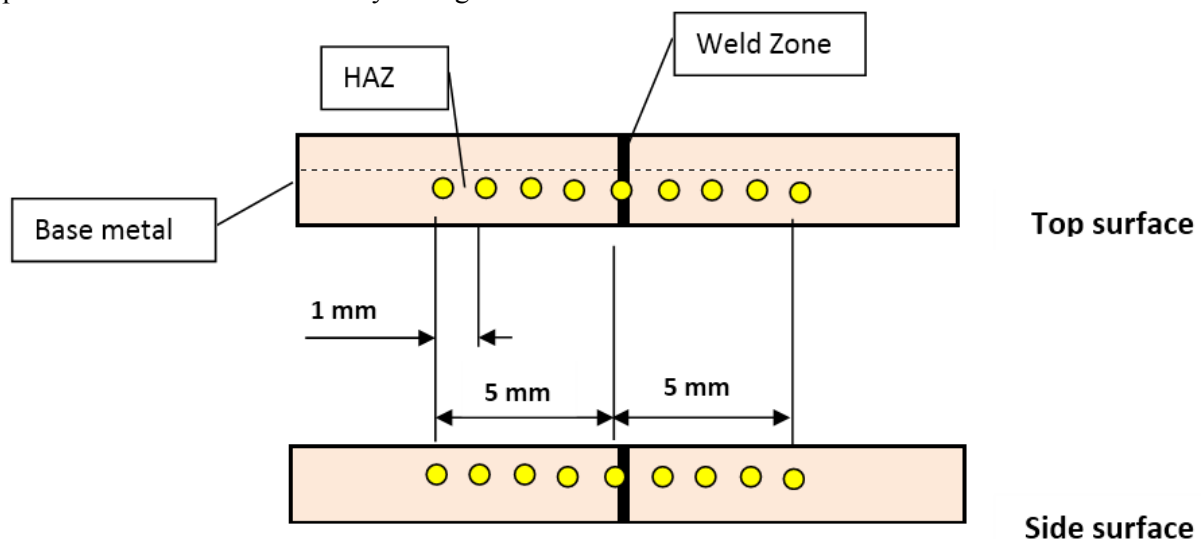


Figure 3 Schematic for specimen shown Base metal-HAZ-Weld zone

ii. Tensile test

Tensile tests on welded and unwelded specimens were performed to observe the mechanical performance of the welded specimens by equipment zwick Roell Z100. The observed property in this test was the Ultimate Tensile Strength [15]. To obtain the geometry that was according to ASTM E8 Standard [16] the material was machined using CNC machining. The tensile test was carried out at Strain rate from 0% to failure = 5 mm/min.

iii. Ferrite content

Ferrite testing is accurate way to measure delta ferrite content in duplex stainless steel. When ferrite content is too high, stainless steel can lose ductility, toughness, and corrosion resistance – especially at high temperatures. If ferrite content is too low, stainless steel welds become susceptible to hot cracking or solidification cracks. For 1.4462 Duplex stainless steel specimen is well prepared surface after grinding and smooth polishing passing with the indenter probing through all the specimen starting with the base metal moving to the heat affected zone followed by the weld zone same on the other side of the weld zone to complete the path pattern through the top and side surface of the specimen. By equipment Fischer MP30 Feritscope by moving speed 0.5mm according to ASTM A799 / A799M [17]

2.4. Corrosion behaviour:

Electrochemical test done several number of experiments done that is related to stainless steel Weldment, to examine the effects of such high-speed welding and tungsten inert gas welding on the corrosion behaviour of the duplex Stainless steel 1.4462 [18]. The instrument used was a PGZ-100 Volta lab potentiostat. The specimen is covered with an epoxy cold mounted and left to harden. After removing from the mould, the specimen is grinded using (180-1200) SiC wet grinding paper, then polished up to 1 μm and finally dried and become ready for the test [19,20]. Electrochemical measurements of the base metal and the welded materials (Laser welded-TIG welded) was carried out in 3.5% NaCl solution, all potentials are measured relative to a saturated calomel electrode (SCE) at 25°C.

- Open-circuit potential (OCP) for every specimen, the OCP was performed for 90 minutes.
- Potential cyclic voltammetry (PCV) is performed (-300 to 700) mV below the OCP of the material until a suitable voltage with a scan rate of 2 mV/s for 1 Cycle.
- The corrosion rate is obtained using the Tafel method.

3. Results and discussion

i. Optical microscope results

Observing that there are different types of defects were happening due to welding as shown in fig.4 and fig.5 for laser welded and TIG welded specimens respectively. The most common defect observed is incomplete penetration and under fill of the weld bead that happen to the laser welded specimen this might be from reflection of the incoming laser off the surface of the stainless steel same for the TIG happened due to the filler rod melting. In order to decrease these defects; then decrease the reflectivity of the laser off the surface of the material. It can be obtained by coating of the surface to absorb and decrease the surface reflection. It has also seen in fig.6,7 in the TIG sample; the inclusions happened on the surface due to the slag of the sample when trying to avoid forming pockets to trap the slag. [21] Figures 8,9 present the difference in the HAZ and the base metal for the elongated grains.

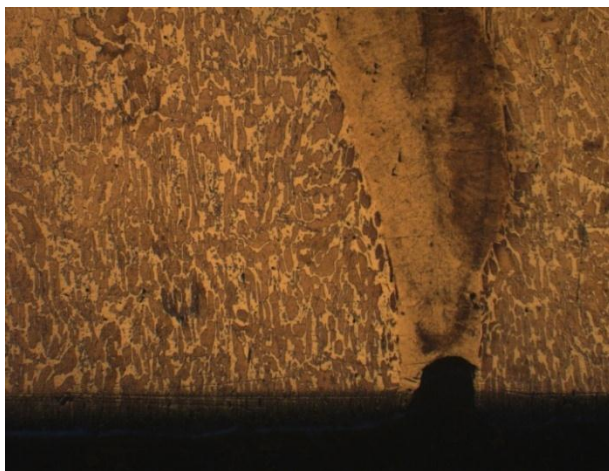


Figure 4-1.4462 8mm thickness Laser weld in complete penetration defect

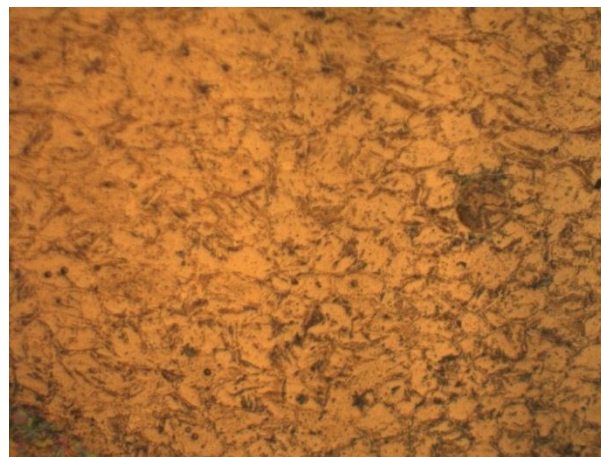


Figure 5- 1.4462 8mm thickness TIG weld inclusion defect

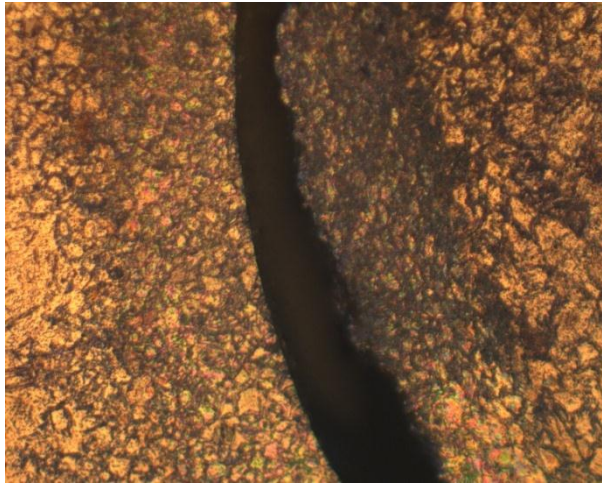


Figure 6-1.4462 8mm thickness TIG weld under fill

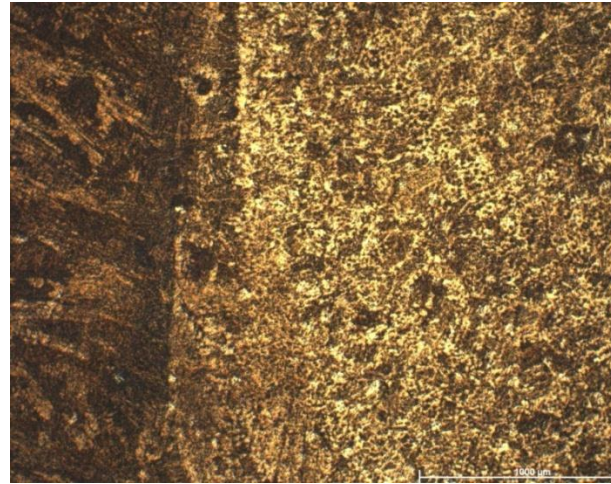


Figure 7- 1.4462 Tig weld line difference in grain size

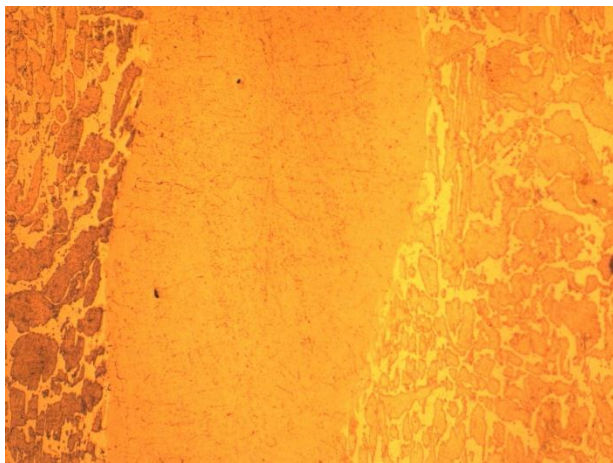


Figure 8-1.4462 difference of grains at different zones



Figure 9- 1.4462 Laser weld around the weld line

ii. Micro structure investigation using electron microscope

Clearly from scanning electron microscope The grain size of this material was very clear in fig.10 due to the use of detector large-field detector (LFD) using TESCAN-Mira3 to show the phases. In figure 11,12 by using EVO-MA15 the help of magnification we can see its very small and may be this explains why the hardness at this region will be very high. these black spots are carbides but after making the EDX and comparing between the HAZ and base metal or even though change in percentage of the iron or chromium so this means that there is no precipitation and the heat generated from the remote scanner welding just make Recrystallization of the grains. In D.S.S there is two phases δ ferrite and γ austenite both are seen clearly. The dark regions are the ferrite where the light ones are the austenite

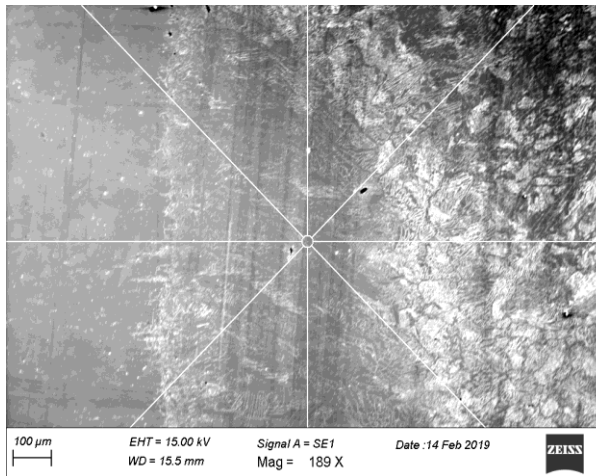


Figure 10- 3 1.4462 D.S.S Tig weld zone

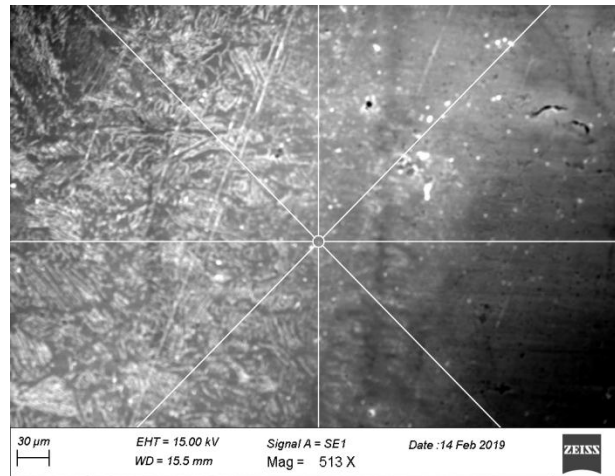


Figure 11- 1.4462 D.S.S Tig weld HAZ

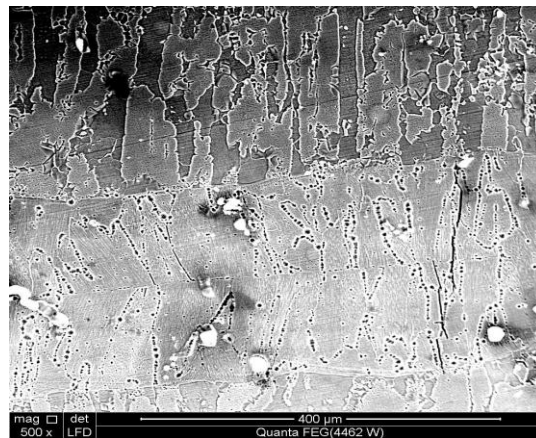


Figure12- 1.4462 D.S.S laser weld zone

iii. Energy-dispersive X-ray (EDX):

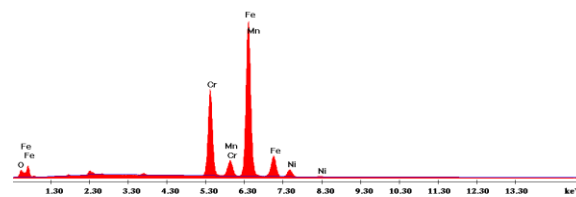


Figure 13 EDX of 1.4462 laser weld in HAZ

Table3. is more cleared by figure13 representing the Energy-dispersive X-ray (EDX) inside the HAZ

Element	Wt%	At%	k-ratio	Z	A	F
O K	2.88	9.24	0.0123	1.1408	0.3723	1.0040
Cr k	22.89	22.63	2.2640	0.8911	0.9858	1.1801
Mn k	2.14	2.00	0.0209	0.9750	0.9962	1.0056
Fe k	67.49	62.11	0.6315	0.--9955	0.9334	1.0070
Ni k	4.60	4.02	0.0381	1.0156	0.8156	1.000
Total	100.00	100.00				

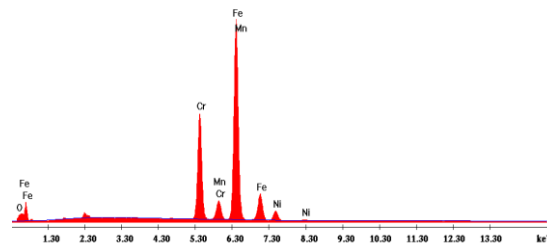


Figure 14 EDX of 1.4462 laser weld Out HAZ

Table 4. is more cleared by figure14 representing the Energy-dispersive X-ray (EDX) away from the HAZ

Element	Wt%	At%	k-ratio	Z	A	F
O K	2.37	7.71	0.0101	1.1417	0.3707	1.0041
Cr k	22.94	22.94	0.2647	0.9919	0.9854	1.1806
Mn k	1.99	1.88	0.0195	0.9758	0.9959	1.0059
Fe k	67.80	63.13	0.6349	0.9963	0.9330	1.0074
Ni k	4.90	4.34	0.0406	1.0164	0.8151	1.0000
Total	100.00	100.00				

iv. Micro hardness test

Hardness test is a general path pattern where the hardness increases towards the weld line zone until it is at its most extreme at the centre of weld, as shown in top surface figures 15 and 16 and for side surface figures 17 and 18. The phenomena may be illuminated by a reason behind welded duplex stainless steel 1.4462. The fundamental reason might be a direct result of the grain refinement and the development of smaller grains as in the small grain, no dislocation can travel more than one unit of distance not like the grain growth area. This type of strengthening is known as Hall-Patch strengthening, which implies more grain boundaries. These grain boundaries give more strength to the material which causes an increase of the hardness. For Duplex stainless steel 1.4462 (318LN) the hardness for the welded specimens were much higher than the unwelded. There is a great increase in the TIG weld over the laser weld compared to the unwelded. Since, a very large increase in the ferrite is observed, where the primary phase becomes the ferrite phase, so a very large increase in the hardness is observed reaching as much as 54% more than the original hardness as seen in Figure 19. Comparison with literature results for the unwelded sample which is 293 HV close to the result in figure 19. It is 318 HV for TIG weld compared to the 310 for laser welded sample which indicates the more over the unwelded sample.

Hardness measurements on the top Surface

The to and side surfaces mark the to wide surface where the weld line and the welding zone are clearly presented and checked, while the side surface clears the key hole depth and the weldability state when checked and tested

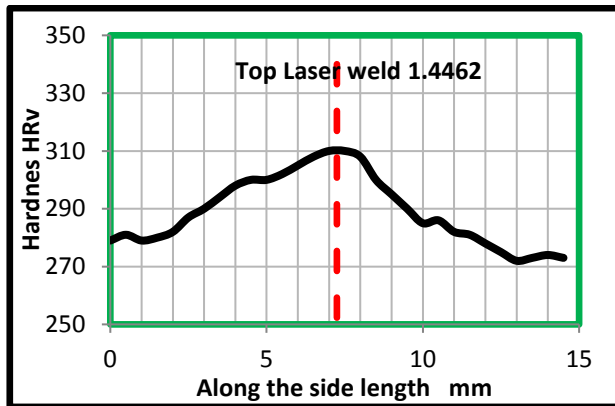


Figure 15-1.4462 D.S.S top surface Laser weld hardness test

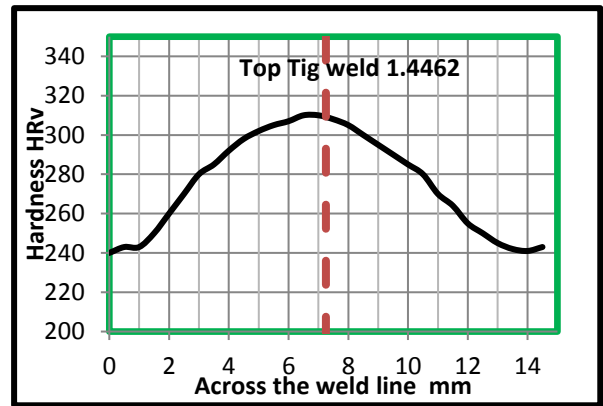


Figure 16-1.4462 Top surface D.S.S TIG weld hardness chart

Hardness measurements on the side Surface:

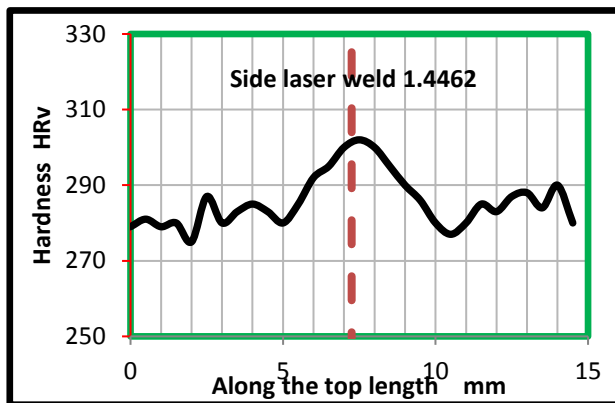


Figure 17 1.4462 D.S.S side surface laser weld hardness test

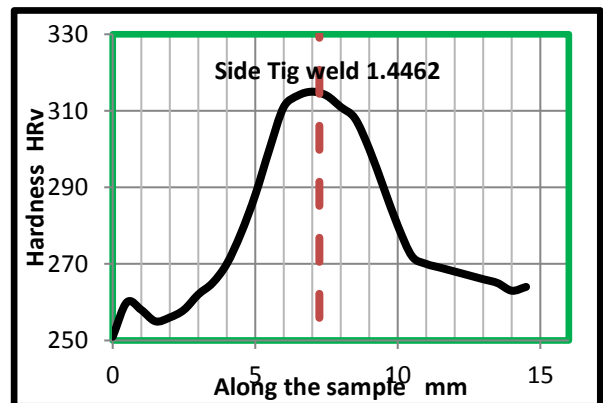


Figure 18 1.4462 D.S.S Side surface TIG weld hardness chart

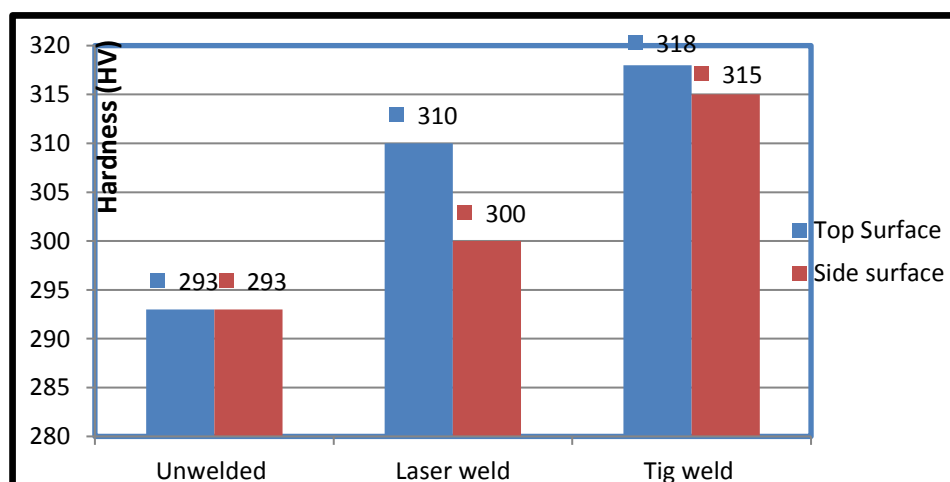


Figure 19- 1.4462 Micro hardness Histogram comparisons

V. Tensile testing:

Tensile strength testing was carried out for laser and TIG welding 8mm thickness for comparison unwelded base metal was used. observed that the weld done to the specimens done well compared to the original unwelded specimen that the tensile strength range from (650 to 800 N/mm²) according to literature review fig.20 After several tests observed that the main reason about failing was some of the weld defects found in the weld zone that contain pores and cracks would weaken the material and can be affected by corrosion resulted in failure of the specimen below suspected breaking part. The incomplete penetration debilitates the material totally as the welding zone turns out to be not exactly the original measure. Compared to micro hardness measurement its assure that in the Laser weld its hardened which cause the failure at lower strength than TIG weld and the base metal. Through visual investigation of the tested specimens, the materials that performed best were the materials that had the least imperfections. In this manner, to choose which materials had the more exact welding conditions, we observe which specimens had the most elevated average ultimate strength.

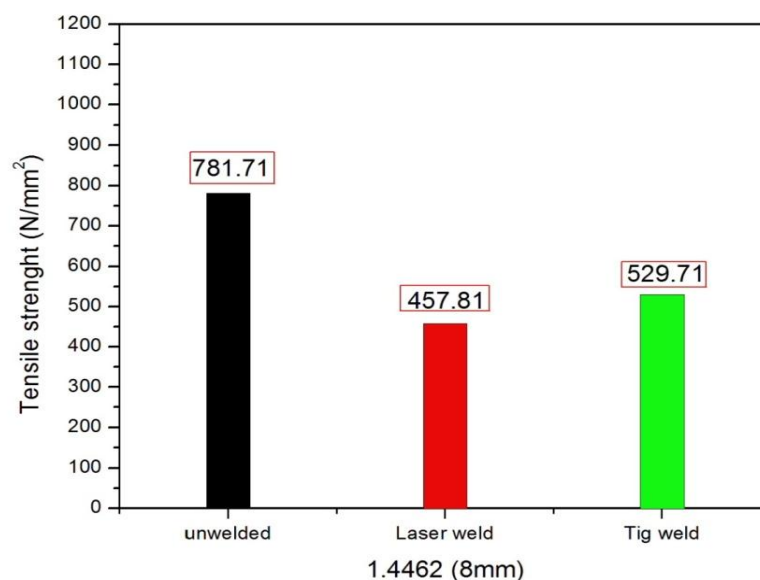


Figure 20 1.4462 D.S.S Tensile strength comparison of the unwelded, laser, and TIG joints

vi. Ferrite content

Ferrite testing is accurate way to measure delta ferrite content in duplex stainless steels. test conducted by FERITSCOPE FMP30. For Duplex Stainless Steel 1.4462, shown during the probe passing through the specimen that the Ferrite % increasing along moving from the base metal to the heat affected zone followed by the maximum in the weld zone which has lower corrosion resistant that will be confirmed later in corrosion study happened due to the precipitate in the HAZ as found in figures (21 and 22) for top surfaces, figure (23 and 24) for side surfaces; Production welds shall be checked on the surface (top-side) along the weld with a calibrated ferrite gauge and shall not exceed 60% ferrite. According to literature: Ferrite content shall be within the following ranges:

- Weld metal—30 % to 65 %,
- HAZ—40 % to 65 %,
- Base metal—40 % to 60 %.

For TIG weld its is subjected that the base metal composition might be conducted nearly to austenitic stainless steel but in the weld metal due to the filler id duplex that's illustration for the low ferrite content % compared to the Laser shown in fig.25

Ferrite content measurements on the top Surface:

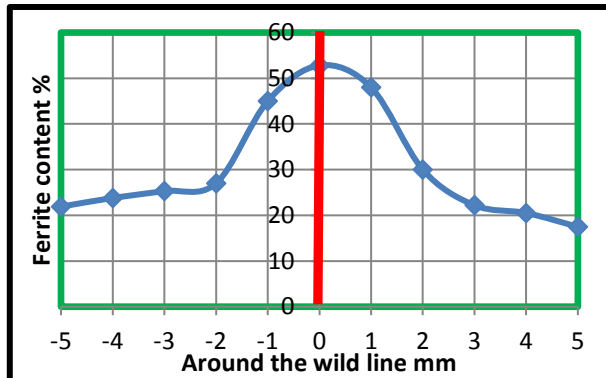


Figure 21-Ferrite%1.4462(318LN) D.S.S Laser weld

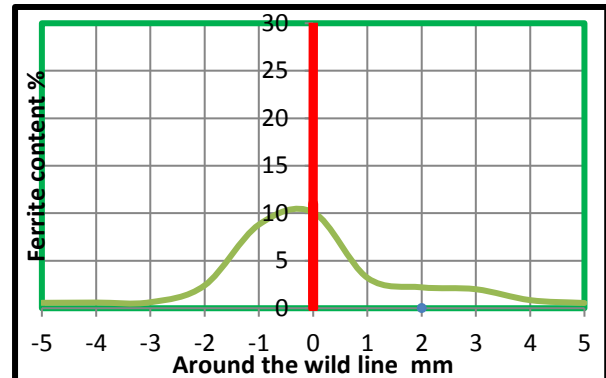


Figure 22-Ferrite % 1.4462 (318 LN) Tig weld

Ferrite content measurements on the side Surface:

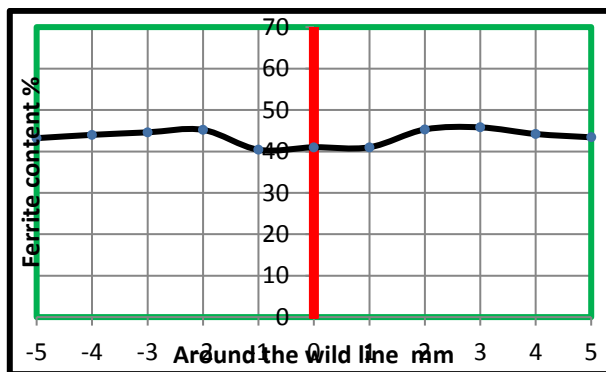


Figure 23-Ferrite % 1.4462(318LN) DS.S Laser weld

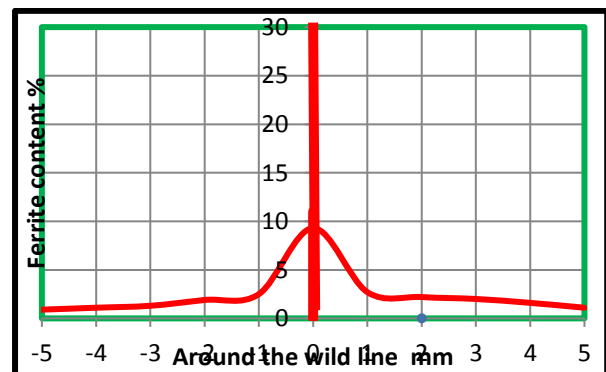


Figure 24-Ferrite % 1.4462 (318 LN) TIG weld

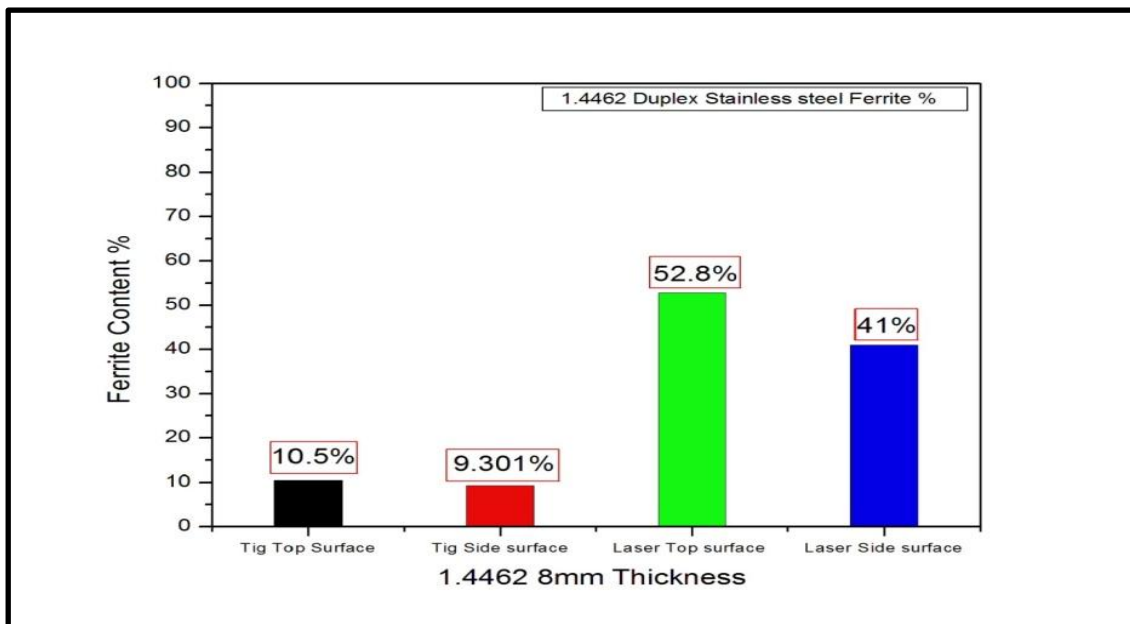


Figure 25- 1.4462 D.S.S Ferrite content % comparison histogram

vii. Electrochemical testing: open circuit potential (OCP):

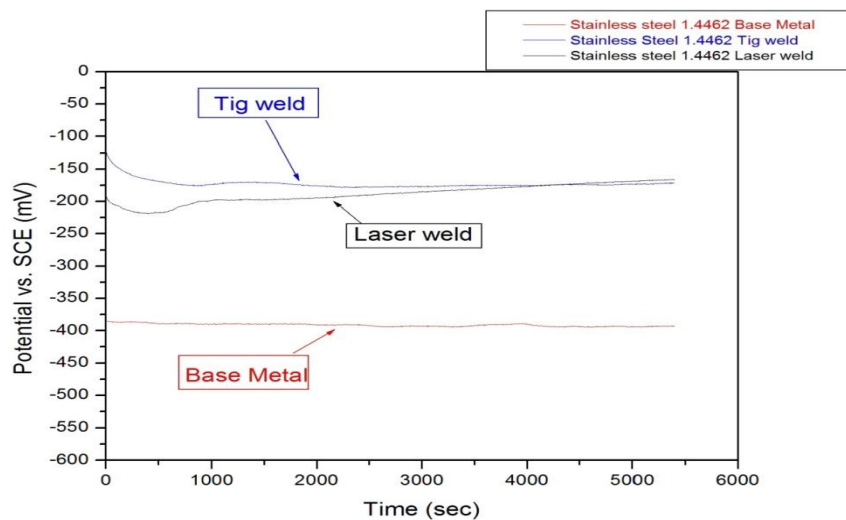


Figure 26- 1.4462 (318LN) D.S.S OCP

In the above fig.26 in D.S.S 1.4462 the laser welded has a higher OCP values than the TIG welded and the Base metal (unwelded). Which illustrates that the welded material (Laser-Tig) has a higher passivity than the unwelded material in environment of 3.5% NaCl. At 4500sec (75mins) the laser -172.12mV compared to TIG which is -162.12mV the base metal (unwelded) is -392.92mV. As going from Laser welded specimen followed by the TIG welded specimen which indicates that the less negative potential direction is indication towards corrosion value happens due to the formation of carbides around the grain. The increase of potential from TIG weld to Laser weld then the base metal may conclude TIG re-passivation more corrosion resistant than Laser weld [27].

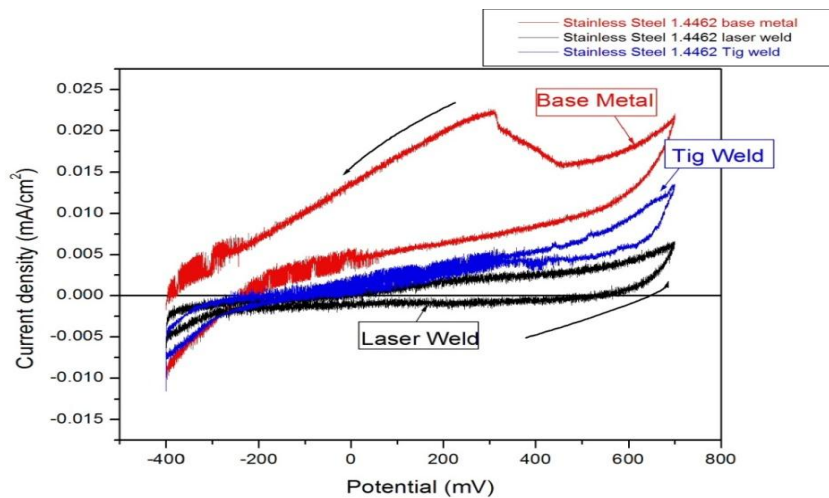


Figure 27 1.4462 D.S.S PCV

After conducting the Potential cyclic voltammetry for scan rate 2mV/sec from -400mV to 700mV[28] it was seen from fig.27 for the laser weld is more pitting resistant comparing it to the corrosion rate of Tig 8.917 $\mu\text{m}/\text{Y}$ to the Laser welded 5.615 $\mu\text{m}/\text{Y}$ from table5.

Table5. Corrosion rate for base metal-Tig weld-Laser weld

Condition	Corrosion rate ($\mu\text{m}/\text{Y}$)	Epping(mV)
Unwelded	14.09275	407.6092
Laser weld	5.615	611.99084
Tig weld	8.917	507.270667

4. Conclusion

Optical microscopy reveals in showing that 1.4462 D.S.S undergoes type A solidification and also in grain refinement as the size of the grain much bigger in the base metal going to the HAZ and then in the weld zone which results in grain growth and elongated through the HAZ observing the increase in the ferrite content becomes the primary phase. There is many Weld defects seen under the microscope which decreased the strength and suspected region for the corrosion attack that need to overcome to result in the good weld and avoid these defects: porosity, incomplete fusion and cracks. Scanning electron microscopy revealed the precipitates at the grain boundaries of the weld line between the weld zone and heat affected zone (HAZ) followed by EDX test to track the Ni, Cr elements composition in the weld zone and out in HAZ and base metal. Micro hardness test processed on the top surface and the side surface to compare the diffusion of weld inside the whole material reveals seen increasing gradually from the base metal to the HAZ and then maximum at the weld zone in the center of weld. Found that the TIG weld and laser weld in both the side and top surface is higher than the base metal. Ferrite content represented the lower corrosion resistant at the weld zones which reached its maximum. Tensile test revealed that the welded specimen for D.S.S 1.4462 which welded by remote Scanner laser is 457.81 N/mm² and 529.71 N/mm² For TIG respectively followed by the 781.71 for base metal almost the same for literature review. Corrosion potential is higher in the welded materials (Laser- TIG) than the base metal in 1.4462 D.S.S. as Shown in OCP the welded materials (Laser- TIG). Pitting corrosion is observed. Finally; it is recommended for further work to improve the welding procedure with different forms of weld joints through avoiding the defects and experimental notes that are mentioned throughout this work.

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