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Characterization of duplex stainless steel weld by Activated TIG welding and its variants

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Abstract: Activated Tungsten Inert Gas (A-TIG) welding, Flux Bounded TIG (FB-TIG) welding and Flux Zone TIG (FZ-TIG) welding are novel chronological variants of TIG welding. These are capable enough to produce more sustainable welds in stainless steel alloys. The present article represents the comparative study on A-TIG welding, FB-TIG and FZ-TIG welds. The single-component activated flux is selected to examine the effect of flux on A-TIG, FB-TIG and FZ-TIG welded 2205 duplex stainless steel. The highest penetration is observed in FZ-TIG welding owing to strong arc constriction and Reversal of Marangoni convection. Further, the microstructure and mechanical properties (i.e. angular distortion, tensile strength and microhardness) are analyzed and compared. The metallurgical characterization of the weldment indicated distinct grain morphologies well in the weld zones compared to a base metal. The peak hardness is observed in FB-TIG weld due to lower heat input. However, FZ-TIG welding is suggested to be a distinguished practice to achieve the utmost weld penetration and tensile strength.

Keywords —: Activated Tungsten Inert Gas welding, Flux Bounded Tungsten Inert Gas welding Flux zone Tungsten Inert Gas welding, microstructure, mechanical properties, penetration.

I. INTRODUCTION

Stainless steel (SS) is an alloy that has high corrosion resistance, weldability, extensive service life, and formability. Stainless steel is a widely used material in various industries such as automotive, construction, defense, rolling, chemical processing, household materials and aerospace [1-3]. Among all stainless steel groups duplex stainless steel typically comprises microstructures consisting of approximately equal proportions of body-centered cubic ferrite and face-centered cubic austenite [4,5]. Duplex stainless steel offers greater mechanical strength and higher corrosion resistance to chloride-induced stress corrosion cracking than most types of stainless steel [6]. Among the various fabrication methods, tungsten inert gas (TIG) is one of the most popular welding processes employed for welding stainless steels, aluminum alloys, titanium alloys and other non-ferrous metals because of its good weld bead surface and high-quality weld metal at low-cost equipment. It is suitable for both thick and thin stainless steel plate [7,8]. However, the TIG welding process possesses limitations like low penetration depth in a single pass, groove design and multipass is required to weld thick sections which decrease productivity and increase the cost of the process. which are less suitable for industrial use [9].

Activating flux tungsten inert gas welding for enhanced weld penetration, initially proposed by Paton Electric Welding Institute of the National Academy of Sciences, Ukraine in the mid-1960s.

A thin layer of activating flux has sheltered the surface of the joint to be welded. The activating fluxes of micro-size are mixed with acetone or ethanol to form a sort of paste. This paste is applied through brushed or with an aerosol applicator like a spray on the required area of the workpiece before welding with optimal coating density as shown in figure 1[12]. Activated flux with TIG (A-TIG) welding has been successfully applied on ferrous as well as on non-ferrous materials for deeper penetration and better mechanical properties [10,11,13].

During the A-TIG welding activated flux produces the resistance to arc and later phase vaporized and constrict the arc column. The energy required for melting the flux reduces the welding efficiency. Moreover, during the welding, it is difficult to track the weld line due to the complete convergence of the weld line with flux.

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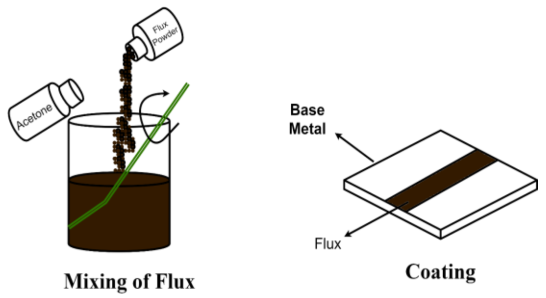

Figure I Mixing and coating of activated flux [12]

Also, after A-TIG welding entrapped flux particles create a poor weld bead surface appearance [14]. These challenges of the A-TIG welding process are overcome by a novel chronological approach, Flux Bounded TIG welding and Flux Zone TIG welding processes.

Sire and Marya (2001) first addressed the Flux Bounded TIG (FB-TIG) welding process on aluminium alloys. In the FB-TIG process, flux coating is applied on two parallel strips by keeping a predetermined gap at the weld line. Hence, the welding arc directly approaches the weld metal directly. Singh et al. (2017) and other researcher reveals that FB-TIG welding was successfully increasing the penetration depth than TIG weld in stainless steel alloys and overcome the limitation of A-TIG weld. However, a slight reduction in penetration than A-TIG weld was observed [12,15].

The new chronological variant FZ –TIG welding is proposed by Huang et al. (2012) modifying the activating flux coating method, established on the concept of arc constriction. The activating flux with a lower melting point, boiling point and current resistivity is applied to the central region of the weld line and activating flux with a higher melting point, boiling point and current resistivity are applied on the side regions of the weld surface before TIG welding respectively. Huang et al. (2012) reported that FZ –TIG welded joint shows a thrice depth of penetration than TIG weld along with the improved surface appearance and mechanical properties in aluminum alloys [16]. Though, a study has not been reported in stainless steel alloys.

In the present work comparative study on A-TIG welding, FB-TIG and FZ-TIG welds are performed under secure weld conditions. Further, the macrostructure, microstructure and mechanical properties (i.e. angular distortion, tensile strength and microhardness) are analyzed and compared.

II. EXPERIMENTAL STUDY

Duplex stainless steel (DSS)2205 plate having the dimensions 50mm×100mm×6mm are prepared by cleaning and polishing with abrasive paper. All experiments are performed on TIG welding (Ador welding) machine as shown in figure 2(a). To maintain the constant arc-length, welding speed and torch angel welding fixture is manufactured by the same authors. As shown in figure 2 (b).

Figure 2 (a) Welding machine (b) welding fixture

According to Ellingham diagram SiO2 flux has a lower amount of Gibbs free energies [17]. Hence, the resistance to the thermal decomposition at elevated temperature is lower in SiO_2. Which dissolved in the weld pool and increase the oxygen content, result in higher penetration [18]. Therefore, to perform A-TIG and FB-TIG welding SiO2 flux is selected. In FZ-TIG welding, SiO2 is selected as inner region which acts as an insulator and constrict the arc column. while Cr_2O_3 flux higher resistivity is selected as outer region flux to attain the best weld bead geometry. The selected fluxes physical properties are shown in table 1.

Table 1. Physical properties of selected oxide flux

Flux	Density (ϱ) (gm/cm^3)	Melting point ^{0}C	Boiling point^{0}C	DG kJ/mol
Silicon dioxide (SiO_2)	2.65	1600	2230	-856
Chromium(III) oxide Dichromium trioxide (Cr_2O_3)	5.22	2435	4000	-1053

A-TIG, FB-TIG and FZ-TIG welding experiments are performed at prefixed parameters as shown in table 2. Parameters are selected from literature.

Table 2 Welding parameters

Welding parameters	Value
Current	185A
Welding speed	120 mm/min
Shielding gas flow rate	12 l/min
Shielding gas	Argon
Vertex angle of electrode	45^0
Electrode	Thoriated Tungsten, Diameter 2.5 mm
Conical length of electrode	3 mm
Torch angle	90^0
Arc length	2mm

Before welding. selected oxide flux mixed with acetone and form a paste like consistency. This paste is spread uniformly on weld metal as shown in figure 3(a) A-TIG

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welding figure 3(b) FB-TIG welding (2mm flux gap) and figure 3 (c) FZ-TIG welding.

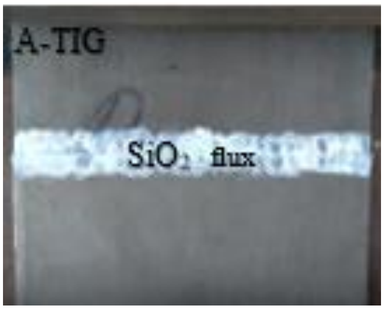

Figure 3 (a) A-TIG flux applied surface

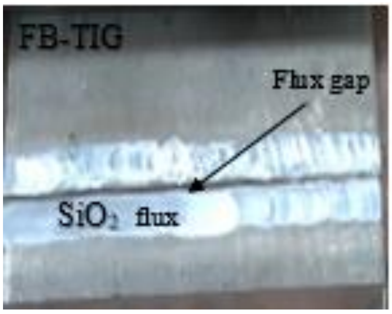

Figure 3 (b) FB-TIG flux applied surface

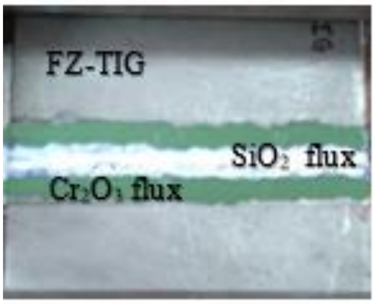

Figure 3 (c) FZ-TIG flux applied surface

After the welding, the weld metal traverse section is detached to analyze the metallurgical and mechanical properties of A-TIG, FB-TIG and FZ-TIG welds. Macrostructure is observed in stereographic microscope and microstructure study performed through optical microscopy. Angular distortion is measured by a digital Vernier height gauge. Microhardness is measured under the load of 100 gf with a dwell time of 10 seconds and tensile testing is performed as per ASME Section IX on the universal testing machine.

III. Result and Discussion

A. Compression of weld bead macrostructure and microstructure

A-TIG, FB-TIG and FZ-TIG welding macrostructures are shown in figure 4. The highest penetration 6.7mm (depth to width ratio 0.9) is achieved in FZ-TIG weld metal. This attributes to constrict arc constriction, insulation effect and reversal of Marangoni convection. Minimum penetration is observed in FB-TIG weld due to weak Marangoni convection. The observed heat input and depth to width ratio is reported in table 3. Maximum heat input is observed in FZ-TIG welding whereas minimum heat input is observed in FB-TIG welding, this is due to less arc interaction with a side region flux and forming a less intense heat density compare to A-TIG and FZ-TIG welding.

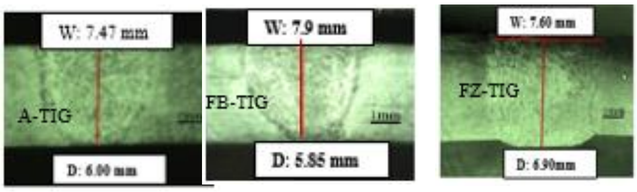

Figure 4 Weld bead geometry

Table 3 Welding process heat input and depth to width ratio

Welding Process	Flux	Voltage (Amp)	Heat input (KJ/mm)	D/W
A-TIG	SiO_2	14.8	1.37	0.80
FB-TIG	SiO_2	14	1.30	0.74
FZ-TIG	SiO_2 and Cr_2O_3	16.5	1.53	0.90

Microstructure of A-TIG, FB-TIG and FZ-TIG studies. The parent metal microstructure of 2205 DSS is shown in figure 5 (a) shows the islands of light green color austenite phase in a dark green ferrite matrix. The 2205 DSS weld pool initially solidified as delta ferrite and then as austenitic phase due to the presence of ferrite stabilizers [19].

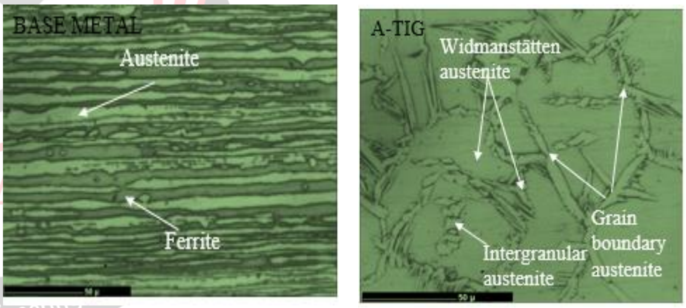

Figure 5 (a) base metal of 2205 DSS (b)A-TIG weldzone

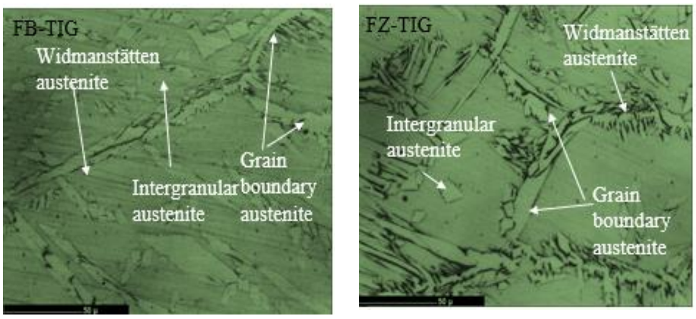

Figure 5 (c) FB-TIG weld zone (d) FZ-TIG weld zone

During the A-TIG, FB-TIG and FZ-TIG welding applied activated flux increases the heat input and thereby the temperature of weld metal. Therefore, the cooling rate is reducing and the formation of delta ferrite to the austenite phase is complete. The weld pool austenite is converted in wedge-shaped Widmanstätten austenite, grain boundary

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austenite and intergranular precipitates in a matrix of ferrite as shown in figure 5(b-d). similar observations are reported by Muthupandi et al. [20] in A-TIG weld metal. Due to higher heat input in FZ-TIG weld than FB-TIG weld more amount of Widmanstätten austenite is observed.

B. *Comparison of mechanical properties*

During the A-TIG, FB-TIG and FZ-TIG welding non-uniform expansion is produced which distorts the weld structure. The deviation in angular distortion is affected by penetration, bead width and plate thickness [21]. The effect of distortion after A-TIG welding was reported by Vasantharaja et al. (2012) in 316LN stainless steel by vertical electronic height gauge [22]. In the present study, the angular distortion of welded plates is measured by a digital Vernier height gauge as shown in figure 6. A-TIG welding and its variants increase the weld penetration and depth to width ratio due to a high degree of energy concentration. So overheating of base metal is prevented and reduces the thermal stress and thereby reduces angular distortion in the weld metal.

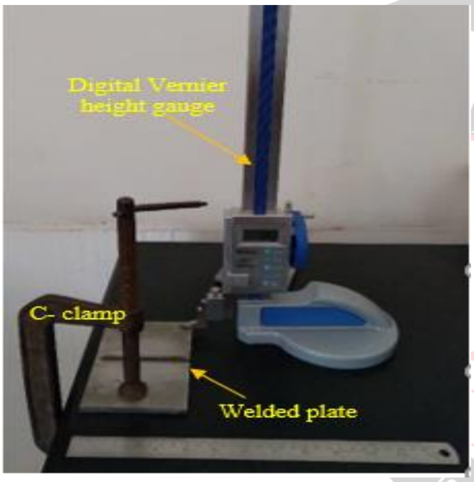

Figure 6 Measurment of angular distortion

However, FZ-TIG weld metal indicates the full penetration and d/w ratio near to one. This shows that volume from top to bottom of the weldment is consistent consequently, angular distortion becomes minimum. Figure 7 shows the effect of depth to width ratio on weld angular distortion in all TIG welding variants.

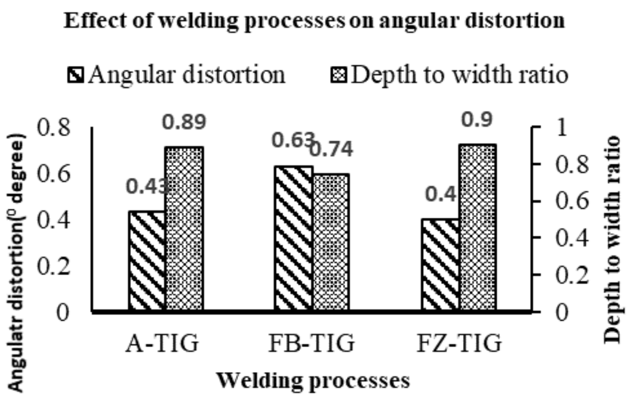

Figure 7 Effect of depth to width ratio on angular distortion

The Microhardness of DSS weld depends upon heat input. It was reported that high heat input leads to slow the cooling rate result in larger grain size with higher content of austenite phase which is responsible for the higher hardness of DSS weldments [23]. Among all welding (A-TIG, FB-TIG and FZ-TIG) processes, the highest heat input (reduction in the cooling rate) is observed in FZ-TIG welding and thereby reducing the delta ferrite and courser the grain size. Minimum microhardness (277HV) is reported with FZ-TIG weld metal as shown in figure 8. Which shows a good correlation between the microhardness and microstructure. A-TIG and FB-TIG weld metal microhardness are higher than base metal this is attributed to the presence of high ferrite than base metal and Widmanstätten secondary austenitic structure. However, FB-TIG welding shows a 13% higher microhardness than the base metal.

All 2205 DSS weld metal is failed at the fusion zone. This is due to the formation of coarsening ferrite grains with Widmanstätten austenite during the solidification of A-TIG, FB-TIG and FZ-TIG weld. In all weld metal, tensile strength is higher than the base metal as shown in figure 8. This is attributed to high heat input, slower cooling rate and formation of Widmanstätten austenite with high miss-orientation of grain in weld metal zones.

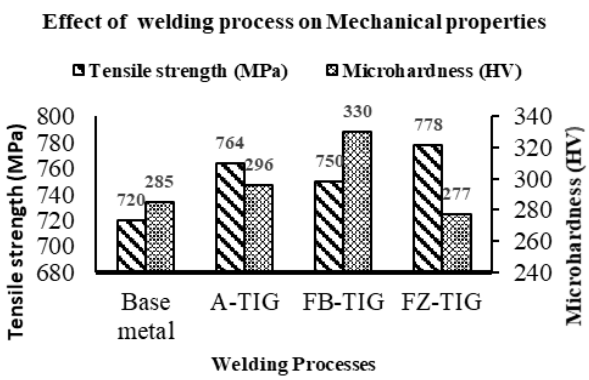

Figure 8 Effect of welding process on Mechanical Properties

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However, the peak tensile strength of 778 MPA is reported in FZ- TIG butt weld metal which is due to complete and secure penetration with formation of large amount of Widmanstätten austenite.

IV. Conclusions

In the present investigation comparison of A-TIG weld metal with its variants in 2205 duplex stainless steel are analyzed and summarized as follows:

A-TIG, FB-TIG, and FZ-TIG welding are capable enough to increase the weld penetration to a great extent in a 6 mm thick plate. However, the most effective technique is FZ-TIG welding to pursuit the highest 6.9 mm weld penetration. FB-TIG welding is the least effective technique due to the less penetration (5.85 mm).

Due to substantial increment in the depth to width ratio in A-TIG and FZ-TIG weld metal, reduces the angular distortion.

Among all welding processes, maximum heat input is reported in FZ-TIG welding. Which is responsible for lesser microhardness due to less delta ferrite. FB-TIG weld metal increases the weld penetration 13% than the base metal.

In all weld metal formation of Widmanstätten austenite with high miss-orientation of grain is observed. Which is responsible for higher tensile strength than the base metal. Moreover, compete and secure penetration in A-TIG and FZ-TIG welding increase the weld tensile properties

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