

Characterization of Mechanical Properties and Corrosion Resistance of SAF 2205 Duplex Stainless Steel Groove Joints Welded Using Friction Stir Welding Process



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Abstract The aim of this work is to characterize the effect of groove joint designs on mechanical and corrosion resistance properties of friction stir welded SAF 2205 duplex stainless steel (DSS) 6.5-mm-thick plate. Nondestructive tests (NDT), such as Radiographic Test (RT), and Visual Test (VT), show that, high-quality welds were produced for V grooved joints with, 60° groove angle, and 2 mm root face, without root gap, with these joints were welded at constant rotating speed of 300 rpm, 25 mm/min traverse welding velocity, and 20 KN down load, using tungsten carbide (WC) base metal conical tool. Evaluating the mechanical properties using destructive tests (DT) such as tensile test, bending test, impact test, Vickers hardness test, showing that, Vickers hardness was increased at the stir zone, the failure was occurred at the base metal, the bending behavior and the impact energy are acceptable, the evaluation of corrosion resistance rate shows that, the corrosion resistance of this joint is higher than that of the base metal. In addition, it was significantly noted that, mechanical properties and corrosion resistance of these joints welded using FSW process are better than that of those joints welded using fusion welding (FW) possesses, shielded metal arc welding (SMAW), and gas tungsten arc welding (GTAW).

Keywords; Duplex stainless steels; Friction stir welding; Groove joints; Mechanical Properties; corrosion resistance

I. INTRODUCTION

DSS is approximately contains 50% austenite and 50% ferrite phases, leading to good Mechanical properties and corrosion resistance. these properties allow weight savings, which reduce the forming and fabrication cost and enabling lighter support structures to use. In addition, the superior corrosion resistance makes them preferably used in certain environments like chemical tanks, tubes for heating exchangers, and paper Machinery [1-3]. Because of having a high corrosion resistance, good weldability, higher impact energy than ferritic stainless steel, and higher tensile properties than austenitic and ferritic stainless steels, duplex stainless steel was used widely in especial industries as food, chemistry, and many other fields due to their high performance, and durability [4-9]. Structure combines a dual phase of ferrite and austenite, these effects of two-stage DSS allow to combine high tensile strength for ferrite and high Hardness for austenite, in both low and high temperature [10]. The beneficial microstructure of DSS may be changed during traditional FW, which results in affecting their performance. Friction Stir Welding (FSW) process results in avoiding these the solidification problems as, alloying elements segregation, liquation and solidification cracks.

DSS and super duplex stainless steels (SDSS), 6 mm thick, Full penetration joints, welded using FSW process, were subjected to tension test, and it is significantly observed that, there is an improvement in tensile and yield strength for all joints. In addition, microstructural characterization and grain refinery was observed in all welded joints [11]. Where, DSS and SDSS solidifies as ferrite phase, its percentage is increased especially in HAZ, that is due to the thermal cycles of weldments, welded using traditional FW processes, which result in a reduction in weldments' toughness compared to the base metal [12,13].

Unlike traditional fusion welding processes, friction welding is classified as a low energy input process, substitute for producing sound joints with slightly change in internal microstructure, and that is results in high performance in service, so FSW preferable to be used in DSS welding. In fact, and from the previous works it is found that, there is a good balance between ferrite and austenite contents, and an increasing in weld strength due to the changes in its internal microstructure [14–18].

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The mechanical properties characterization and microstructure evaluation had been carried out for 8 mm thick, SAF 2507 SDSS pipe, welded using FSW process. Sound welds with high quality were produced, when using a tool made of polycrystalline cubic boron nitride, 38 KN down load force, 50 mm/min traverse speed, and 200 rpm rotating speed. The tensile strength and Hardness were increase in SZ, and the fracture occurred at base metal [19]. FSW was used to weld 2 mm square joint of SAF 2205 DSS plate, using WC tool, at fixed rotating speed of 600 rpm, and it is noted that, good welds were obtained at traverse speed range of 50-200 mm/min [15]. The effect of FSW parameters in terms of rotating speeds, traverse speeds, and downward forces on the mechanical properties of welded SAF 2205 DSS 6.5 mm thick plate using FSW process, were investigated, and it is noted that, the welds showed an improvement of hardness compared to the as-received materials. The best values of yield stress, and ultimate tensile stress, with ductile fracture were obtained at rotating speed of 300 rpm, traverse speed of 25 mm/min, and downward force of 20 KN [20]. The corrosion characteristics of lean DSS specimens welded using FSW process, were investigated, it is noted that, increasing traverse speed leads to increasing grain refining, which results in more steady forming of passive films, and improvement their corrosion resistance. Accordingly, these specimens have better corrosion resistance than the based metal [21]. Despite the potential advantages of FSW process, it is facing some economical and practical difficulties in welding of high strength material such as, SAF 2205 duplex stainless steel, these difficulties are arising from, short life cycle, continuous wear, and fracture of tool used, that is due to high friction and transverse force of welded metals. So the objectives of the present work are to characterize the soundness of SAF 2205 welded joints using visual inspection and radiographic test, then evaluating the tensile, bending, impact, and hardness properties of the weldments, finally studying the groove joints effect on tool wear and its life span.

II. EXPERIMENTAL WORK

A. Material and Methodology

Using the commercial grades of the SAF 2205 duplex stainless steel, 6.5 mm thickness plate, which have the chemical analysis, and mechanical properties, shown in Tables 1 and 2, in order to produce weldments using the FSW machine, model (EG-FSW-M1), at the FSW and processing lab that belongs to Faculty of Engineering, Suez University, which allows vertical and horizontal control of the tool and work peace, respectively, and the down load with which the tool is sinking into the joint. The most important FSW parameters of the process, which applied throughout the project, and were kept constant such as, rotating speed of 300 rpm, traverse speed of 25 mm/min, down load of 20 KN, and 3° tool's tilt angle. The tool made of WC based material with specially designed probe of 12 mm diameter, that is tapered to 5 mm diameter with 5.5 mm length, at the contact with the 20 mm diameter shoulder. The materials to be welded also kept to be 6.5-mm-thick SAF 2205 DSS plate, the joints type were, three butt joints with different groove geometries, and without root opening, were welded using FSW process. For ease in identifying specimens, Sp1, Sp2, and Sp3 were selected as naked names for joint designs 60° U-shape with 2 mm root face, 60° single V-shape without root face, and 60° single V-shape, with 2 mm root face, respectively, Figs. 1a, 1b, and 1c, in addition, Sp4 and Sp5 were selected for the two joints welded using traditional FW processes, SMAW and GTAW respectively, Figs. 1d and 1e. SMAW joint was performed using DCEP process, with parameters of E 2209 filler wire, 27-29 volt, 80-85 amber current, and (900- 1133 J/mm) Heat Input and, GTAW joint was performed using DCEN with parameters of 2.4 mm tungsten electrode diameter type EWTH 2, 10-15 lit/min argon flow rate, ER 2209 filler wire, (10-14.5 V) volt, (116-159 A) current, and (766- 1548 J/mm) Heat Input.

Table 1, Chemical analysis of the SAF 2205 DSS plates (in wt. %).

Component	C	Si	Mn	P	S	Cr	Ni	Mo	N
Reference ¹	0.03	1.0	2.0	0.030	0.020	22-23	4.5-6.5	3-3.5	0.14-0.2
Base metal	0.016	0.37	1.50	0.024	0.0015	22.40	5.70	3.2	0.18

¹, single values are the maximum.

Table 2, mechanical properties of SAF 2205 DSS plates.

Component	Tensile strength (MPa)	Yield strength (MPa)	Elongation %	Hardness	
				Brinell	Rockwell
Reference	655	450	25	293	31
Base metal	820	702	32.5	243	27

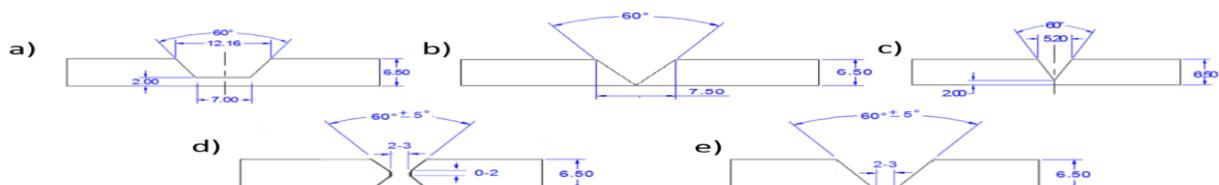


Fig. 1. Drawings of different groove joint geometries for, a) Sp1, b) Sp2, c) Sp3, d) Sp4, and e) Sp5

B. Non Destructive Testing (NDT)

To obtain accurate DT results, all welded joints are inspected using NDT, such as VT, and RT to reveal the soundness and appearance of them before applying the mechanical tests. VT was applied on welded joints using naked eyes, and RT was applied using gamma ray camera, Ir 192 radiation source, and D7 radiographic films, with applying single wall single image technique (SWSI).

Destructive Testing (DT)

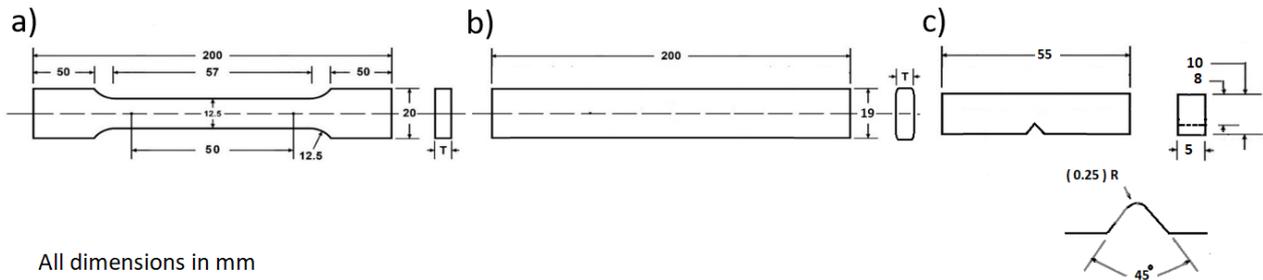
To evaluating the mechanical properties of the weldments, DT such as tension test, bending, impact and, hardness tests, must be applied on sound joints.

Tensile Testing: Transverse sections were taken from each joint to prepare two tension test specimens with dimensions shown in Fig. 2a, to determine the strength, and elongation percentage of the welded joints. Tension test was conducted according to ASME IX and ASTM E8 [22, 23], using universal testing machine (Tinius Olsen) Fig. 3, which located at PETROJET laboratory – Cairo, with 600 KN capacity and initial strain rate of 0.05 mm/sec.

Bend Testing: Three-point bend test was performed for evaluation of the weldments’ quality, using same universal testing machine (Tinius Olsen) Fig. 3. The cap and root were removed flush to be smooth, the specimen dimensions were 200 x 19 x 6.5 mm thickness as shown in Fig. 2b,

according to ASME IX [22]. The teste was carried out at room temperature, the specimens were bent in a U-shaped, where the weld was transverse to the longitudinal axis of the specimen, which is bent so that the weld root surface becomes the convex surface of the bent specimen, the interpretation of the results will be carried out by examining the convex surface of the bent specimens for open cracks.

Toughness Testing: Charpy V-notch toughness test is a dynamic test, where a notched specimen is struck and broken by a single blow of freely swinging pendulum in a specially designed testing machine (Tinius Olsen) Model IT 542, it has an available energy of 542 J, and located at PETROJET laboratory – Cairo Fig. 4. The temperature of tested specimens was conditioned and controlled at -40°C, each sample of the test specimens shall consists of three specimens with dimensions of 55 x 10 x 5 mm thickness, Fig. 2c, according to ASME IIIIV, and ASTM E-23 [24,25]. Notch was made in the centerline of weld metal, and intersection of weld line with specimens and HAZ at mid-thickness of the specimens. The test values will be the average of the measured tests of the energy absorbed for the three specimens of each set.



All dimensions in mm

Fig. 2. Test samples plot of welded specimen for, a) Tension test , b) Bend test, c) Impact test



Fig. 3. Tensile / bend Test Machine



Fig. 4. Impact Test Machine

Vickers Hardness Testing: The Vickers hardness testing (HV) was applied using a fully-automated hardness testing machine (Qness) model Q10M, which located at Egyptian British University (BUE), according to ASTM E92 [26], under a force of 10 Kgf for 15 sec dwell time, to check the hardness along three transverse lines at cap, filling, and root, across the fusion zone, stir zone, HAZ / thermos mechanically affect zone, and base material for the cross sections of all welded joints.

C. Electrochemical Testing

Corrosion Behavior Testing: The corrosion behavior was studied by applying Potentiodynamic testing technique, to assess the tendency of the weldments to corrosion attack, According to ASTM G5 [27], and ASTM G3 [28]

which indicate the agreements applicable to electrochemical measurements in the corrosion test. The test was carried out in 3 wt. % NaCl aqueous solutions at 22 ± 1 °C. The dimensions of the specimens for both base metals and the weldments were 6.5 x 20 x 10 mm. the specimen prepared according to ASTM E3 [29] and the final cleaning in an ultrasonic cleaner. The samples were mounting coated to cover all the samples area, except cross-sectional area of the weldments, where these areas were exposed to a testing solution and the samples then it served as the working electrode. The graphite rod was used as gage electrode, whereas The reference electrode was saturated with the calomel electrode K/KCl type. The scanning was always started after 5 min immersion time for stainless steel. The corrosion rate will be measured in millimeter per year (mmpy) according to corresponding current density. The reference electrode was saturated with the calomel electrode.

Visual and Radiographic Testing Results: Visual and radiographic tests show that; for FSW weldments of U-joint, there is good appearance with much flash, internal cavity almost along the joint length at advancing side, and around 2 mm reduction in thickness, this lack of filling was due to the lack of material flow and the large volume of joint groove. For FSW weldments of V-joint without root face, there is a partially good appearance with much flash, and internal cavity along the joint length at advancing side, due to the lack of filling and material flow, due to the large volume of the groove. the reduction in thickness was around 1mm. For FSW weldments of V-joint with 2mm root face, it was observed that, good appearance of the weld surface, good surface conditions, with little flash, no reduction in thickness, and no internal defects along the joint length, that is due to suitable joint design, suitable welding parameters, and adequate material flow. For fusion-welded joints, which welded using traditional FW processes, SMAW, and GTAW respectively, good appearance, sound and free from internal defects weldments were observed for both two joints, Figs. 5 and 6.

III. RESULTS AND DISCUSSION

A. Nondestructive Testing Results

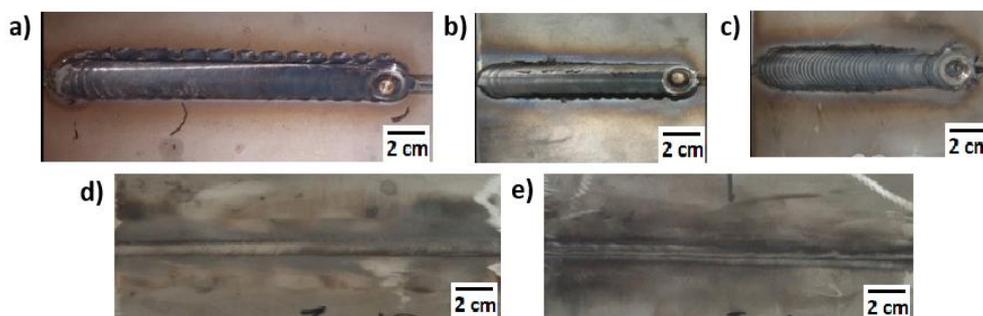


Fig. 5. Visual appearance for, a) SP1, b) SP2, c) Sp3, d) Sp4, and e) Sp5.

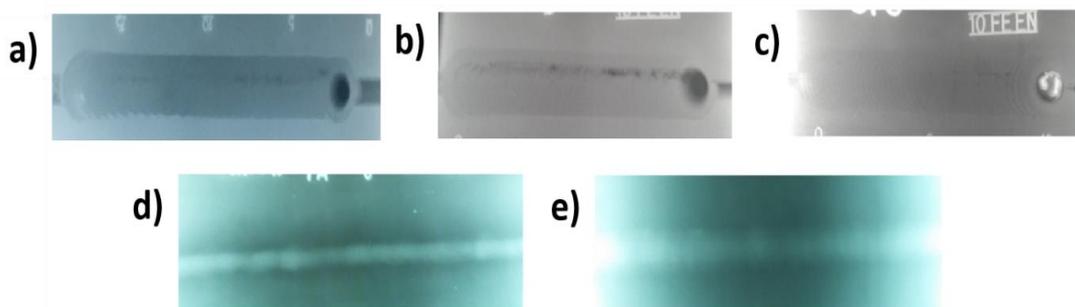


Fig. 6. Specimens radiographic films, a) SP1, b) SP2, c) Sp3, d) Sp4 and, e) Sp5.

B. Destructive Testing Results

Tensile Testing Results: For friction stir welded joints, it is found that; for Sp1 (U-joint), the test values were, 595 MPa in yield strength, 598 MPa in maximum tensile strength, and 15 % elongation percentage, which are less than the requirements of based metal, and fracture occurred on the stir zone. For Sp2 (V-joint without root face), the test values were, 605 MPa in yield strength, 627 MPa in maximum tensile strength, and 17.5 % elongation percentage, which are slightly less than the requirements of based metal, and fracture occurred on the stir zone with brittle fracture appearance. For Sp3 (V-joint with 2 mm root face), the test values were, 725 MPa in yield strength, 845 MPa in maximum tensile strength, and 35 % elongation percentage, which are more than the requirements of based metal, and fracture occurred on based metal, with ductile fracture

appearance. It is significantly noted that, joint No. Sp3 has the best values between the groove joints welded by FSW process, Figs 7 and 8. For fusion welded joints, it is noted that, the tensile test values were 570 MPa in yield strength, 711 MPa in maximum tensile strength, and 17.6 % elongation percentage, and values were yield stress 620 MPa, ultimate tensile stress 747 MPa, and 25 % elongation percentage, the fracture occurred at base metal for the joints Sp4 and Sp5, welded using SMAW and GTAW respectively, it is clearly observed that the joint No. Sp5, welded by GTAW is better than the ones welded by SMAW.

It is significantly observed that, the friction stir welded joint, which designed as, V-shape with 60° groove angle, and 2 mm root face without root opening, has the best tensile test values between all friction stir welded groove and square joints [20], and traditional fusion welded joints Fig. 8.

Bend Testing Results: No cracks or any other imperfections were observed for bended specimens, as shown in Fig. 9, this could be related to the quality of the weldments, so the test was considered acceptable [21].



Fig. 7. Fracture for Sp3, the tensile specimen of groove joint with V shape, 2 mm root face, and welded by FSW.

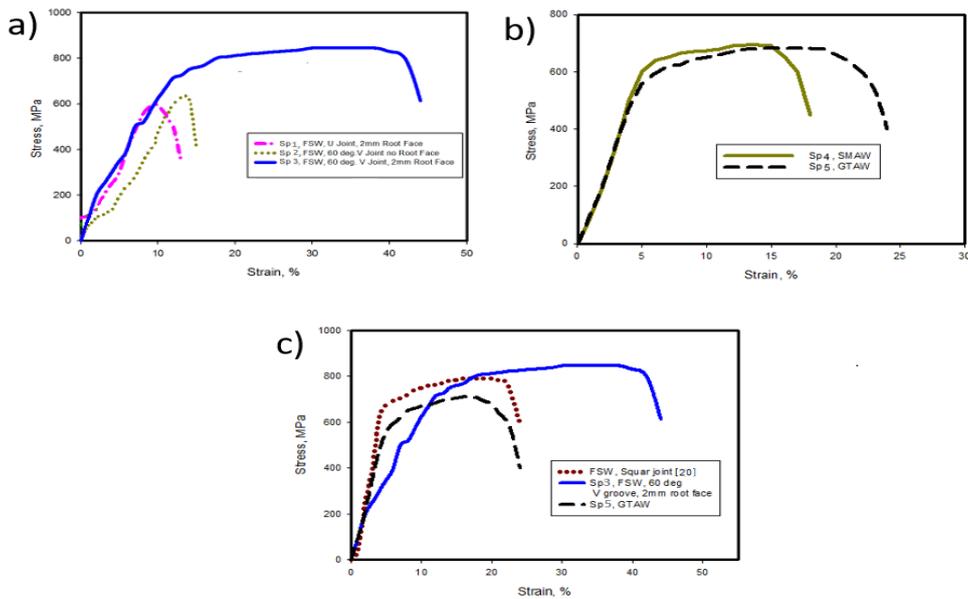


Fig. 8. Stress strain curves for, a) Groove joints welded by FSW, b) Groove joints welded by SMAW and GTAW and, c) A comparison between the best of both groove and square[20] joints welded by FSW, joints welded by SMAW and, joints welded by GTAW.

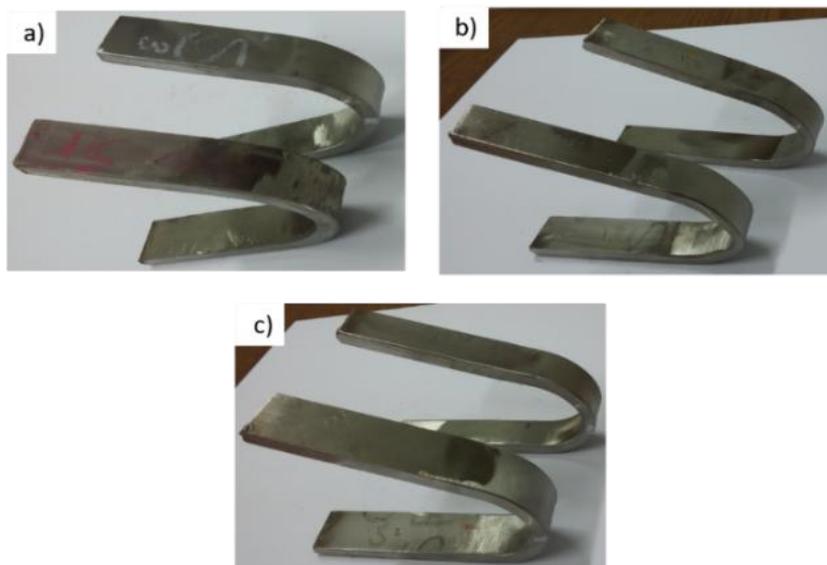


Fig. 9. Bended specimens of welded joints, a) Sp3 FSW joint, b) Sp4 SMAW joint. and c) Sp5 GTAW joint.

Impact Testing Results: The Impact Test at weld metal centerline and the intersection between weld and based material on both sides show that, the average toughness for weld metal and HAZ of joint Sp3, which welded by FSW, were 48 and 75 J respectively, and that for the joints Sp4 and Sp5, which welded by SMAW and GTAW were 26, 63 J, and 47, 70 J respectively, Fig. 10. It is noted that, for groove joints which welded using FSW process, not only strength

and Vickers hardness were improved but also the toughness is improved as well. This could be related to ferrite number and fine grain structures of SZ, TMAZ and HAZ of joint welded using FSW process, compared with the joints welded with SMAW and GTAW processes where, grain coarsening formed due to high heat input during FW caused loss of toughness at HAZ and FZ.

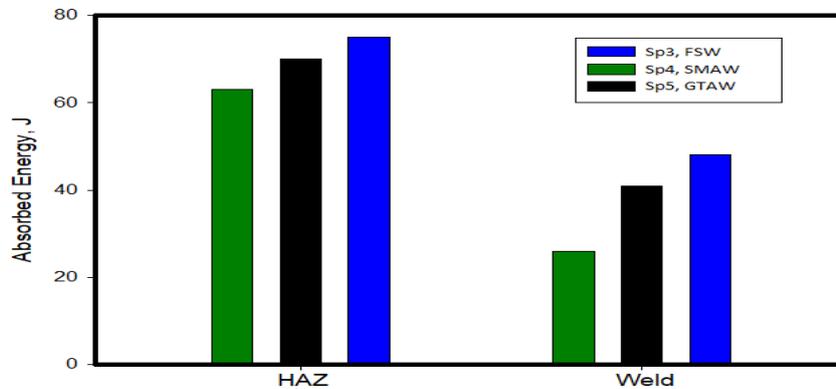


Fig. 10. Impact test at -40°C for joints Sp3 FSW, Sp4 SMAW, and Sp5 GTAW.

Vickers Hardness Testing Results: Figures, 11 - 14, show 3 hardness profiles of the welded SAF 2205 DSS plates, represent three transvers hardness lines at cap, filling, and root, of fusion zone, stir zone, heat affected zone, thermo-mechanically affect zone, and based material for all welded joints. For FSW weldment of Sp3 welded using FSW process, it is markedly obvious that, the overall Vickers

hardness at stir zone reached about 280 HV, slightly higher than the advancing side, and is higher than that of those weldments Sp4 and Sp5, which welded using traditional FW processes SMAW, and GTAW, that is due to grain refining for the joint welded by FSW process and, resulted in an increase in hardness values [14,15,19].

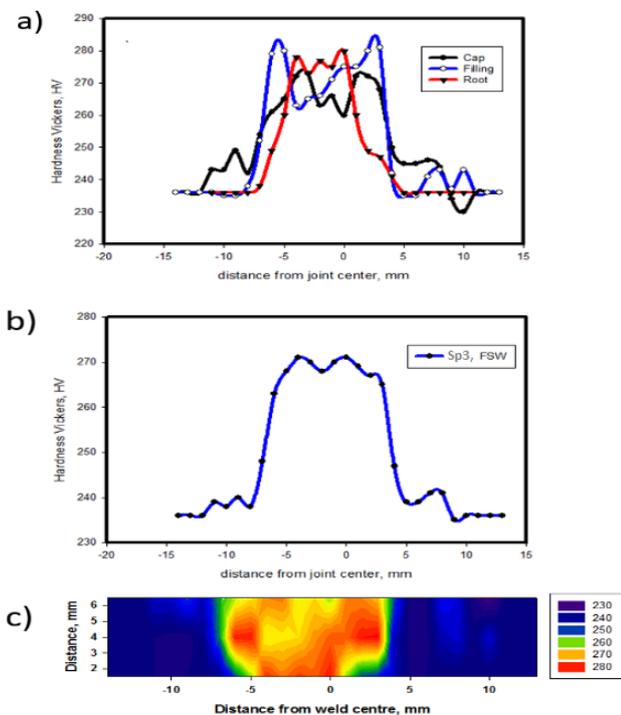


Fig. 11. Sp3, diagrams for, a) Joint zones transverse hardness profiles, b) Average transverse hardness profile, c) Joint HV contour.

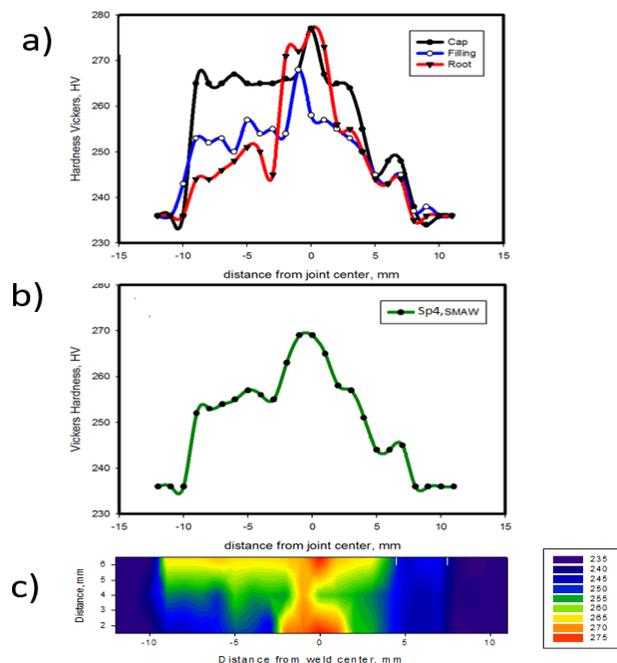


Fig.12. Sp4. diagrams for, a) Joint zones transverse hardness profiles, b) Average transverse hardness profile, c) Joint HV contour.

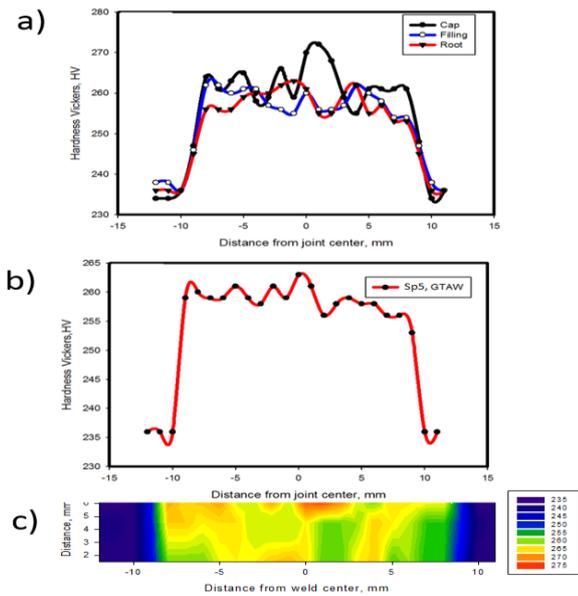


Fig.13. Sp5, diagrams for, a) Joint zones transverse hardness profiles, b) Average transverse hardness profile, c) Joint HV contour.

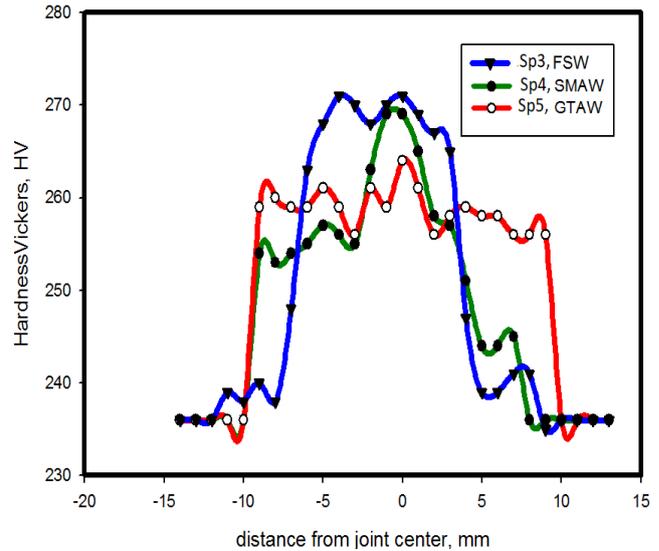


Fig. 14. A comparison diagrams for average transverse hardness profiles for the three joints Sp3, Sp4, and Sp5.

C. Electrochemical Testing Results

Corrosion Testing Results: Corrosion Testing Results show that, the potentiodynamic polarization curves of the SAF 2205 DSS BM, Sp3, Sp4 and Sp5 weldments, have a corrosion potential of -1088 mV, -947.134 mV, -1010 mV, and -1001 mV respectively, and the corresponding average corrosion rates were 3.4522, 0.16916, 0.74132, and, 8.781 mmpy respectively as shown in Fig. 15, suggesting that, FSW joint as a completely nobler than BM, SMAW and GTAW joints. As a whole, this could be related to the high

heat input during fusing welding compared to FSW processes, because of the FSW performed without filler metal and consisted of DSS base metal interfered with itself, which leads to higher corrosion resistance. Furthermore, it significantly noted that, the refining of the specimen's grains due to FSW leads to improving their corrosion resistance. Accordingly, these specimens have higher corrosion resistance than both based metal and fusion welded joints.

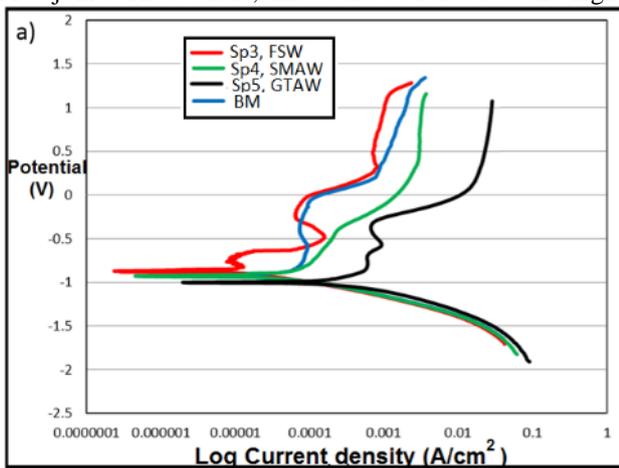


Fig. 15. a) Comparison between tafel polarization curves for, SAF 2205 DSS BM, Sp3 FSW, Sp4 SMAW, and Sp5 GTAW, b) Comparison between the average corrosion rates of the same specimens

IV. CONCLUSION

The effect of different groove joint designs on the mechanical properties and corrosion resistance of friction stir welded SAF 2205 DSS, 6.5 mm thickness plates was investigated. For V joints with, 60° groove angle, 2 mm root face, no root gap, and fixed welding parameters, as traverse speed of 25 mm/min, rotating speed of 300 rpm, axial load of 20 KN, and 3° tilt angle, it is noticed that:

1. Sound welds with good appearance and a very slight reduction in thickness were successfully produced.

2. improving mechanical properties as tensile strength, impact energy, and hardness for produced joints.
3. The groove joints welded by FSW process, have higher corrosion resistance than, both based material, and welded joints using the traditional fusion welding processes SMAW and GTAW.

4. Using of groove joints instead of square joints in FSW of SAF 2205 DSS, with applying the same welding parameters, reduce tool's wear and increase its lifespan about 3.5 times, accordingly, the FSW process can be widely used economically for high strength materials.

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