Research Article

Effect of Binary Oxide Flux on Weld Shape, Mechanical Properties and Corrosion Resistance of 2205 Duplex Stainless Steel Welds

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Received 23 August 2020; Revised 3 October 2020; Accepted 26 October 2020; Published 6 November 2020

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Duplex stainless steel (DSSs) is characterized by excellent corrosion resistance with high strength. Twelve single-component fluxes (TiO2, Fe2O3, Cr2O3, ZnO, ZrO2, CaO, Mn2O3, V2O5, MoO3, SrO, MgO, and La2O3) were tested in the initial experiment using activated Tungsten inert gas (ATIG) technic, and then three couples of oxides were selected as binary fluxes (Fe2O3-Cr2O3, ZnO-Mn2O3, and V2O5-Mn2O3) for the rest of the study. The results show that the depth weld of binary oxides (Fe2O3-Cr2O3, ZnO-Mn2O3) was increased by 3.7 times in comparison with tungsten inert gas (TIG) weld bead. The hardness and the tensile strength of welds carried out with Fe2O3-Cr2O3 and ZnO-Mn2O3 binary fluxes were close to those of the parent metal. Weld bead executed with ZnO-Mn2O3 oxides has more capability to withstand sudden loads. Potentiodynamic polarization tests were performed. The metal welded with flux composed of Fe2O3-Cr2O3 has been found the most resistant to corrosion.

1. Introduction

DSSs are widely used in petrochemical industry, chemical industry, transport/chemical tanks, and offshore-gas which require materials that are more resistant than ordinary stainless steel to corrosive media, high temperatures, and high pressures [1]. The ferrite/austenite ratio in DSS must be close to 50 : 50. The DSSs are characterized by higher strength, higher resistance to pitting corrosion, and resistance against stress corrosion cracking when compared to austenitic stainless steel. DSSs exhibit greater toughness and better weldability than ferritic stainless steel [2]. The two-phase structures of ferrite and austenite combine the beneficial effects of the phases and allow the steel to obtain high strength (ferrite) and toughness (austenite) even at low temperatures [3]. The most convenient method of joining parts is welding. Tungsten inert gas (TIG) welding process is widely applied in the stainless steel fabrication industry when weld quality is required. However, the productivity achieved by this process is low because of its shallow depth of penetration [4]. Achieving full penetration of welds and increasing productivity are the main objectives in the welding industry. Conventional TIG welding can be improved by activated flux. This technic is named activated tungsten inert gas process (ATIG) welding. Oxides, chlorides, and fluorides powders are generally dissolved into acetone or methanol to get a paste that represents an activating flux. A thin layer of flux is deposited prior to the welding operation. Historically, ATIG was invented by the EO Paton Institute of Electric Welding in the sixties [5, 6]. ATIG offers the possibility of increasing the penetration depth using the same conventional TIG welding equipment and parameters. It has the advantage of eliminating the need for edge
preparation, increasing the penetration depth, and reducing the number of weld pass. Consequently, the productivity of the ATIG process could be increased up to 3 times compared to the conventional TIG process [7–21]. Three types of mechanisms were introduced to explain the high penetration of ATIG welds:

(i) Marangoni convection mechanism in TIG process is characterized by centrifugal convection where the molten metal moves from the center of weld pool to the edges, leading to a wide and shallow weld bead [22]. The increase in ATIG weld penetration can be attributed to the reversal of Marangoni convection [23]. The molten metal flows from edges toward the center. The centripetal movement is related to oxygen liberated from oxides during welding operation. Oxygen, tellurium, selenium, and sulfur as surfactant element even in small quantities contribute to having a centripetal convection leading to having a depth weld bead [24–31].

(ii) The arc constriction mechanism is related to the migration of fluorine or chloride toward the ATIG arc weld and reacts with the outer arc electrons. The latter phenomenon contributes to a constriction of the arc. The arc constriction increases the temperature at the anode because of the increase in the current density at the anode (arc spot is constricted). Elements such as fluorides contribute to the increase of the arc voltage associated [32–35].

(iii) The third mechanism was proposed by Sire et al. in 2002 [36,37] and illustrated numerically by Lowke, Tanaka, and Ushio in 2004. The flux used is characterized by high melting point and high electrical resistivity. A flux narrows the electric arc to focus on a small anode spot area. Doing so, the current density increases and the depth weld is enhanced [38, 39].

First, twelve oxides were tested. The single-component fluxes used in the initial experiment were TiO₂, Fe₂O₃, Cr₂O₃, ZnO, ZrO₂, CaO, Mn₂O₃, V₂O₅, MoO₃, SrO, MgO, and LaO₂.

According to the obtained weld aspects, the following oxides Fe₂O₃, Cr₂O₃, ZnO, Mn₂O₃, and V₂O₅ were selected. Three binaries mixed components Fe₂O₃-Cr₂O₃, ZnO-Mn₂O₃, and V₂O₅-Mn₂O₃ were chosen. Design of experiments (DOE) was used to predict the best combination of the tested binary oxides. Mixing method based on a simplex lattice degree one is the key tool used to optimize the flux combination in order to enhance the depth D and D/W ratio. In this study, measurements of the weld bead geometry were performed for evaluation of the DSS 2205 welds quality. Microstructure studies were carried out using the scanning electron microscopy (SEM). For ferrite/austenite proportion measurements, area image processing software of Microvision Instruments was used. Mechanical characterization of the weldments was carried out by conducting the hardness, tensile, and impact tests and corrosion resistance studies have been investigated for TIG and ATIG welds.

Our purpose in this work was to identify the convenient binary flux to get full-penetrated weld bead with lower provided energy, which is the goal sought by industries.

This study can be a contribution to expanding research dedicated to ATIG welding of DSSs since it will allow the selection of the most appropriate oxides to weld 6 mm thickness sheets in a single pass without affecting the mechanical properties and the corrosion resistance of joints.

2. Materials and Methods

2.1. Material. The material used was the DSS grade 2205 whose chemical composition is shown in Table 1.

The experiments consist of welding 20 cm line on a rectangular plate of 6 mm thickness. Before welding, the plates were cleaned with acetone. The flux powders were dried in furnace to eliminate the humidity and then mixed with methanol in 1:1 ratio. A layer less than 0.2 mm thick was then deposited on the surface to be welded.

2.2. Welding Procedure. TIG machine was used. A water-cooled torch with a standard 2% thoriated tungsten electrode rod having a diameter of 3.2 mm has been used for the experiments. The torch was mounted on a motorized carriage as shown in Figure 1. A series of tests have been carried out with 150 A welding current and speed welding of 15 cm/min. As it is recommended to weld DSSs within the range of 0.2–1.5 kJ/mm to avoid precipitation of brittle intermetallic phases [40], a suitable energy of 0.54 kJ/mm is provided. The welding parameters selected for welding are listed in Table 2.

After welding, the samples were cut far from the welding starting point to be sure that the arc welding was stabilized. Specimens for weld morphology, mechanical testing, and corrosion study are shown in Figure 2.

The specimens for morphology study were prepared by the usual metallurgical polishing methods and etched with a solution of one volume of water, one volume of hydrochloric acid (HCL), one volume of nitric acid (HNO₃), and one volume of fluoride acid. Penetration of welds was checked for each cross section using Motic software integrated with an optical microscope.

2.3. Microstructure Study. The microstructure study was conducted on JEOL JSM-7600F scanning electronic microscope (SEM) in order to view the differences in microstructure after the welding in both TIG and ATIG welding. The microstructure was taken on fusion zone.

2.4. Tensile Test. The tensile tests were carried out at room temperature (24°C) with a computer control electrohydraulic servo universal testing machine model WAW-300E at a test rate of 0.5 mm/min. The specimens were cut according to ASTM E8M-04 as shown in Figure 3.

2.5. Hardness Test. Vickers hardness measurements were obtained by a digital hardness tester model HVS-50 according to ASTM E92-82 with a standard load of 98 N. For


Table 1: Chemical composition of duplex stainless steel grade 2205.

| Elements | Weight (%) |
|----------|------------|
| C        | 0.016      |
| Mn       | 1.35       |
| Si       | 0.47       |
| P        | 0.025      |
| S        | 0.001      |
| Cr       | 22.42      |
| Ni       | 5.71       |
| Mo       | 3.15       |
| Nb       | 0.008      |
| Cu       | 0.21       |
| Co       | 0.14       |
| N        | 0.17       |
| Fe       | Balance    |


each sample, the considered result was the average value of nine indentations in the weld bead as well as in heat affected zone (HAZ) as shown in Figure 4. The approximate distance between the two indentation lines is about 0.5 mm.

2.6. Impact Test. The impact tests were performed with the Charpy “V” notch impact testing machine model JBS-500. The specimens were cut according to ASTM E23 and broken in the impact test in the weld zone and in HAZ. Impact tests were carried out on 3 samples for each of the points at room temperature (24°C).

2.7. Corrosion Behaviour. In order to investigate the corrosion resistance, potentiodynamic polarization tests were used by a potentiostat system AUTOLAB-PGSTAT302N. The samples were cut to the dimensions of 20 × 20 mm² and polished to 1200 grit with SiC Emri papers. The tests were conducted on the base metal BM, TIG welded material, and ATIG welded material with three different fluxes. The potentiodynamic tests were carried out at room temperature in 3.5% NaCl and at a scan rate of 1 mV/s. Silver chloride (Ag/AgCl) was used as the reference electrode, platinum (Pt) as the auxiliary electrode, and the sample as the working electrode.

2.8. Design of Experiment Methodology. Design of experiments (DOE) is a systematic, rigorous approach to engineering problem-solving. DOE is used to obtain the maximum amount of useful information with the least amount of experimentation. The mixing method is larger recommend technique when combinations of two or more elements or compounds are mixed. For the DOE, the mixing method in Minitab 17 software (Version 17.1.0, Minitab, LLC, Pennsylvania, USA) was applied.

First of all, twelve oxides were tested. Among these oxides, three pairs of oxides were selected as three binary fluxes. Based on the simplex lattice degree one designs, 5 combinations have been selected for each binary. The optimizer module available in Minitab 17 was used to get the optimal formulation of flux for each binary which is expected to give the best depth and D/W ratio of the weld. Finally, using the optimal formulation, the ATIG welds line has been carried out and used in the rest of the study.

3. Results and Discussion

3.1. Weld Bead Aspect

3.1.1. Mixture Design. In order to compare the effect of monoxide on the weld bead aspect. Twelve oxides (TiO₂, Fe₂O₃, Cr₂O₃, ZnO, ZrO₂, CaO, Mn₂O₃, V₂O₅, MoO₃, SrO, MgO, and LaO₃) were tested. The results of the morphology of single oxide are reported in Table 3.

The oxides selected must fulfill two major criteria. Welds must have higher depth penetration D and ratio D/W must be equal or greater than the target value of 0.8 [41,42]. According to the previous criteria, the following oxides Fe₂O₃, Cr₂O₃, ZnO, Mn₂O₃, and V₂O₅ have been selected. The second step in our study was to select a pair of oxides based on two criteria. The first one consists of comparing the melting temperature of the two components of the binary oxides with the melting temperature of DSS. Hence, the first binary oxides (Fe₂O₃, Cr₂O₃) are characterized by their melting temperature which is greater than that of DSS 2205. The second binary is composed of ZnO oxide which has a high melting temperature and Mn₂O₃ oxide which has a lower melting point compared to DSS 2205. Finally, the third binary oxide is constituted by two oxides V₂O₅-Mn₂O₃ whose melting points are lower than the duplex 2205 melting point as shown in Table 4.

The second criterion consists of categorizing the three binaries in three levels of estimated average weighted dissociation energy (ΔHₛ) as shown in Table 5. From this table, we can see that the third binary V₂O₅-Mn₂O₃ necessitates the highest energy to liberate oxygen. On the other hand, a second binary ZnO-Mn₂O₃, needs the lowest estimated dissociation energy. In the latter case, oxygen is liberated earlier in order to play its role as a surfactant. Based on weld morphology results, we will be able to judge the most appropriate criteria that we should consider in the selection of the oxides for DSSs.

Based on the simplex lattice degree one design, five combinations have been prepared for each binary flux. The optimizer module available in Minitab 17 has been used to get the optimal formulation of flux which is expected to give the best depth D and D/W ratio of the weld. Finally, using the optimal formulation, ATIG weld line has been carried out as well as another weld line without flux (TIG).

The results of the depth D and D/W ratio for different proportions of the three selected binary oxides are shown in Table 6.

Optimiser module available in Minitab software, version 17, was used to predict the responses of the optimal flux with the level of desirability up to 0.99 for both depth D and D/W ratio. The composite desirability is very close to 0.99 which indicates that the parameters achieved favorable results for all responses, which means that both responses are within their acceptable limits. The optimal combinations of binary
oxides are represented in Table 7. The predicted values are listed in Table 8.

3.1.2. Experimental Validation. The confirmation test is the last step in the experimental process. A confirmation test was conducted based on the optimum flux composition obtained in the Mixing Design method. The experimental values of depth \( D \) and \( D/W \) ratio of the optimal flux ATIG weld are reported in Table 9. The results show that the depths \( D \) of ATIG 1 and ATIG 2 are greater than TIG weld by 3.7 times. The depth of ATIG 3 weld is greater than TIG weld by 3.55 times. Compared to the TIG ratio, the ratio \( D/W \) was improved by 5.3, 5.7, and 3.7 times, respectively, from first binary to the third binary.

The penetration weld of optimized flux is greater than the maximum value predicted by software values. Based on morphology results, the ATIG 1 and ATIG 2 welds exhibit deeper weld penetration (7.4 mm) compared to the remaining binary. ATIG 2 weld presents the highest \( D/W \) ratio (1.30) followed by ATIG 1 weld (1.23). It seems that taking the melting temperature alone as a criterion is not appropriate to select the expected oxides to use. However, dissociation energy could be taken into consideration to select the oxides. It is necessary to avoid oxides with high energy of dissociation; otherwise, the provided energy will be lost to liberate activating elements.

TIG molten metal behaves as pure metal with centrifugal convection leading to wide and shallow weld bead as shown in Figure 5(a). However, ATIG weld metal has a centripetal movement related to oxygen liberated from oxides during the welding operation as shown in Figures 5(b)–5(d). In ATIG technic the full-penetrated weld is achieved in a single pass which prevents the formation of a secondary austenite phase [43].

3.1.3. Microstructural Assessment. Micrographs are represented in Figures 6(a)–6(d). The weld bead microstructure consists mainly of a matrix of \( \delta \) ferrite and various types of austenite as reported by various authors [44]. The formation of austenite in DSS 2205 begins initially on intergranular sites named grain boundary austenite (GBA) and then follows the formation of side plates (slats) Widmanstätten austenite (WA) and intragranular austenite (IGA) sites in \( \delta \) ferrite matrix. The appearance of intragranular austenite (IGA) type is in globular form. We notice that the density of intragranular austenite (IGA) decreases in the case of ATIG 3 weld bead as shown in Figure 6(d).

For DSS, degradation of mechanical properties due to unbalanced ferrite/austenite proportions can be considered as a serious issue during the welding operation. The measurement of austenite proportions in the ferrite matrix was performed using areas image processing software from Microvision Instruments as shown in Figures 7(a)–7(d). The measurements were taken in 5 different locations in the weld zone (one in the symmetric axis of the weld and the
Figure 4: Hardness test locations in the FZ and HAZ of ATIG (a) and TIG (b).

Table 3: Morphology of single oxide ATIG welds.

| Oxides  | TiO<sub>2</sub> | Fe<sub>2</sub>O<sub>3</sub> | Cr<sub>2</sub>O<sub>3</sub> | ZnO | ZrO | CaO | Mn<sub>2</sub>O<sub>3</sub> | V<sub>2</sub>O<sub>5</sub> | MoO<sub>3</sub> | SrO | MgO | LaO<sub>2</sub> |
|---------|----------------|-----------------|-----------------|-----|-----|-----|----------------|----------------|----------------|-----|-----|----------------|
| W (mm)  | 8.90           | 8.50            | 8.29            | 8.08| 8.24| 7.50| 9.20           | 9.34           | 8.50           | 8.50| 8.50| 8.34           |
| D (mm)  | 6.30           | 6.80            | 6.80            | 7.15| 4.00| 3.50| 7.45           | 9.64           | 6.70           | 3.70| 3.50| 4.00           |
| D/W     | 0.71           | 0.80            | 0.82            | 0.88| 0.49| 0.47| 0.81           | 1.03           | 0.79           | 0.44| 0.42| 0.53           |

Table 4: Comparison between melting temperature of oxides and duplex stainless steel.

| Oxides  | Melting point (°C) | Melting point of DSS 2205 (°C) | ΔT = |Tm 2205 − Tm oxide| Binary fluxes |
|---------|--------------------|--------------------------------|------|----------------|----------------|
| Fe<sub>2</sub>O<sub>3</sub> | 1565               | 120°C (Tm oxide is higher than Tm 2205) | Fe<sub>2</sub>O<sub>3</sub>-Cr<sub>2</sub>O<sub>3</sub> |
| Cr<sub>2</sub>O<sub>3</sub> | 2335               | 890°C (Tm oxide is higher than Tm 2205) | Fe<sub>2</sub>O<sub>3</sub>-Cr<sub>2</sub>O<sub>3</sub> |
| ZnO     | 1975               | 530°C (Tm oxide higher than Tm 2205) | Fe<sub>2</sub>O<sub>3</sub>-Cr<sub>2</sub>O<sub>3</sub> |
| Mn<sub>2</sub>O<sub>3</sub> | 940                | 505°C (Tm oxide less than Tm 2205) | ZnO-Mn<sub>2</sub>O<sub>3</sub> |
| V<sub>2</sub>O<sub>5</sub> | 670                | 775°C (Tm oxide less than Tm 2205) | V<sub>2</sub>O<sub>5</sub>-Mn<sub>2</sub>O<sub>3</sub> |
| Mn<sub>2</sub>O<sub>3</sub> | 940                | 505°C (Tm oxide less than Tm 2205) | V<sub>2</sub>O<sub>5</sub>-Mn<sub>2</sub>O<sub>3</sub> |

Table 5: Estimated average weighted dissociation energy.

| Oxides  | Fe<sub>2</sub>O<sub>3</sub> | Cr<sub>2</sub>O<sub>3</sub> | ZnO | Mn<sub>2</sub>O<sub>3</sub> | V<sub>2</sub>O<sub>5</sub> | Mn<sub>2</sub>O<sub>3</sub> |
|---------|-----------------|-----------------|-----|----------------|----------------|----------------|
| ΔH<sub>f</sub> (KJ/mol) | 822.2           | 1139.7          | 350.6| 957.5         | 1550.6         | 957.5         |
| ΔH<sub>f</sub> (KJ/mol) | 981             | 654             | 1254| 1254          | 1254           | 1254 |

Table 6: Different compositions of fluxes, depth of D and D/W.

| Exp. no. | Fe<sub>2</sub>O<sub>3</sub> (%) | Cr<sub>2</sub>O<sub>3</sub> (%) | D (mm) | W (mm) | D/W | ZnO (%) | Mn<sub>2</sub>O<sub>3</sub> (%) | D (mm) | W (mm) | D/W | V<sub>2</sub>O<sub>5</sub> (%) | Mn<sub>2</sub>O<sub>3</sub> (%) | D (mm) | W (mm) | D/W |
|----------|-----------------|-----------------|--------|-------|-----|--------|----------------|--------|-------|-----|----------------|----------------|--------|-------|-----|
| 1        | 100             | 0               | 6      | 4     | 1.5 | 100    | 0                | 3.6    | 7.2   | 0.50| 100            | 0                | 6      | 4.83  | 1.24 |
| 2        | 75              | 25              | 6.1    | 4.32  | 1.41| 75     | 25               | 4.90   | 6.7   | 0.73| 75            | 25               | 5.6    | 4.62  | 1.21 |
| 3        | 50              | 50              | 4.6    | 4.1   | 1.12| 50     | 50               | 6.92   | 6.59  | 1.05| 50            | 50               | 5.3    | 4.60  | 1.15 |
| 4        | 25              | 75              | 5      | 4.2   | 1.19| 25     | 75               | 5.28   | 7.04  | 0.75| 0              | 100              | 5.5    | 4.58  | 1.2  |
| 5        | 0               | 100             | 6      | 5     | 1.2 | 0      | 100              | 5.93   | 6.89  | 0.86| 25            | 75               | 5.5    | 4.58  | 1.2  |
Table 7: The optimal composition of flux.

| Compositions                  | Binary flux 1 ATIG 1 | Binary flux 2 ATIG 2 | Binary flux 3 ATIG 3 |
|------------------------------|----------------------|----------------------|----------------------|
| 89% Fe₂O₃ + 11% Cr₂O₃       | 89% Fe₂O₃ + 11% Cr₂O₃| 89% Fe₂O₃ + 11% Cr₂O₃|
| 59% ZnO + 41% Mn₂O₃        | 59% ZnO + 41% Mn₂O₃ | 59% ZnO + 41% Mn₂O₃ |
| 92% V₂O₅ + 8% Mn₂O₃         | 92% V₂O₅ + 8% Mn₂O₃ | 92% V₂O₅ + 8% Mn₂O₃ |

Table 8: Predicted responses (D, D/W) of weld executed with optimal flux.

| Responses | Binary flux 1 | Binary flux 2 | Binary flux 3 | Desirability (%) |
|-----------|---------------|---------------|---------------|------------------|
| D (mm)    | 6.66          | 5.9           | 6             | 99               |
| D/W       | 1.5           | 0.85          | 1.2           | 99               |

Table 9: Morphology of TIG and ATIG welds.

|          | ATIG 1 | ATIG 2 | ATIG 3 | TIG  |
|----------|--------|--------|--------|------|
| D (mm)   | 7.4    | 7.4    | 7.1    | 2.0  |
| W (mm)   | 6      | 5.7    | 8.3    | 8.83 |
| D/W      | 1.23   | 1.30   | 0.85   | 0.23 |

Figure 5: Morphology of TIG and ATIG welds: (a) TIG, (b) ATIG 1, (c) ATIG 2, and (d) ATIG 3. (a) TIG weld bead. (b) ATIG 1 weld bead. (c) ATIG 2 weld bead. (d) ATIG 3 weld bead.
two others on both sides of the axis) and the results were the average of these measurements.

The results reported in Table 10 show that the ferrite proportion is up to 59% when the conventional TIG process was used. However, the ferrite proportions of ATIG 1 and ATIG 2 present a mean value of 54% and 52%, respectively. Generally, the ferrite proportion in DSS parent metal is about 48–50%. The binary fluxes used in ATIG 1 and ATIG 2 welds enable getting mechanical properties close to the parent metal. This phenomenon is particularly noticeable with binary oxides used in ATIG 2 where the ferrite proportion is maintained in acceptable limits. Contrariwise, the ferrite proportion of ATIG 3 rises to 58% which can be considered as the higher limit to avoid deterioration of mechanical properties and corrosion resistance. Table 10 shows also standard deviation (σ) which represents a measure of the amount of variation or dispersion of a set of values. We notice that the Standard deviation is less than 5.

3.2. Mechanical Testing

3.2.1. Hardness Test. The conducted experimental values obtained for hardness in fusion zone (FZ) are shown in Table 11. The mean value of hardness of TIG (284 HV) is slightly higher than the mean hardness values of all binary tested fluxes specimens. The mean hardness value of ATIG 3 is 278 HV which is greater than those of ATIG 1 (273 HV) and ATIG 2 (275 HV). This result can be mainly attributed to the difference in ferrite proportions in the weld bead. As cited above, the ferrite proportions of ATIG 3 are higher than those of ATIG 1 and ATIG 2. Moreover, Table 11 shows small disparities in the hardness values of the maximum and minimum obtained which indicate hardness homogeneities in the joint.

For hardness measurements in FZ, the standard deviation is less than 9 HV.

The conducted experimental values obtained for hardness in HAZ are shown in Table 12. The hardness of ATIG weld in HAZ is not affected by the used type of binary flux. Since all ATIG beads are full-penetrated and have slightly the same profiles, the cooling rate is almost the same and, consequently, they probably have the same ferrite/austenite proportions. The result of TIG hardness in HAZ (267 HV) is slightly higher than the results of the ATIG welds which are (263, 265, and 261 HV) for ATIG 1, ATIG 2, and ATIG 3, respectively. This difference in hardness is due to excess of ferrite fraction related to fast cooling seen in the shallow TIG weld bead. For hardness measurements in HAZ, the standard deviation is less than 5.5 HV.

3.2.2. Tensile Test. The conducted experimental values obtained for ultimate tensile strength (UTS) are shown in Figure 8. The UTS of ATIG 2 has a higher value than that of TIG and also of the remaining ATIG welds while the
Figure 7: Ferrite/austenite proportions measurements for TIG and ATIG welds (SEM magnification 200×). (a) TIG weld zone (200×). (b) ATIG 1 weld zone (200×). (c) ATIG 2 weld zone (200×). (d) ATIG 3 weld zone (200×).

Table 10: Ferrite volume fraction measurement.

| Sample   | Number of measurements | Minimum measured | Maximum measured | Mean ferrite (%) | Standard deviation σ |
|----------|------------------------|------------------|------------------|------------------|---------------------|
| TIG      | 5                      | 56               | 62               | 59               | 4.76                |
| ATIG 1   | 5                      | 52               | 58               | 54               | 2.90                |
| ATIG 2   | 5                      | 49               | 56               | 52               | 4.94                |
| ATIG 3   | 5                      | 55               | 60               | 58               | 2.82                |

Table 11: Measurements of hardness of TIG and ATIG in FZ.

| Sample   | Number of measurements | Min hardness HV | Max hardness HV | Mean hardness HV | Standard deviation σ |
|----------|------------------------|-----------------|-----------------|------------------|---------------------|
| TIG      | 9                      | 272             | 293             | 284              | 7.79                |
| ATIG 1   | 9                      | 261             | 291             | 273              | 8.89                |
| ATIG 2   | 9                      | 263             | 289             | 275              | 8.32                |
| ATIG 3   | 9                      | 273             | 287             | 278              | 4.20                |

Table 12: Measurements of hardness of TIG and ATIG in HAZ.

| Sample   | Number of measurements | Min hardness HV | Max hardness HV | Mean hardness HV | Standard deviation σ |
|----------|------------------------|-----------------|-----------------|------------------|---------------------|
| TIG      | 9                      | 263             | 278             | 267              | 4.63                |
| ATIG 1   | 9                      | 251             | 271             | 263              | 5.42                |
| ATIG 2   | 9                      | 256             | 271             | 265              | 5.31                |
| ATIG 3   | 9                      | 259             | 269             | 261              | 4.80                |
UTS value of ATIG 3 is the lowest one. The difference in tensile strength between the ATIG 1 weld (790 MPa) and parent material (825 MPa) is small. On the other hand, the UTS of ATIG 2 weld is equal to the UTS of the parent material.

WenoticethatthefracturesofTIG,ATIG1,andATIG2weldsoccurfarfromtheweldzonewhereastheyoccuratthe weld bead for ATIG 3.

3.2.3. Impact Test. Due to a small penetration attained in TIG weld bead (2 mm) and very narrow HAZ width, the impact test has been carried out only on ATIG welds.

The impact test values were obtained from the experimental work which is shown in Tables 13 and 14. The absorbed energy in FZ and in HAZ has high values in the case of ATIG 2 welds compared to ATIG 1. Moreover, ATIG 3 weld has the least ability to withstand sudden loads. The absorbed impact energy in ATIG 3 decreases due to the presence of ferrite at high levels (around 58%). The lower toughness in FZ in comparison to HAZ can be explained by the high oxides in FZ. For all impact test measurements, the standard deviation is less than 10 J/cm².

Figure 9 represents fractographic images of impact Charpy “V” notch test conducted on scanning electronic microscope (SEM). The micrographs in Figures 9(a) and 9(b) taken in FZ show the formation of microvoids, with multiple dimples which demonstrate that the fracture is in a ductile mode for ATIG 1 and ATIG 2 whereas, for ATIG 3, the weld bead shows smaller impact energy, and absence of dimple networks as shown in Figure 9(c). A similar correlation between dimple and impact energy was reported by several authors [45,46].

3.2.4. Corrosion Resistance Investigation. Figure 11 shows the obtained potentiodynamic curves of DSS base metal BM, TIG welded material, and ATIG welded material with three different fluxes ATIG 1, ATIG 2, and ATIG 3.

The electrochemical parameters are listed in Table 15. The results show a significant influence of different fluxes on the corrosion behavior of DSS welds. The corrosion potential is a static indicator of electrochemical corrosion resistance, which reveals the susceptibility of materials to corrosion, and the corrosion rate is a kinetic characteristic of surface material. It was observed that there is a shift in corrosion potential $E_{cor}$ in NaCl environment to more positive value from base metal to different weld metals. This $E_{cor}$ shift toward the positive potential from base metal is followed by welded samples ATIG 2, TIG, ATIG 3, and ATIG 1, respectively. On the other hand, the value of the corrosion rate was larger for base metal than the welded samples. The lower corrosion rate value was found to be in ATIG 1 as compared to other samples. It is evident that the metal welded with flux composed of 89% Fe₂O₃ and 11% Cr₂O₃ had a higher corrosion potential $E_{cor}$ (~605 mV) and a lower corrosion rate (CR = 0.109 mm/y), which indicate that the weld obtained from this flux exhibits better corrosion resistance than the weld obtained from other fluxes and TIG weld as well as the base metal.
Table 14: Absorbed energy in FZ for ATIG welds.

| Sample | Number of measurements | Min energy absorbed (J/cm²) | Max energy absorbed (J/cm²) | Mean energy absorbed (J/cm²) | Standard deviation σ |
|--------|------------------------|-----------------------------|----------------------------|-------------------------------|----------------------|
| ATIG 1 | 3                      | 171                         | 189                        | 181                           | 9.19                 |
| ATIG 2 | 3                      | 215                         | 230                        | 223                           | 6.36                 |
| ATIG 3 | 3                      | 141                         | 160                        | 152                           | 9.89                 |

Figure 9: Fractograph of duplex stainless steel 2205 impact charpy "V" notch in TIG and ATIG in welded zone. (a) ATIG 1 FZ (500×). (b) ATIG 2 FZ (500×). (c) ATIG 3 FZ (500×).

Figure 10: Continued.
4. Conclusions

The present work investigated the effects of binary oxides fluxes (Fe$_2$O$_3$, Cr$_2$O$_3$; ZnO, Mn$_2$O$_3$; and V$_2$O$_5$, Mn$_2$O$_3$) on bead geometry, the mechanical behavior of weldment, and corrosion resistance of DSS 2205 sheet produced by ATIG welding. According to the obtained results, the following conclusions can be drawn:

(i) All optimal binary fluxes give full-penetrated welds. The ratios for all welds were greater than a target value of 0.8. The highest depth weld bead was achieved by the 89% Fe$_2$O$_3$ + 11% Cr$_2$O$_3$ and 59% ZnO + 41% Mn$_2$O$_3$ combinations composed of 89% Fe$_2$O$_3$, 11% Cr$_2$O$_3$. The depth weld of binary 1 was increased by 3.6 times (7.4 mm) in comparison to the conventional TIG weld bead (2.8 mm).
(ii) The oxide dissociation energy is an important criterion to select oxides fluxes for any stainless steel TIG weld operation. It is necessary to avoid the oxides with high enthalpy of formation; otherwise, there will be loss of energy during the welding operation. 

(iii) The microstructure of welds in DSS is composed of a matrix ferrite, austenite at the boundary ferrite grains, Widmanstätten, and intragranular austenite. There is neither trace of secondary austenite nor trace of the intermetallic phases. The balance of ferrite/austenite proportions was close to parent metal for welds executed by binary 89% Fe$_2$O$_3$ + 11% Cr$_2$O$_3$ and binary 59% ZnO + 41% Mn$_2$O$_3$.

(iv) The hardness and tensile strength were not significantly affected by using binary 1 and binary 2. The weld carried out using flux 59% ZnO + 41% Mn$_2$O$_3$ has the highest impact resistance.

(v) The metal welded with flux composed of 89% Fe$_2$O$_3$ and 11% Cr$_2$O$_3$ has better corrosion resistance.

**Data Availability**

The data used to support the findings of this study are included within the article.

**Conflicts of Interest**

The authors declare no conflicts of interest.

**Acknowledgments**

This work was supported by the Deanship of Scientific Research at Prince Sattam Bin Abdulaziz University, KSA, under the research project number 2019/01/11045.

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