Effect of Welding Process on Microstructure, Mechanical and Pitting Corrosion Behaviour of 2205 Duplex Stainless Steel Welds

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Abstract. An attempt has been made to weld 2205 Duplex stainless steel of 6mm thick plate using conventional gas tungsten arc welding (GTAW) and activated gas tungsten arc welding (A-GTAW) process using silica powder as activated flux. Present work is aimed at studying the effect of welding process on depth of penetration, width of weld zone of 2205 duplex stainless steel. It also aims to observe the microstructural changes and its effect on mechanical properties and pitting corrosion resistance of 2205 duplex stainless steel welds. Metallography is done to observe the microstructural changes of the welds using image analyzer attached to the optical microscopy. Hardness studies, tensile and ductility bend tests were evaluated for mechanical properties. Potentio-dynamic polarization studies were carried out using a basic *GillAC* electro-chemical system in 3.5% NaCl solution to observe the pitting corrosion behaviour. Results of the present investigation established that increased depth of penetration and reduction of weld width in a single pass by activated GTAW with the application of SiO_2 flux was observed when compared with conventional GTAW process. It may be attributed to the arc constriction effect. Microstructure of the weld zones for both the welds is observed to be having combination of austenite and delta ferrite. Grain boundary austenite (GBA) with Widmanstatten-type austenite (WA) of plate-like feature was nucleated from the grain boundaries in the weld zone of A-GTAW process. Mechanical properties are relatively low in activated GTAW process and are attributed to changes in microstructural morphology of austenite. Improved pitting corrosion resistance was observed for the welds made with A-GTAW process.

1. Introduction

Duplex stainless steels (DSS) are generally used in the petrochemical, oil and gas, paper and pulp industries due to high strength, good toughness and resistance to pitting, crevice corrosion and stress corrosion cracking [1–4]. Proper balance between the phase formation of austenite and delta ferrite along with major alloying elements like chromium, molybdenum, Nitrogen and Nickel affects the desired properties [5,6]. In industrial applications, Gas tungsten arc welding is one among the conventional fusion welding process and often used in manufacturing of duplex stainless steel (DSS). Due to the severe thermal cycles during the fusion welding, it resulted in imbalance of austenite/delta-ferrite phase along with formation of detrimental phases [7] and consequently, loss of mechanical properties and decrease in localized corrosion resistance dramatically. In order to avoid the above problems, present work has great significance to investigate the microstructure, mechanical and corrosion behavior of 2205 DSS weld joint. Microstructural changes of a weld joint may not be uniform as the temperature variation during the welding thermal cycle [8], which leads to different mechanical properties and corrosion behavior. In General, typical weld joint can be divided into three zones, i.e. fusion zone, weld interface (PMZ/HAZ) and base metal. However, if welding procedure, parameters of the fusion welding are not properly controlled, which may leads to reduced corrosion resistance. Weld thermal cycle in the fusion welding may also leads to liquation cracking and solidification cracking in weld zone and grain coarsening in the heat-affected zone (HAZ). It is due to the fusion welding process having great influence on the duplex structure, both in the weld zone and heat affected zone. Fusion welding process is generally used for the joining of structural components. Kang and Lee [6] studied the relationship between the pitting corrosion behavior and the ferrite/austenite phase ratio of fusion zone by changing the chromium element. Zhang et al. [9] investigated and studied on the effect of gas tungsten arc welding and post-weld heat treatment on the pitting corrosion behavior of the DSS weld metal. Liou et al. [10] also studied on the effect of nitrogen content and cooling rate on the microstructure and stress corrosion cracking (SCC) behavior in the simulated heat affected zone of 2205 DSS. Welding of Duplex Steels using GTAW process is carried out primarily to produce excellent weld quality and surface finish compared to other arc welding processes. However due to its lower productivity and higher weld thermal cycles it is limited in applications, these problems can be overcome by adopting the new variant of GTAW process, called Activated GTAW (A-TIG) which is having major advantages like higher productivity and increasing depth to width ratio of penetration thereby reducing the number of passes along with reduced heat input & distortion. In present work, an attempt has been made to weld 2205 duplex stainless steel (DSS) with conventional gas tungsten arc welding (GTAW) and activated – gas tungsten arc welding (A-GTAW) process. It is aimed to observe the microstructural changes and to correlate with mechanical properties and corrosion resistance.

2. Experimental Details

The material used in this study is duplex stainless steel (DSS) of 200X130 X 6mm^3. Chemical composition and base metal properties of DSS 2205 are given in Table1. 2205 DSS of 6mm thick plates were welded with 2209 filler using conventional gas tungsten arc welding (GTAW) and activated – Gas tungsten arc welding (A-GTAW) process. Commercially available activated flux whose chemical composition is 100% Silica (SiO_2) is used in the present work. Welding parameters used for welding were given in Table 2 and the welded plates were shown in Fig.1. Weld specimens were cut and polished and etched with Villella's reagent (100ml Ethanol+5ml HCl+1gm Picric Acid). Depth of penetration and weld bead width (BW) were measured at 10X magnification using optical microscope. Microstructure studies were characterized at weld zones using optical microscopy. Phase analysis has been carried with the help of Image Analysis Software. Phase/volume fraction module was chosen and analyzed images of microstructures. Estimated volume fractions of identifiable phases and for calculating the volume fraction of ferrite in different weld zones i.e. GTAW& A-GTAW Tresholding (Gray count) method has been chosen. According to this method the software counts all the pixels in the image that fall within the gray scale range set for a particular phase. The area occupied by the phase or constituent of interest is computed and the volume fraction derived from this area as per ASTM E562.Micro hardness values were recorded towards the longitudinal directions of the weld with a load of 0.5Kgf for 20 seconds as per ASTM E384-09 using Vickers hardness tester. Tensile testing is carried out using a universal testing machine at room temperature as per ASTM-E8. Face bend ductility testing of the welds were conducted as per ASTM E190-92. Pitting corrosion resistance of base metal and welds were determined using potentio-dynamic polarization testing in aerated 3.5%NaCl solution.

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Table 1 Chemical & mechanical properties of 2205 duplex stainless steel:

Chemical									Mechanical		
C%	Mn%	Si%	S%	P%	Cr%	Ni%	Mo%	N	YS	UTS	%EL
0.019	1.43	0.75	0.001	0.020	22.16	4.62	3.14	0.161	450(Min.)	620(Min.)	25(Min.)

Table 2 Welding parameters for Bead on runs

Current	130-150A
Voltage	11 V
Arc Gap	2 mm
Travel Speed	160 mm/ min.
Shielding Gas	99.997 % Argon
Power source	Warpp INTIG-400i
Flux composition	100% SiO_2

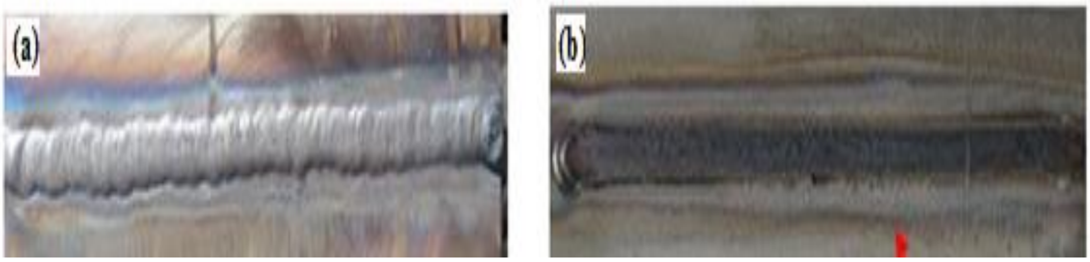


Fig. 1 DSS 2205 Welded plate (a). GTAW and (b) A-GTAW

3. Results and Discussions

2205 Duplex stainless steel (DSS) welded with conventional GTAW & Activated GTAW process by using 100% SiO_2 flux. Optical macrostructure with measured depth of penetration & weld bead width of both GTAW and A-GTAW 2205 DSS is shown in Fig. 2 and given in Table 3. Conventional GTAW process exhibited a shallow penetration with wider weld bead width than A - GTAW. Increased depth of penetration in A-GTAW was attributed by activated flux to arc constriction. DSS weld plates of 6mm thick, a single pass is not sufficient (thickness>3mm) to fill completely using GTAW process and hence multi-pass has been carried to fill the complete joint. In A-GTAW process, Sio_2 flux has increased depth of penetration of 5.4 mm in single pass and relatively reduced width of weld zone was achieved.

Table 3 Depth of penetration & welding width of GTAW & Activated GTAW welds

Welding Observations	GTAW	Activated GTAW
Depth of Penetration in single pass	2.8 mm	5.4 mm
Weld bead width	8 mm	7.2 mm

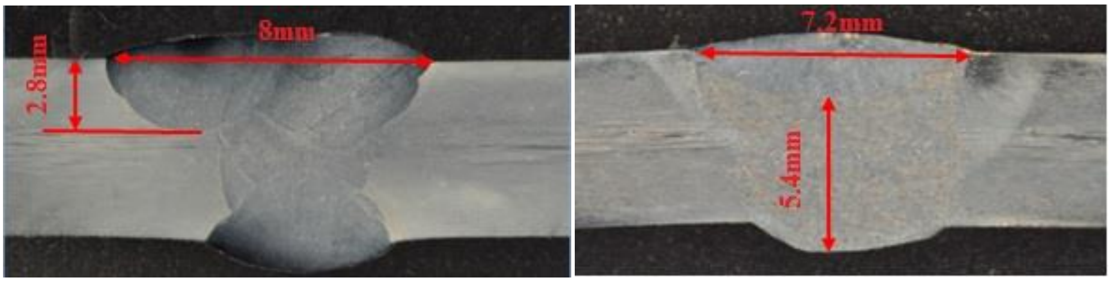


Fig. 2 Optical Macrograph of GTA & A-GTA welded DSS 2205 Stainless steel

3.1. Base metal Microstructure

Optical microstructure of 2205 Duplex Stainless Steel revealed fine grains of ferrite with austenite and is shown in Fig. 3. In general, Ferrite and austenite ratio in 2205 duplex stainless steel depends mainly upon the major elements in the chemical composition. Presence of ferrite with austenite provides better intergranular corrosion (IGC) and stress corrosion cracking (SCC) resistance compared to austenitic stainless steels [11, 13]. Hot cracking tendency may also be avoided by the presence of ferrite in the matrix.

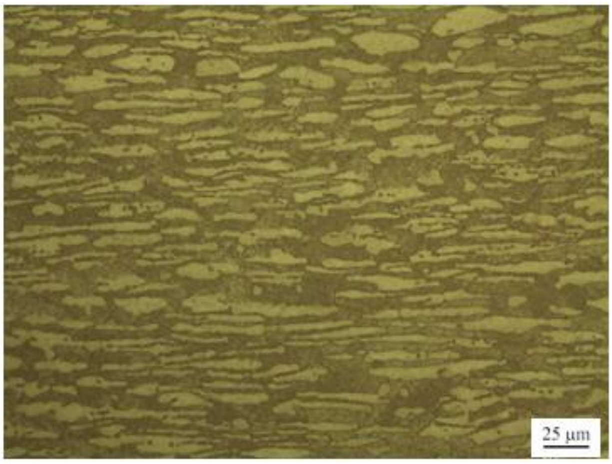


Fig. 3 Optical Microstructure of DSS 2205 Stainless steel

3.2. Weld microstructure

Microstructure analysis was performed on the test pieces of conventional GTAW & Activated GTAW welds. Optical micrographs of weld are taken at 500X magnification. Welding may leads to initial dissolution of primary austenite followed by grain growth in the δ-ferrite and thereby again formation of austenite during cooling [14]. Rate of high heat input and slow cooling rate results reformation of austenite during cooling. However, it also tends to form intermetallic compounds in the weld zone and heat affected zone under slow cooling rate. Figs. 4 and 5 show the optical microstructure of weld zone and weld interface of GTA welded DSS 2205 stainless steel.

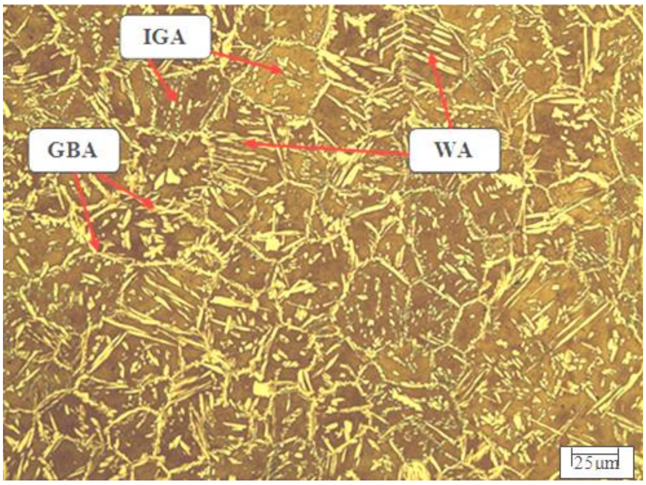


Fig. 4 Optical Microstructure of weld zone of GTA welded DSS 2205 Stainless steel

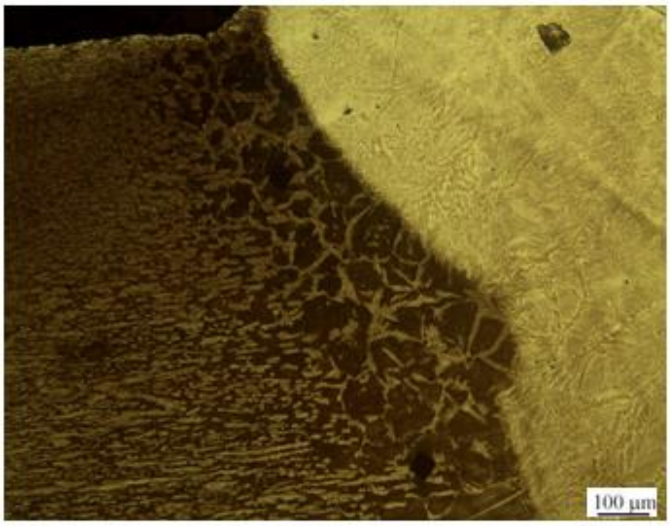


Fig.5 Optical micrographs of weld interface of GTA welded 2205 Duplex Stainless Steel

In Duplex stainless steel welds, three types of austenite were formed in the weld metal during solidification: (a) austenite nucleated at the prior ferrite grain boundaries (GBA); (b) Widmanstätten-type austenite (WA) of plate-like feature nucleated from the grain boundaries; and (c) intergranular austenite precipitates in ferritic grains (IGA). During cooling of weld metal, GBA was initially formed at the ferrite grain boundaries because the higher free energy at these locations. Then, WA was nucleated from the GBA and grew into the interior at a certain angle. At the same time, a great deal of IGA was formed in the ferrite grains due to the high content of nickel which was present in the filler wire. In addition, a large amount of γ_2 (secondary austenite) appeared in this zone.

Figs. 6 and 7 shows the optical microstructure of weld zone and weld interface of 2205 Duplex Stainless Steel welded by activated GTAW welding process with SiO_2 flux. Weld microstructure revealed that the grain boundary austenite (GBA) with Widmanstatten-type austenite (WA) and plate-like features nucleated from the grain boundaries. By using silica flux (SiO2) penetration capacity increased in A-GTA welded 2205 duplex stainless steel. Higher weld depth-to-width ratio was achieved with activated GTAW welding process compared with the conventional GTAW [15].

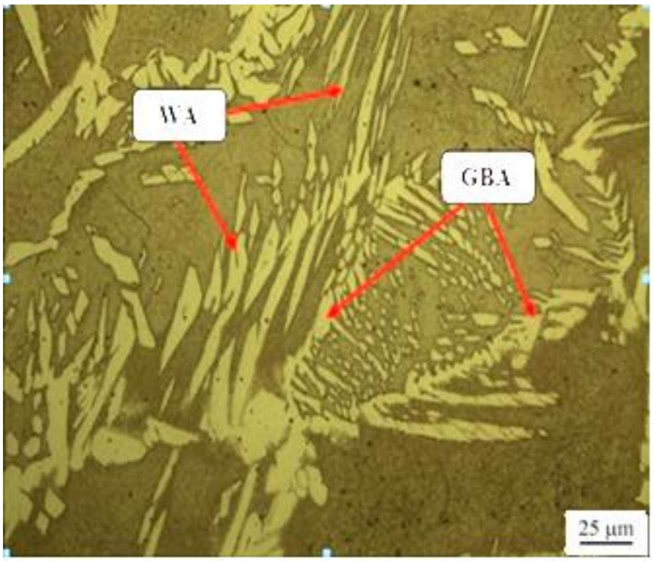


Fig. 6 Optical Microstructure of Weld Zone of A-GTA welded DSS 2205 Stainless steel

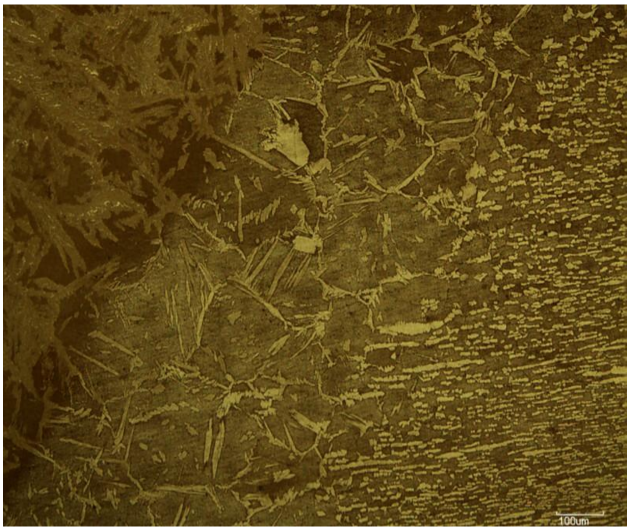
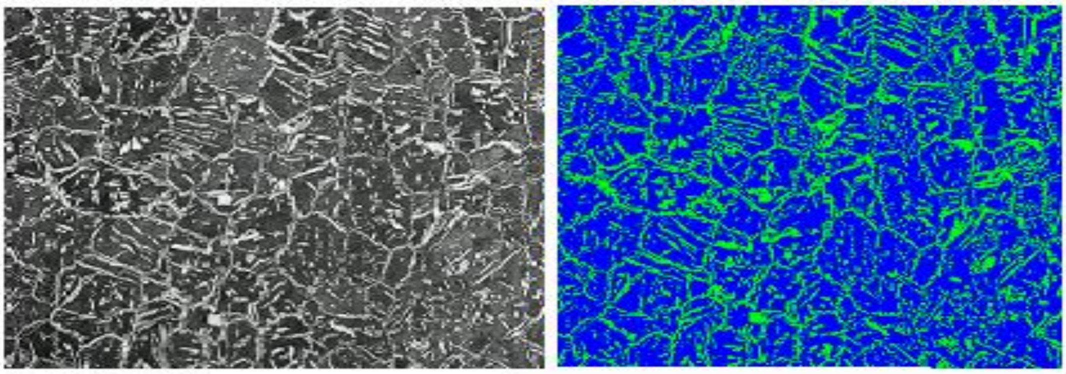


Fig.7 Optical micrographs of weld interface of A- GTA welded 2205 Duplex Stainless Steel



Results Summary
VOLUME FRACTION
Fields Measured 1
Total Area 1.232 sqmm
Standard ASTM E 562

Measurement	ferrite	austenite
Volume%	70.942	29.058
Estimated Volume%	70.942	29.058
Std dev.	0	0
95% CI	0	0
%RA	0	0

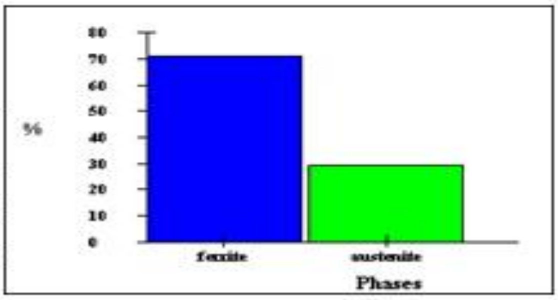
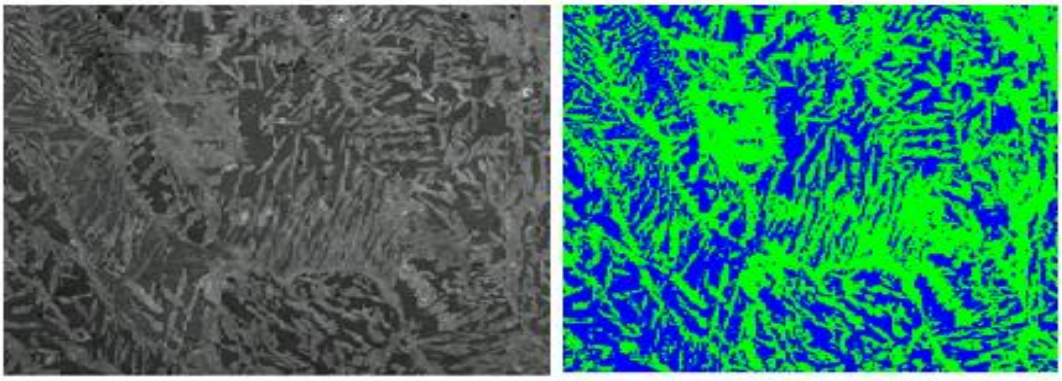


Fig. 8 Phase/volume percentage in weld zone of GTAW of Duplex Stainless Steel



Results Summary
VOLUME FRACTION
Fields Measured 1
Total Area 1.276 sqmm
Standard ASTM E 562

Measurement	ferrite	austenite
Volume%	42.559	57.441
Estimated Volume%	42.559	57.441
Std dev.	0	0
95% CI	0	0
%RA	0	0

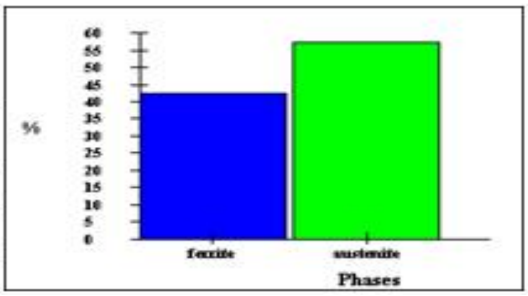


Fig. 9 Phase/volume percentage in weld zone of Activated GTAW of Duplex Stainless Steel

Figs. 8 and 9 show the phase/volume fraction of weld zones of GTA and A-GTA welded 2205 Duplex stainless steel. Phase/volume fraction module was chosen and analyzed images of microstructures. Estimated volume fractions of identifiable phases and for calculating the volume fraction of ferrite in different weld zones i.e. GTAW & A-GTAW Tresholding (Gray count) method has been chosen. According to this method the software counts all the pixels in the image that fall within the gray scale range set for a particular phase. The area occupied by the phase or constituent of interest is computed and the volume fraction derived from this area as per ASTM E562. It has been observed that activated gas tungsten arc welding (A-GTAW) process has reduced ferrite content when compared to conventional gas tungsten arc welding process. Ferrite phase volume percentage in weld zone of conventional GTAW is observed as 71% whereas 43% is observed in weld zone of activated GTAW. Reduced ferrite phase may be attributed to the activated flux and arc constriction effect in activated gas tungsten arc welding (A-GTAW) process.

3.3. Hardness Studies

Fig. 11 shows the optical macrograph of Vickers hardness indentations of 2205 DSS GTA and A-GTA welds. Vickers hardness values were measured at various locations across the weldments in both conventional GTAW & Activated GTAW and given in Table 4.In both welds, it is observed that there is a slight increase in hardness values of weld zone compared with heat affected zone and base metal. At heat affected zone, hardness values are increased due to change in micro structure & increased cooling rates than the base metal. There is an increase in hardness value of weld zone of duplex stainless steels by conventional GTAW mainly due to the strain induced hardening, weld induced residual stresses and secondary austenite precipitates in the weldment. Nowacki and Łukojć [16] reported that the secondary austenite phases exhibited higher hardness compared to ferrite and primary austenite phases in the weldment. It has been observed that the hardness value of HAZ of duplex stainless steels welded by conventional GTAW is increased slightly than base metal because of coarser ferrite grains, which are due to higher heat input and rapid cooling which results less amount of austenite formation.

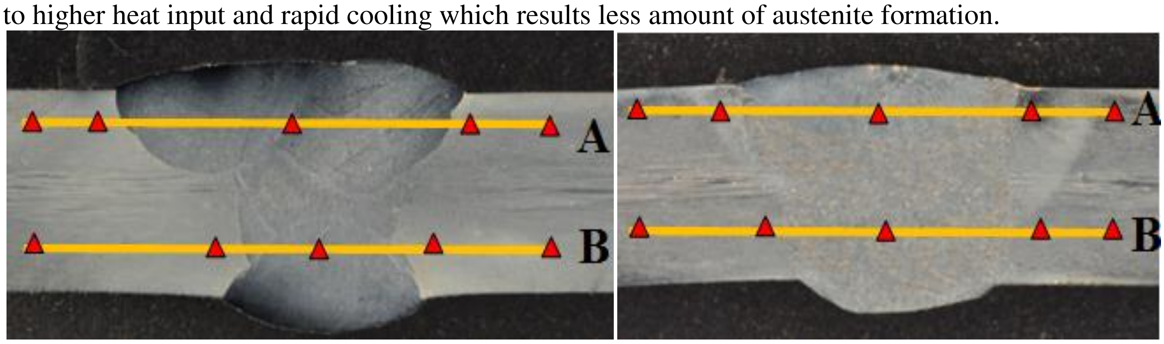


Fig. 10 Optical Macrograph of Hardness cross section of DSS 2205 GTAW and A-GTAW

Table 4 Vickers Hardness Values (VHN) of 2205 Duplex stainless steel GTA and A-GTA welds

Weld/Region	Base metal-1	HAZ-1	Weld	HAZ-2	Base metal-2
GTAW	267	272	295	279	267
A –GTAW	267	272	288	281	267

Fig. 11 shows the failed tensile test specimens of 2205 duplex stainless steel conventional GTAW & Activated GTAW. Standard test specimens were prepared transversely to the weld joint as per the standard ASTM E8M. The acceptance criterion for tensile test is to obtain UTS value not less the minimum specified tensile strength of base metal. The minimum specified tensile strength value of base metal of grade 2205 is 620Mpa. The tensile values obtained in both the weld joints i.e. conventional GTAW & activated GTAW are meeting the requirement. 2205 DSS Conventional GTAW weldments exhibits higher yield strength and ultimate tensile strength when compared to the base metal. Nickel enriched filler metal (ER 2209) probably promoting the strength in the weldment. The higher hardness induced due to welding also be the reason for experiencing higher strength in the DSS weldment. In case of activated GTAW weldment, yield strength and ultimate tensile strength values are less compared to that of GTAW weldment.

Table 5 Tensile properties of 2205 Duplex stainless steel GTA & A-GTA welds

Specimen	YS (Mpa)	UTS (Mpa)	% Elongation	Fracture Location
BASE	452	655	26	Center
GTAW	754	875	28	Weld
A-GTAW	661	848	30	Weld

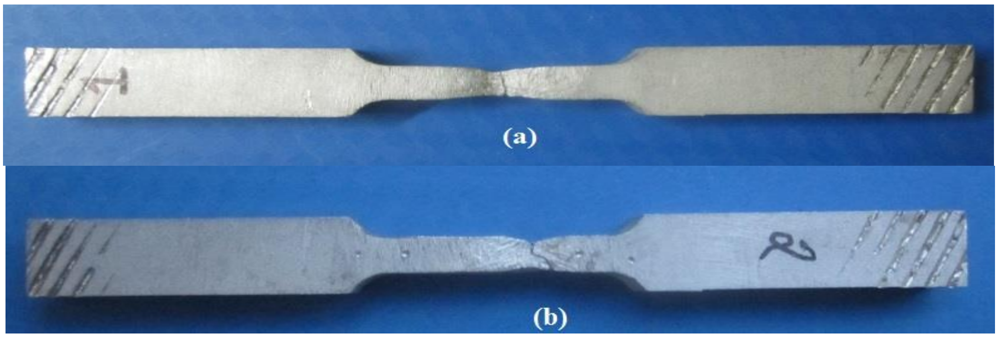


Fig. 11 Failed Tensile Test Specimen of 2205 Duplex stainless steel (a) GTAW (b) A - GTAW

3.4. Pitting Corrosion

Fig. 12 shows the potentio-dynamic polarization behavior of 2205 duplex stainless steel and its welds. The potential at which current drastically increases is observed as critical pitting potential (Epit) and values were given in Table 6. Pitting corrosion resistance is observed to be sensitive to microstructure. It is observed that pitting corrosion resistance of A-GTAW is relatively higher when compared to GTAW and base metal. In GTAW, relatively more active sites of austenite and ferrite interfaces were observed when compared to that of A-GTAW. Hence, improved pitting corrosion resistance is observed for A-GTAW and is attributed to reduction in galvanic interaction between austenite and delta ferrite.

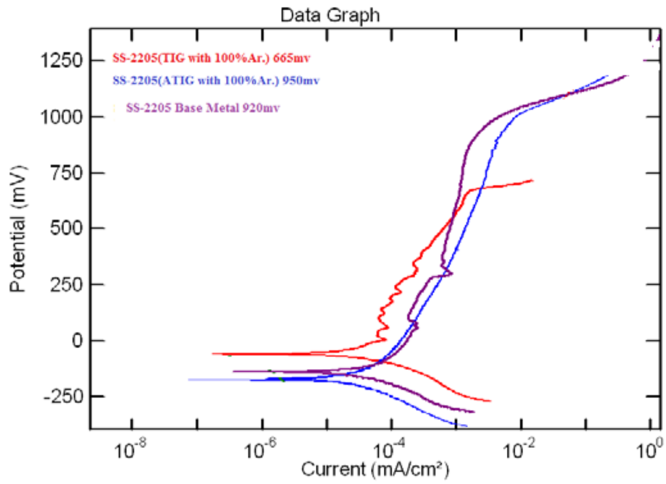


Fig. 12 Potentio-dynamic polarization behaviour of 2205 duplex stainless steel and its welds

Table 6 Pitting potential (Epit) of 2205 Duplex stainless steel GTA & A-GTA welds

Specimen	Pitting potential (Epit)
BASE	920 mV
GTAW	665 mV
A-GTAW	950mV

4. Conclusions

Duplex Stainless Steels of grade 2205 are successfully welded using conventional GTAW and activated GTAW welding process. Relatively more about 52% increase in depth of penetration achieved by activated GTAW process in a single pass than conventional GTAW process on a 6 mm thick plate. Weld bead width of activated GTAW is reduced by more than 11% for the same welding currents with SiO_2 flux.

1. Microstructural change influences the mechanical properties and pitting corrosion of 2205 Duplex stainless steel and its welds. Weld zone observed to have austenite along with delta ferrite in both the welds. The area fraction of delta ferrite in the weld zone of conventional GTAW is higher when compared to that of activated GTAW.
2. Tensile properties and hardness revealed that activated GTAW is as efficient as conventional GTAW process in producing defect free & ductile weld metals.
3. Pitting corrosion resistance of activated GTAW is observed to be significantly higher and is attributed to the microstructural changes that occurred during welding along with reduction in active sites of austenite and ferrite interfaces.
4. Overall study established that activated – GTAW is recommended for welding 2205 duplex stainless steel having more than 5mm thickness in single pass with improved mechanical properties and pitting corrosion resistance.

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