CHAPTER 01 Introduction

1.1 Preamble

Present chapter discusses about stainless steel welding methods and applications. The respective sections elaborate the Activated Tungsten Inert gas welding (A-TIG) process and its variants. Apart from this, the chapter discusses about the need of research, defines the objective of present investigation, methodology to fulfill the objectives and thesis outline.

1.2 Background

Stainless steel is an alloy that has high corrosion resistance, weldability, extensive service life, formability and non- magnetic properties. Stainless steel is a commonly used material in various industries such as automobile, construction, petrochemical, household materials and aerospace (Hall & Fekete, 2017; Nishimoto, 2001; Gooch, 2000). In stainless steel, Chromium forms a protective coating on the surface which isolates the material from the reactive environment (Bhadeshia & Honeycombe, 2017). Stainless steel can be tempered and utilized in wide temperature ranges from red hot temperatures to cryogenic temperatures (McGuire, 2008). Stainless steel is categorized into five major groups austenitic stainless steel, ferritic stainless steel, Duplex Stainless Steel (DSS), Martensitic stainless steel, Precipitation hardening stainless steel. Austenitic stainless steel is the most familiar and common type of stainless steel. They consist of high-quality mechanical properties with good corrosion resistance. Low carbon austenitic stainless steels are chosen for the structural components of the prototype fast breeder reactor (PFBR) due to their high-temperature mechanical properties (Tseng K. , 2013). Ferritic stainless steel has lower weldability than austenitic stainless steel. Ferritic stainless steel has been developed by incorporating nickel and/or titanium. This steel has good mechanical characteristics and is used in welded structures (Azevedo, Ferraresi, & Farias, 2010). DSS consists of approximately equivalent proportions of ferrite (body-centered cubic) and austenite (face-centered cubic). These two phases possess varying affinities for alloying elements in DSS (Miura, Koso, Kudo, & Tsuge, 1990; Sun, Kuo, Annergren, & Pan, 2003). DSS offers greater mechanical strength and higher corrosion resistance to chloride-induced stress corrosion cracking than most types of stainless steel (Sridhar, Kolts, & Flashe, 1985).

Moreover, instead of austenitic stainless steel, DSS is used in defence and military services for the fabrication of water bowsers to increase the payload capacity (Magudeeswaran, Nair, Sundar, & Harikannan, 2014). However, at elevated temperatures, these alloys endure degradation in mechanical properties due to increase of ferrite/ austenite ratio in weld metal (Pramanik, Littlefair, & Basak, 2015; Ramkumar, Pattapu, Radhakrishna, Tiwari, & Anirudh, 2016). Hence, the welding methods that control the ferrite/austenite ratio in the weld metal are very important. In the present work, 2205 DSS is used which combat the common corrosion problem encountered with 300 series stainless steel.

To weld thin sections (up to 3 mm) of stainless steel, Shielded Metal Arc Welding (SMAW) and resistance welding processes are used (Noda, 1993). The Friction Stir Welding (FSW) process has the potential to weld stainless steel up to 3 mm thickness (Sunilkumar, Muthukumaran, Vasudevan, & Reddy, 2020). Also in FSW, the material for tool selection is very important due to the expeditious tool wear (Parikh, Badgujar, & Ghetiya, 2019). Stainless steel is also welded by Metal Inert Gas welding (MIG), and Submerged-Arc Welding (SAW) process. In the MIG welding process, alloying elements are passed across the arc and get oxidized (Lau & North, 1988). Despite providing weld of great quality, SAW is not usually used in the industry because the high heat input can deform the stainless steel weld (Niagaj, 2014; McPherson, Chi, McLean, & Baker, 2003), also, it is difficult to control alloy transformation (Kearns, 1982; Nowacki & Rybicki, 2005). In the last decade, Electron Beam Welding (EBW), Laser Beam Welding (LBW) and Plasma Arc Welding (PAW) processes were extensively used to weld a thick section of stainless steel alloys due to their great penetration capability (Taban, 2008; Ragavendran & Vasudevan, 2020; Migiakis, Daniolos, & Papadimitriou, 2010). However, electron and laser beam welding processes are sensitive to the accuracy of joint preparation and the PAW process is very sensitive to weld parameters with high investment costs (Niagaj, 2014; Cui, et al., 2017). Among the various welding methods, Tungsten Inert Gas (TIG) welding is the most popular welding process for welding stainless steel, aluminum alloys, titanium alloys and other non-ferrous metals. TIG welding process offers good weld bead surface and high-quality weld joint at a low cost of equipment. It is suitable for both thick and thin stainless steel plates (Sharma & Dwivedi, 2019; Dey, Albert, Bhaduri, & Mudali, 2013; Huang H. , Shyu, Tseng, & Chou, 2006). However, TIG welding has some limitations like shallow penetration in a single pass. The process without filler material is known as an autogenous TIG welding, generally able to weld stainless steel alloys maximum up to 3 mm thickness (Singh, Dey, & Rai, 2017). To increase the penetration of the TIG welding process in a single pass, an ample amount of research has been carried out in the past few decades (Niagaj, 2014; Vidyarthy & Dwivedi, 2016; Anbarasu, Yokeswaran, Godwin Antony, & Sivachandran, 2020). Higher penetration depth can be achieved by increasing the current; however, it leads to excessive widening of the weld width with no extensive penetration (Badheka V. J., 2016; Vidyarthy & Dwivedi, 2019; Kusano & Watanabe, 2002). A few years ago, the keyhole TIG process was developed but due to high sensitivity to arc voltage generally results in extreme loss of material (Feng, et al., 2015; Jarvis & Ahmed, 2000). For welding, the thick section addition of filler rod, edge preparation and multi-pass are required, which leads to less productivity and increases the cost of the product (Toppo, Pujar, & Arivazhagan, 2016; Kumar, Ahmad, & Singh, 2019; De Dinechin, Chagnot, Castillan, Blanchot, & Baude, 2002). These limitations make it less suitable to weld a thick section in the nuclear and oil industries. Use of a thin layer of active flux consisting of oxides or halides on the plate before welding was initially proposed by Paton Electric Welding Institute of the National Academy of Sciences, Ukraine in the mid-1960s (Niagaj, 2003). Activated flux with TIG (A-TIG) welding has been successfully used to improve penetration of the stainless steel weld joint (Pandya, Badgujar, & Ghetiya, 2021; Vidyarthy & Dwivedi, 2016). Therefore, the detail investigation on A-TIG welding process is performed. A-TIG welding process is also known as flux assisted Gas Tungsten Arc welding (F-GTAW).

1.3 Activated Tungsten inert gas (TIG) welding process

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 work piece before welding with optimal coating density as shown in Figure 1.1. The liquid carrier evaporates, leaving a layer of the activating flux, adhering to the surface of the material to be welded.

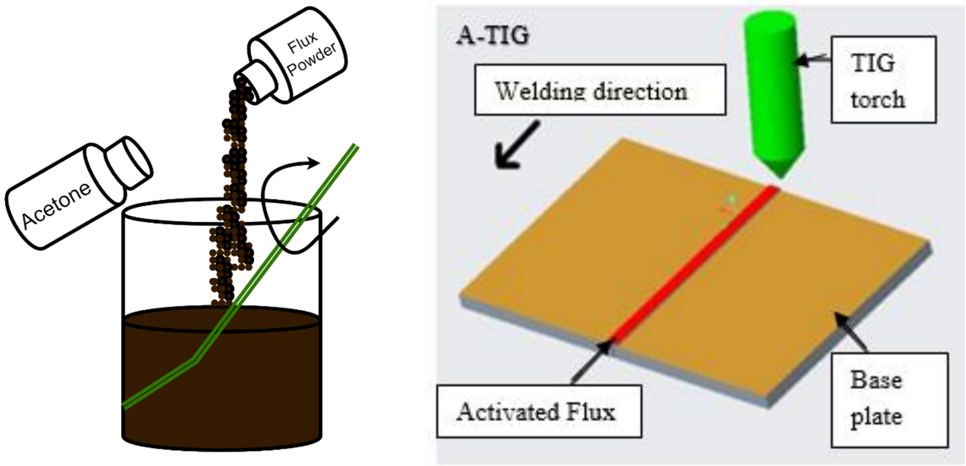

Figure 1.1 Preparation and coating of flux paste

During the welding, activated flux is heated and evaporated at arc temperatures. This increases the penetration capability up to 300 % as compared to the TIG welding process (Lucas, 1996). Lucas and Howse (1996) presented that A-TIG welding has been successfully used to improve penetration of the weld in comparison to the conventional TIG and plasma processes. A-TIG welding process was successfully applied on ferrous as well as on non-ferrous materials for deeper penetration and better mechanical properties (Vora & Badheka, 2016). Tanaka (2005) noted that the existence of a relative high concentration of surface-active elements, such as sulfur and oxygen in the base metal makes the penetration deeper.

1.4 Variants of Activated Tungsten Inert Gas (A-TIG) welding process

During the A-TIG welding activated flux offers the resistance to arc and later stage 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. Also, after welding entrapped flux particles create a poor weld bead surface appearance (Venkatesan, Muthupandi, & Fathaha, 2017). These challenges of A-TIG welding process are overcome by novel chronological approach Flux Bounded TIG welding and Flux Zone TIG welding processes.

1.4.1 Flux Bounded TIG welding

Sire and Marya (2001) first addressed the Flux Bounded TIG (FB-TIG) welding process on aluminium alloys. In this process, flux coating is applied on two parallel strips by keeping a predetermined gap at the weld line as shown in Figure 1.2. Hence, welding arc directly comes in contact with flux uncovered weld metal. The literature reveals that FB-TIG welding is successfully increasing the penetration depth than TIG weld in a few grades of stainless steel alloys. However, a slight reduction in penetration than A-TIG weld was observed, but it overcomes the shortcomings of the A-TIG welding process (Singh, Dey, & Rai, 2017; Chakravarthy, Agilan, & Neethu, 2019).

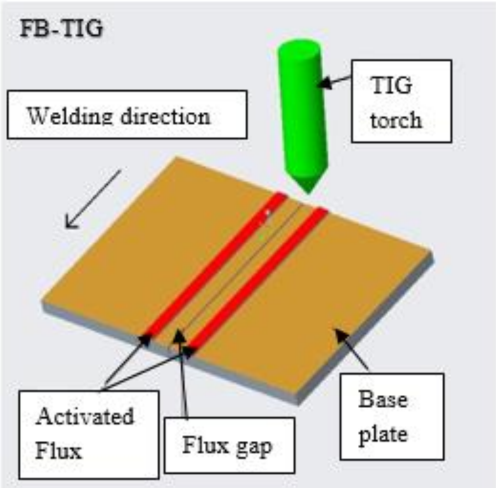

Figure 1.2 A schematic diagram of FB-TIG welding

1.4.2 Flux Zone TIG welding

Compared to A-TIG, the FB-TIG welding process gives a satisfactory weld surface appearance. However, the weld penetration in FB-TIG weld joint is inadequate in stainless steel alloys (Singh, Dey, & Rai, 2017). The new chronological variant FZ-TIG welding is proposed by Huang et al. (2012) by altering the activating flux coating method, founded on the theory of arc constriction. In this method activating flux thermophysical properties with a lower melting point, boiling point and current resistivity are applied to the central region of the weld line and activating flux with a high melting temperature, boiling temperature and current resistivity are applied on the side regions of the weld surface before welding. During the welding centre region, flux only gets melted and evaporates and negative iron increases the current density and reverses the Marangoni convection. While outer region flux acts as an insulator and contracts arc root which results in higher penetration. The gap between the outer coat flux is filled with centre coat flux as shown in Figure 1.3.

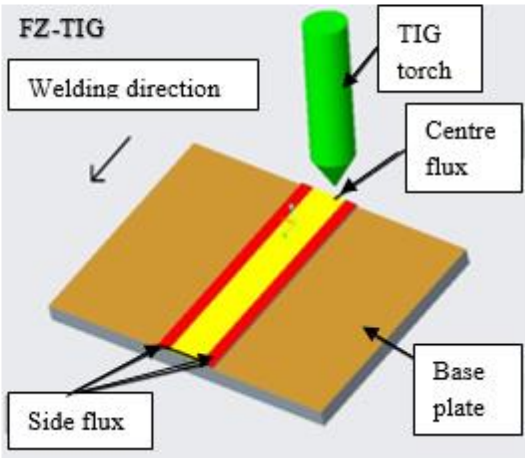

Figure 1.3 A schematic diagram of FZ- TIG welding

FZ–TIG weldments of aluminium alloys, depth of penetration was thrice than that achieved with TIG welding along with improved surface appearance. Along with this, improvement in mechanical properties and surface finish in aluminium alloys were also reported (Huang, Fan, & Shao, 2012). However, no study has been reported on stainless steel alloys. This provides an opportunity for further research.

1.5 Motivation of research

As aforementioned the major limitation of TIG welding process is its inability to weld thick stainless steel materials in a single pass. This decreases the productivity of the weld joint. A-TIG welding is successful in increasing the penetration to a great extent in stainless steel alloys. A substantial amount of work has been performed to weld different grade of stainless steel by A-TIG welding process.

The 2205 DSS is a new substitute for austenitic stainless steel for many applications. DSS ferrite/austenite ratio is greatly affect the mechanical and chemical properties. Hence, it is important to study the method which controls the ferrite/austenite ratio. However, limited literature is available to weld 6 mm thick DSS by A-TIG welding process. Therefore, a detailed investigation is required to study its macrostructure, microstructure and mechanical properties after TIG and A-TIG welding process. Furthermore, the literature reveals that during A-TIG welding, the weld line is not visible due to complete convergence by activated flux. Also, entrapped flux particles create a poor weld bead surface appearance. This drawback overcomes by FB-TIG welding process. The available literature reflects that FB-TIG welding is performed in very few grades of stainless steel. Therefore, further study is required to weld 2205 DSS by FB-TIG weld and compare with A-TIG weld joint. Moreover, literature reflects that FB-TIG weld joint shows lesser penetration depth than A-TIG weld joint. Therefore, a new chronological approach FZ-TIG welding applied on aluminium alloys. However, no study has been reported in stainless steel alloys. Considering the current status, to rationalize the performance of the FZ-TIG weld joint, a comparison of A-TIG, FB-TIG, FZ-TIG welded joints under the same welding conditions can be investigated.

1.6 Objectives

The objectives of the present work are as follows:

- Development of fixture to perform TIG welding, A-TIG welding and its variants
- To perform the A-TIG welding on 2205 Duplex SS and analyze the effect of welding parameters on metallurgical and mechanical properties
- To optimize A-TIG welding process parameters using multi-objective optimization technique
- To perform FB-TIG welding and analyze the effect of welding current on FB-TIG weld
- To perform the FZ-TIG welding and compare A-TIG, FB-TIG and FZ-TIG welded joints under the same welding conditions to rationalize the performance of the A-TIG welding process.

1.7 Methodology

Following methodology is followed to achieve above-mentioned objectives.

- Development of fixture to perform autogenous TIG welding, A-TIG welding and its variants.
- Selection of grade of stainless steel and fluxes to perform the A-TIG, FB-TIG and FZ-TIG welding. Trial experiments are performed
  - To identify the range of input parameters and fluxes for A- TIG Welding Process.
  - To identify the flux gap and best flux for FB-TIG welding process.
  - To find the best combination of flux for a central and outer region in FZ- TIG welding process.

- After determining the working range of process parameters and fluxes for A-TIG welding, experiments are conducted using Design of Experiments (DOE). Empirical relations by the regression are developed to predict the response as a function of considered process parameters.
- The microstructure of the welded joints is evaluated using Scanning electron microscope (SEM). Tensile testing is performed as per ASME section IX. Vickers Micro hardness is measured as per ASME E-384-17.
- Multi-objective optimization by RSM is performed to obtain the optimum parameters for A-TIG welding process. Verification experiments are performed to check the adequacy of the developed model and optimized parameters. At optimum parameter, the impact test is performed as per ASTM A240 standard to measure literal expansion.
- Effect on metallurgical characteristics in light of variations in tensile strength and micro hardness of change in welding current is studied in FB-TIG welding.
- Compare A-TIG, FB-TIG, FZ-TIG welded joints under the same welding conditions to check the performance and adaptability of A-TIG welding and its variants.
- Thesis writing.

1.8 Thesis outline

The purpose of the present research is to study A-TIG welding processes on 6 mm thick 2205 DSS to achieve the satisfactory weld bead geometry along with mechanical and metallurgical properties in a single pass. Moreover, the experimentation and analysis on novel chronological variants of A-TIG welding process such as FB-TIG and FZ-TIG welding processes are also incorporated. The presentation of this report is organized into 7 chapters.

In Chapter 2 systematic literature survey has been carried out to understand the mechanisms and forces act in A-TIG welding process. The study discussed the effect of welding parameters on weld penetration and bead width. Moreover, A-TIG welding performance has been reviewed concerning the microstructure and mechanical properties of stainless steel. The chapter ends with the recent development and scope of current research.

Chapter 3 comprises of development of welding fixtures to maintain constant arc length and torch speed during TIG, A-TIG welding and its variants. Detail information of material sand flux selection to perform A-TIG, FB-TIG and FZ-TIG welding. A detailed of methodology employed for testing and characterization for determining various properties of the welded joint. The chapter ends with layout of experiments.

Chapter 4 demonstrates the experimental trials conducted to identify the working range of parameters (welding current, torch speed) and the right type of flux to perform A-TIG welding on 2205 DSS. This is followed by systematic experimentation of A-TIG welding and corresponding discussions for the combination of the different parameters on macrostructure, microstructure and mechanical properties are studied in detail. Apart from this, to improve the performance of weld joints, multi-objective optimization is performed using Response Surface Methodology (RSM) approach. The conformity experiment is performed on optimized process parameters to check the conformity of the developed mathematical model. Furthermore, impact test is performed at optimized parameters to identify the literal expansion of A-TIG weld joint.

Chapter 5 encompasses the weld bead appearance obtained by A-TIG welding and the need for FB-TIG welding. Effect of flux gap (vary from 2 mm to 7 mm) and fluxes (SiO_2, TiO_2 and Cr_2O_3) on weld bead geometry are studied by performing FB-TIG welding. This is the initial phase of FB-TIG weld to identify the best flux gap and flux for the FB-TIG weld joint. The analysis leading to the study of the effect of different heat inputs on macrostructure, microstructure and mechanical properties (tensile strength, microhardness) on FB-TIG weld joint.

Chapter 6 establish the comparison of macrostructure and weld bead appearance obtained by A-TIG and FB-TIG weld joint under constant weld conditions. Along with this, the chapter, showcase the performance of Flux Zone TIG welding (a new chronological variant of A-TIG) on 2205 DSS. The effect of eight different combinations (centre region flux and side region flux) of fluxes on weld bead geometry is analyzed. Furthermore, to rationalize the performance of the FZ-TIG weld joint, a comparative study of A-TIG, FB-TIG and FZ-TIG weld joint is carried out.

Chapter 7 concludes the present experimental investigation on the performance of A-TIG welding and its variants on 2205 DSS. Also, it throws light on key thrust areas for the future scope which can further increase the adaptability of the A-TIG welding and its variants.