Suez Canal Engineering
Energy and Environmental
Science Journal
Faculty of Engineering – Suez Canal University
Year 2024, Volume 2, NO. 1, pages 42-50

A Comparative Study Between FSW and GTAW Techniques Based on Power Consumption and Mechanical Properties of SAF2507 Super Duplex Stainless Steel

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Article Info:

Article History:
Received: 08\04\2024.
Accepted: 15\05\2024
Published: 30\07\2024

DOI:
10.21608/sceee.2024.282140.1019

Abstract

This study presents a comparative investigation of both Gas Tungsten Arc Welding (GTAW) and Friction Stir Welding (FSW) techniques for welding SAF 2507 super duplex stainless steel plates. Both fusion and solid-state welding methods are widely utilized in the metal fabrication industry, each offering distinct advantages and limitations. FSW, recognized as a promising solid-state welding approach, is assessed alongside GTAW to validate its efficacy concerning power consumption and weld quality. The welded joints on 6 mm-thick SAF 2507 super duplex stainless steel plates, commonly used in power stations and petroleum service companies, were examined. Additionally, the viability of FSW as a groove filling welding technique was explored. Tungsten carbide tools are utilized to produce butt-joints under specified parameters (applied load 15 KN, rotation speed of 400 rpm, transverse speed 25 mm/min, tilt angle 3 degrees). For comparison, the same SDSS plates were welded using gas tungsten arc welding (GTAW). The joints produced using a 60-degree V-shape groove with a 2 mm root face were examined and characterized using visual inspection, radiographic test, liquid penetrant test, hardness test, and tensile test. The results indicate that FSW was used successfully to weld SDSS joints with a groove-like defect. The comparison aimed to determine which of these welding techniques consumes less energy and produces sound joints. FSW was found to consume less energy and produce better mechanical properties in the weld zone.

Keywords: *Friction stir processing. Super duplex stainless steel. SAF 2507. gas tungsten arc welding; mechanical properties, power consumption.*

Suez Canal Engineering, Energy and Environmental Science Journal (2024), ***2***(1), 42-50.

1. Introduction

Super duplex stainless steel (SDSS), particularly grade 2507, is extensively utilized across various industrial sectors due to its exceptional properties, including chemical, petrochemical, marine, and mining industries (Beheshty et al., 2018). Characterized by a dual-phase structure comprising ferrite (α) and austenite (γ) alloys, 2507-SDSS offers a remarkable balance of high strength and toughness, even in harsh environments and low temperatures(Du et al., 2012)(Abubaker et

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al., 2020)(Cao et al., 2022)(Giorjão et al., 2019) .Welding processes play a crucial role in integrating SDSS into various applications, with the efficiency of SDSS welds being particularly sensitive to changes in the α and γ ratio(Ahmed, Abdelazem, et al., 2021) .

Among the fusion welding techniques suitable for welding 2507-SDSS, gas tungsten arc welding (GTAW) stands out for its ability to produce efficient and clean welds(Yousefieh et al., 2011) (Verma & Taiwade, 2017). However, the productivity of GTAW diminishes for thicker joints, especially those exceeding 3 mm in thickness(Mourad et al., 2012)(Neissi et al., 2016) . Given the higher thermal conductivity and lower thermal expansion of 2507-SDSS compared to duplex stainless steel (DSS), minimizing heat input during welding is essential to prevent property degradation(Abubaker et al., 2020) .

In the realm of solid-state joining techniques, friction stir welding (FSW) has emerged as a promising method for welding SDSS due to its low heat input during the welding process (Ahmed, IA Habba, et al., 2021)(Ahmed et al., 2017)(Ahmed, Habba, et al., 2021). However, one of the main challenges in applying FSW to weld alloys with high melting temperatures is the limited tool life, necessitating the development of cost-effective tool materials like tungsten carbide (WC) (Esmailzadeh et al., 2013)(Gite et al., 2019)(Mohan & Wu, 2021). The geometry of the FSW tool pin and shoulder also plays a crucial role in extending tool life(Gite et al., 2019) .

Therefore, this study aims to assess the effects of FSW and GTAW processes on welding 6 mm thick 2507-SDSS, focusing on their impact on the mechanical properties and power consumption of the weldments. By comparing these welding techniques, this research seeks to provide valuable insights into selecting the optimal welding approach for SDSS applications while ensuring minimal heat input and energy efficiency.

2. EXPERIMENTAL WORK

2.1. MATERIAL

In this study, initial materials comprised 6 mm thick SAF 2507-SDSS plates, measuring 100 mm in width and 200 mm in length, sourced from RAHUL Company, located in Bogra, Bangladesh. The composition of the SAF 2507-SDSS plates, as provided by the supplier, is detailed in Table 1. For welding the SAF 2507-SDSS joints, Tungsten carbide tool (WC) based material manufactured by IhIe company in Königsbach-Stein, Germany, was employed. The chemical compositions and properties of the manufactured WC Tool, as per the supplier's specifications, are outlined in Table 2.

Table 1 The 2507-SDSS chemical composition.

Element	**Content (wt. %)**
Cr	26
Ni	8
Mo	5
Mn	1.2
Si	0.8
P	0.035
C	0.03
S	0.02
Fe	Bal.

Table 2 The nominal composition and properties of the applied FSW WC tools.

Grade	Cki 10 (K40UF)
ISO	K30-K40
WC+$\boldsymbol{Cr_3C_2}$+VC%	90
CO%	10
Density	14.45
Hardness, HV	1610
Bending Strength, MPa	>4000
Grain size, µm	0.6

2.2. GTAW OF 2507-SDSS

The Gas Tungsten Arc Welding (GTAW) method was employed for the entire welding process, encompassing root, filling, and final passes, utilizing a 2.4 mm diameter ER2594 filler metal rod. ASME code section IX guidelines were strictly adhered to during the GTAW welding procedure for the 2507-SDSS, which was executed using the Magma weld RS 500 M manual GTAW machine in Istanbul, Turkey. Preheating was intentionally omitted to prevent adverse effects on the properties of the welded SDSS alloys due to excessive heating. Additionally, the maximum temperature during the GTAW inter-pass did not surpass 100 °C to minimize the formation of intermetallic phases(Yousefieh et al., 2011).

The composition of the ER2594 welding consumable rod, presented in Table 2, contains 2.2% more nickel compared to the 2507-SDSS, aiding in the transformation of solid delta α into γ (Ahmed, Habba, et al., 2021). A schematic drawing of the butt weld joint design for the 2507-SDSS, featuring a 60° V-shape groove with a 2 mm root face and a 4

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mm root gap, is depicted in Figure 1. Detailed information regarding the GTAW process for the 2507-SDSS is provided in Table 3.

During the GTAW process, a manual stainless steel brush was utilized to remove oxide scales [8]. Table 4 provides comprehensive details of the GTAW procedure for the 2507-SDSS, including parameters and execution specifics.

Table 3 The nominal composition of the ER2594 (in wt. %).

Element	Content (wt. %)
Cr	27.2
Ni	8.69
Mo	2.88
Mn	0.91.59
Si	0.043
P	0.012
S	0.013
Fe	Bal.

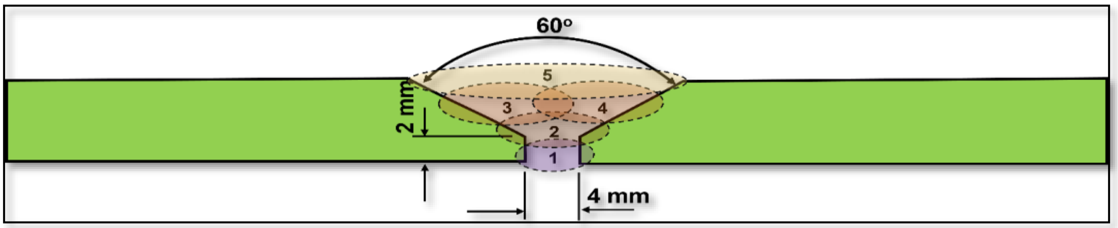

Fig. 1 schematic drawing of the 2507-SDSS for the GTAW process.

Table 4 GTAW welding parameter

Pass No.	Interpass temp. °C	Electrode	Amps	Volt	Travel speed mm/min	Heat input KJ/mm
1	-	ER2594 – 2.4 mm diameter	94	10.2	45	1.278
2	70		105	10.6	70	0.954
3	87		110	11.5	90	0.843
4	100		120	12.2	95	0.947
5	92		105	12	90	0.840

2.3. FSW OF 2507-SDSS

Figure 2 depicts a schematic representation of the butt weld joint design for the 2507-SDSS, featuring a 60° V-shape groove with a 3 mm root face and no root gap. Friction stir welding (FSW) was conducted using the EG-FSW-M1 machine model situated at the Faculty of Petroleum and Mining Engineering, Suez University, Suez, Egypt (Ahmed et al., 2019).

During the FSW process, the tool was controlled vertically while the work piece was controlled horizontally. Downward forces were applied to ensure the production of sound welds on the 6 mm plates, oriented normal to the rolling direction, using a specially designed WC tool. The downward velocity was set at 3 mm/min, and the joints were securely fixed on the FSW machine table using a custom-made fixture.

Based on preliminary FSW trials and available literature, the following parameters were employed: an axial load of 15 kN, rotation speed of 400 rpm, transverse speed of 25 mm/min, and a tilt angle of 3°. The FSW tool, consisting of a shoulder and pin, was fabricated from tungsten carbide (WC) materials, with the tool holder made from W302 cold work steel, as illustrated in Figure 3. WC was chosen due to its ability to withstand the high shearing stress and heat generated during FSW of SDSS alloys. The specified dimensions for the shoulder diameter, pin length, pin tip diameter, and tapered angle were 20 mm, 5.5 mm, 5 mm, and 31°, respectively.

Figure 3 displays an exploded view of the WC tool and holder assembly. Prior to the FSW welding process, mechanical cleaning of the joints was conducted using a stainless-steel wire brush to eliminate oxides and contaminants. Fixture plates were used to secure the joints onto the FSW machine table, as depicted in Figure 4a, while Figure 4b shows a rear view photograph captured during the FSW operation.

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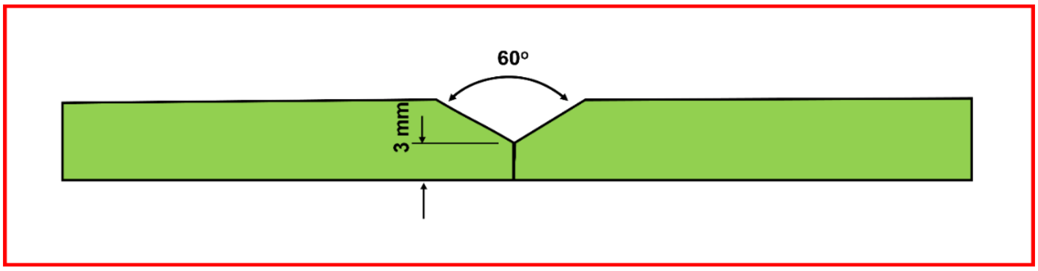

Fig. 2 Schematic drawing of the butt joint design of 2507 SDSS FSW joint.

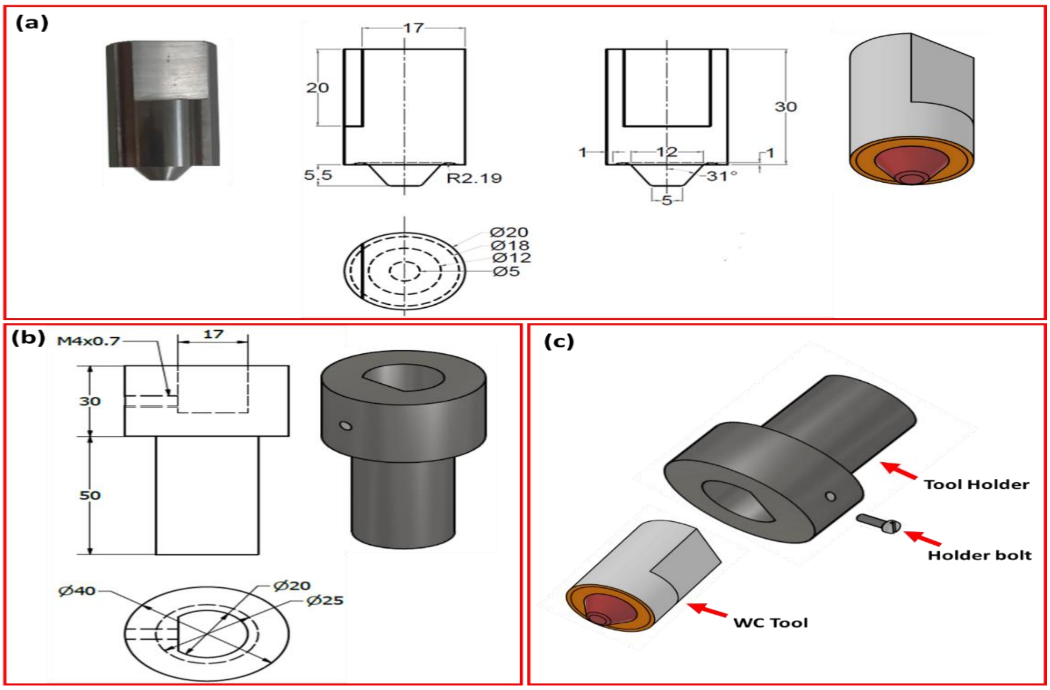

Fig. 3 (2D) and (3D) drawings of (a) the applied WC tools and (b) the WC tool holder, and (c) exploded drawing of the applied WC tool.

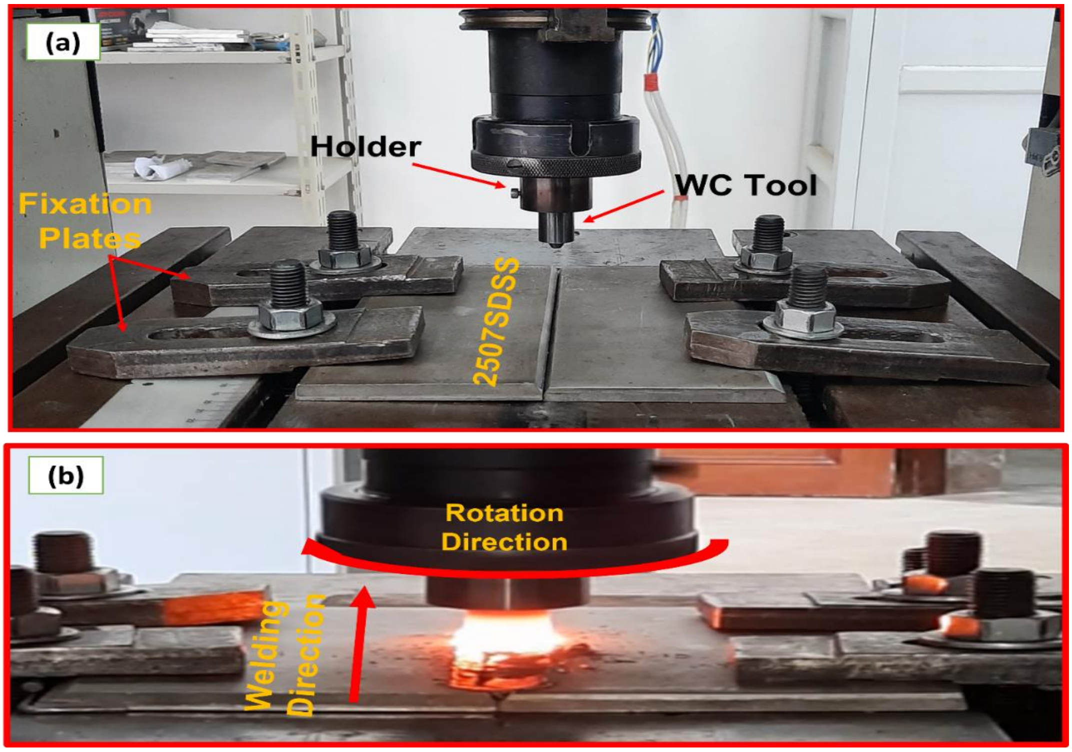

Figure 4 (a) FSW facilities and fixture plates, (b) photograph during friction stir welding of SDSS.

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3. CHARACTRIZATION OF WELDED JOINTS

Following the completion of both welding techniques, a series of nondestructive tests were conducted to ensure the integrity of the welded joints. Visual inspection, liquid penetrant testing (PT), and radiographic testing (RT) were employed to identify any surface or internal defects within the joints.

Liquid penetrant testing (PT) was utilized to detect surface defects such as cracks and surface porosity on the welded joints. Meanwhile, radiographic testing (RT) was performed using a Gamma-ray camera (Model 880 MAN-027, NSW, Australia) equipped with an Iridium-192 gamma ray source and AGFA D7 radiographic films to identify any internal defects within the joints.

Subsequent to the nondestructive testing, cross-sectional samples perpendicular to the welding direction were obtained from the weld seam using a wire cut machine (Model JOEMARS AWT655S, Taichung, Taiwan) to facilitate hardness and tensile testing.

The hardness evaluation of the cross-sections was conducted using a Vickers Hardness Tester machine (Type HWDV-75, TTS Unlimited, Osaka, Japan) employing a 2000 gf load and a 15-second dwell time.

Tensile specimens were extracted perpendicular to the welding direction and prepared according to ASTM E8/E8M-16a standards. The dimensions of the tensile test specimens are illustrated in Figure 5.

Tensile testing was conducted at room temperature with a ramhead speed of 0.5 mm/min utilizing a universal test machine (Instron 4208, 300 kN capacity, Norwood, MA, USA).

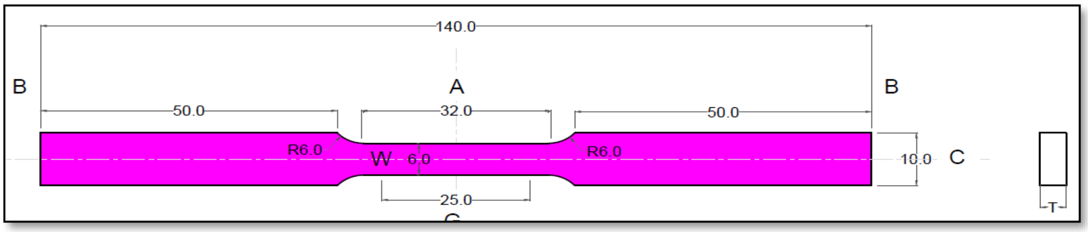

Fig. 5 Dimensions of the tensile test specimen according to ASTM E8/E8M-16a; all dimensions in mm.

4. RESULTS AND DISCUSSION

4.1. NON-DESTRUCTIVE TESTS

Figure 6a provides a top view of the SAF 2507-SDSS joint welded by FSW at parameters of 400 rpm, 25 mm/min feed speed, 15 kN applied load, and a tilt angle of 3°. The image demonstrates the excellent surface appearance and complete filling of the groove, indicating a successful welding process.

Liquid penetration testing is a critical non-destructive method employed to detect surface defects in welded joints. Figure 6b displays the results of the liquid penetration test conducted on the FSWed joint. The absence of any defects detected during this test confirms the findings of visual inspection, highlighting the high quality of the welded joint.

Radiographic testing is essential for evaluating weld quality by detecting internal defects that may not be visible externally. Figure 6c shows the radiographic image of the FSWed joint, revealing a sound weld with complete groove filling. The joint, welded at rotation speed 400 rpm, feed speed 25 mm/min, and applied load 15 kN, exhibits no internal defects, ensuring its structural integrity and reliability.

The successful results of both the liquid penetration test and radiographic testing validate the effectiveness of the FSW process in producing high-quality welds with complete groove filling and minimal defects.

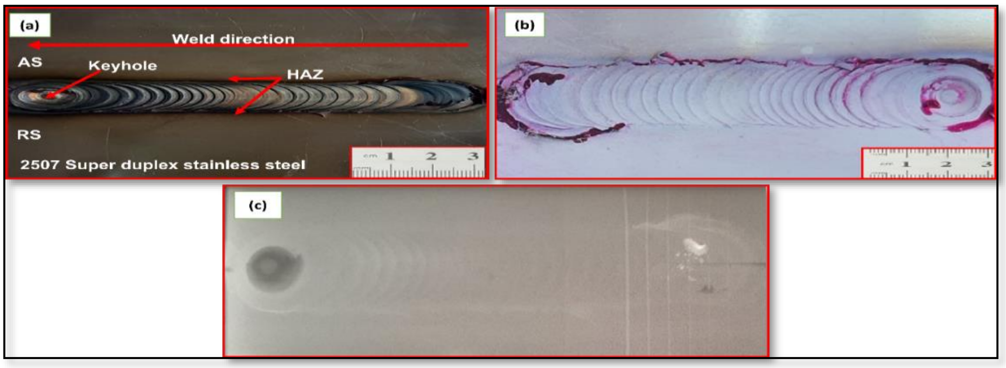

Fig. 6 Top view of the 2507 SDSS FSWed joint, (a) FSW at 400 rpm, 25 mm/min, 15 kN and tilt angle 3°, (b) image for liquid penetration test of 2507 SDSS welded by FSW and (c) Radiographic images of the 2507 welded by FSW

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Figure 7 depicts the top view of a SAF 2507 SDSS joint welded using multi-pass GTAW. Visual inspection of the joint, fabricated with a V-groove shape featuring a 60-degree angle, 2 mm root face, and 4 mm root gap, revealed no defects, indicating excellent surface quality.

Subsequent non-destructive testing, including liquid penetration and radiography, further validated the quality of the GTAWed joint. Figure 7b shows the results of the liquid penetration test, which exhibited a favorable surface appearance without any detectable defects, indicating satisfactory surface conditions.

Figure 7c presents the radiographic image of the welded joint, revealing no internal defects along its length. This outcome can be attributed to the appropriate joint design, optimal welding parameters, and effective material flow during the GTAW process.

Overall, the findings from both visual inspection and non-destructive testing highlight the successful fabrication of the SAF 2507-SDSS joint using multi-pass GTAW, demonstrating excellent surface appearance and structural integrity.

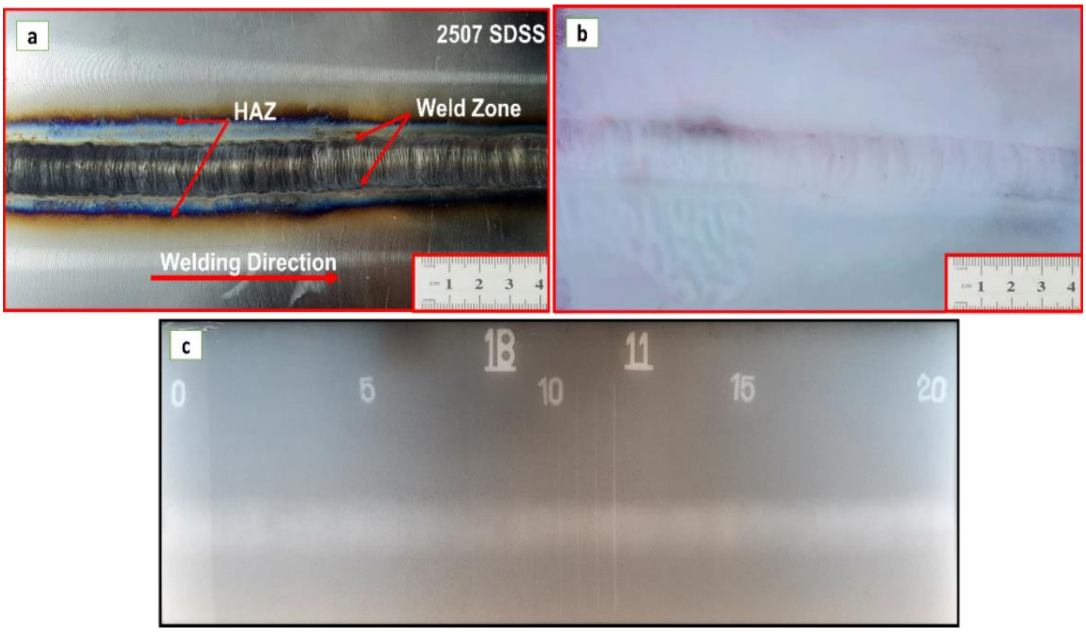

Fig. 7 (a)Top view of 2507 SDSS with multi pass GTAW, (b) image for liquid penetration test of 2507 SDSS with multi pass GTAW, (c) Radiographic images of the 2507 with multi pass GTAW.

4.2. DESTRECTIVE TESTING

4.2.1. HARDNESS AND ULTIMATE TENSILE STRENGTH

To evaluate the mechanical properties of the weld zone from the designed groove between the SDSS two plates under various welding techniques, tensile and hardness tests were conducted.

The FSWed joint was tested to evaluate ultimate tensile strength (UTS) and hardness, and compared with that of the SDSS BM, GTAW. The hardness was measured along the welded cross-section through two lines to evaluate the upper and lower weld zones. Figure 8 illustrates the ultimate tensile strength and average hardness measurements obtained from the 2507 SDSS BM as well as the friction stir welded joint and traditional fusion welding GTAW. It is observed that the UTS value for the BM sample of 1273 MPa, where the UTS for the FSWed joint is 1256 MPa, which is relatively close to the initial plate value and represents 98% of the value of BM. Whereas the ultimate tensile strength value for the GTAW sample is 1163 MPa which confirm the superiority of the Fswed joint over other welding method.

It is clear that the maximum hardness values for FSWed joint reach up to 377 HV at the SZ and gradually decrease by passing from TMAZ and HAZ to 300 HV and 280 HV, respectively. on the other hand, the maximum hardness values for GTAW reach up to 348 HV at the center of the weld zone, the hardness gradually decreases as we move to the HAZ, with value of 269 HV. In contrast, the hardness values are 311 HV in the non-affected zone related to the as-received SDSS BM. This increase in the hardness of the SZ over the BM is related to the refined and more uniform grain structure compared to the SDSS initial plate

In terms of hardness properties, the FSWed joint achieved the highest hardness values compared with BM and GTAW joint hardness values. Furthermore, its hardness exceeded the hardness value of SDSS BM, GTAW as given in figure 8.

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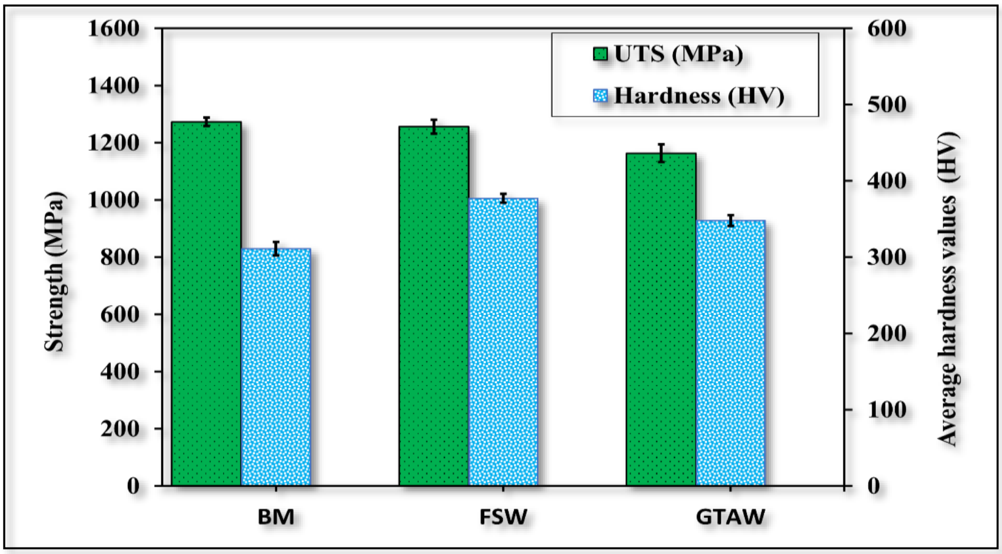

Fig. 8 Ultimate tensile strength and average hardness values of the 2507 SDSS BM, FSW, and GTAW.

4.2.2. POWER CONSUMPTION BASED ON MEASUREMENTS

In the context of fusion welding processes such as Gas Tungsten Arc Welding (GTAW) and Friction Stir Welding (FSW), accurately assessing power consumption is essential for various reasons, including cost estimation and process optimization.

For GTAW, voltage and amperage readings are typically automatically recorded from the welding machine's control panel. These readings are then cross-checked using additional tools such as an avometer and clip ampere on the power supply cord to ensure accuracy and reliability.

In the case of FSW, voltage and amperage readings are taken in both idle and working conditions. The readings from these situations are then averaged to provide a representative value for power consumption during the welding process.

To calculate power consumption accurately, both mathematical and theoretical approaches are used. The power consumption can generally be determined using the following equation:

$$\text{power consumption} = \frac{V \times I}{1000} \times \frac{T}{60} \times \frac{1}{E} \qquad \text{(Tatiane Machado, 2017)}$$

Where:

V: the voltage in volts
I: the current in Amps
T: the welding time in minutes
E: the efficiency of the welding machine

Note:

E=0.6 (for welding transformer)
E=0.25 (for welding generator) (Tatiane Machado, 2017)

Table 5. Results of Voltage and Ampere Readings

Measured Parameter	GTAW	FSW, Idle Condition	FSW, Loaded Condition
Voltage (V)	11.3	380	380
Current (I)	107	17	19
Weld line length (mm)	200	200	200
Traveling speed m/min	0.078	0.025	0.025
Welding time, min	13.85	10.66	10.66
Power Consumed W	465.2 Whr	1912 Whr	2137 Whr Power consumed in welding = 2137-1912 = 225 Whr

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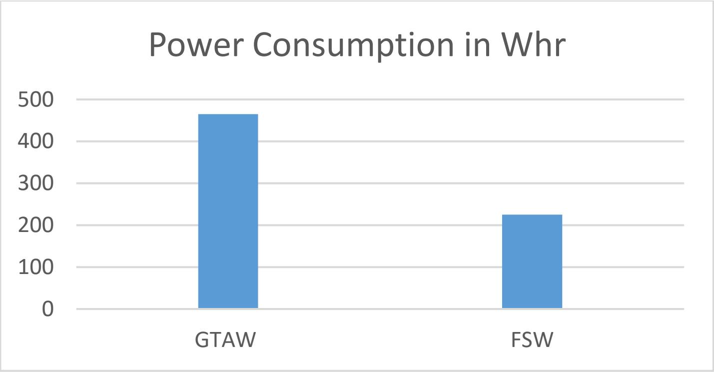

Fig.9 Power consumed comparison chart

The results of the measured parameters are given in Table 5. Power consumed in case of FSW is 225 Whr which proofs that too small energy is needed to execute the welding process when it is compared with the other technique.

Figure 9 give a comparison between welding techniques based on power consumption.

5. CONCLUSIONS

The influence of various welding techniques (FSW, GTAW) on the power consumption and mechanical properties of 2507 SDSS welds was investigated and evaluated. Based on the results, the following conclusions can be inferred:

1. SDSS SAF 2507 was successfully welded by FSW and GTAW techniques. Notably, FSW exhibits the lowest value of power consumption to fulfill a sound weldment compared with GTAW.
2. Utilizing the FSW technique with specific welding parameters, including a rotation speed of 400 rpm, travel speed of 25 mm/min, and a downward force of 15 KN, effectively fills 6mm thick SDSS butt joint designed a 60° V-groove with a 3 mm root face, without root gap.
3. Achieving sound and flawless joints of 2507 super-duplex stainless steels can be accomplished by employing multi-pass GTAW with the utilization of ER2594 filler material.
4. The joint produced by FSW achieved the highest hardness value compared to the hardness values of BM and GTAW. Additionally, its hardness surpassed the hardness of the SDSS BM.

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