Chapter 1: Introduction

1.1 Background

High alloy steels based on the Fe- Cr, Fe- Cr- C and Fe- Cr- Ni systems with minimum of 10.5% Cr is defined as stainless steel [1, 2]. If present in appropriate quantity, chromium forms a layer of chromium oxide on the surface of the steel. This hard and tenacious layer of oxide film prevents further oxidation of the material, thus increasing the material's corrosion resistance. This oxide layer also provides heat resistant property for high temperature applications by protecting the underlying material [3].

There are five types of stainless steel (ferritic, austenitic, martensitic, duplex, and precipitation hardened) [4]. Ferritic stainless steel is the type of stainless steel, in which the ferrite phase is dominantly present due to the presence of more amount of ferrite stabilising elements like chromium over austenite stabilising elements [1]. In this steel, the chromium percentage lies in the range of 10.5–30 wt% with some microalloying elements such as Mo, Al, Ti, Nb, Cu, S with virtually no nickel. This steel was developed to provide a cheaper substitute for costly austenitic stainless steel material. Nickel is the main alloying element in austenitic stainless steel, and the price of this element decides the cost of austenitic stainless steel. The stainless steel industries consume about 75% of the total production of nickel, such high demand for nickel element causes the high price of this element and thus makes the austenitic stainless steel as a costly engineering material [5]. Also, the price of nickel has been increasing from 4000 US dollar to 50000 US dollar from 1999 to 2007 [6]. Such high fluctuation in the price of nickel, unstabilized the market price of austenitic stainless. To resolve this problem, it was necessary to provide an alternative of austenitic stainless steel, and as a result, ferritic stainless steel has been developed in which nickel element is absent or present in very small percentages

[7]. This steel is cheaper than austenitic stainless steel, along with several advantages and a few disadvantages over the austenitic stainless steel [8-13]. Many grades of this steel have been developed by varying the chemical composition, such as AISI grades 409, 430, 434, 439, 444, 446, etc.

Some ferritic grades such as 409 and 430 are more widely used throughout the world. Generally, ferritic stainless steel possessed lower ultimate tensile strength, lower impact strength, and lower corrosion resistance in ambient environments than austenitic stainless steel. However, it possesses high tensile strength than carbon steels and low alloy steels. Also, it possesses much superior corrosion resistance property than the carbon steels in ambient environments [13]. Thus, it can be considered to fill the gap in the requirement of properties that are expected from austenitic stainless steel and carbon steels [14]. Its high thermal conductivity and lower coefficient of thermal expansion compared to the austenitic stainless steel make ferritic stainless steel the preferred material over the austenitic stainless steel in some applications such as electric press and heat exchanger tubes [15]. Generally, this steel possesses lower resistance to general corrosion and localized corrosion attack in ambient conditions. But, most grades of ferritic stainless steel possess excellent pitting corrosion resistance, crevice corrosion resistance and stress corrosion cracking in chloride environment, which makes it a better alternative to austenitic stainless steel since austenitic stainless steel gives poor performance in chloride environments [16]. Apart from these properties, it also offers some advantages over the austenitic stainless steel like higher yield strength, excellent high temperature oxidation resistance, excellent creep resistance, ferromagnetic property, less prone to springback effect during cold forming and easier to machine and work [17]. It possesses a large variation of chromium percentages and other alloying elements (Ti, Mo, Nb, etc.), that is why different grades of ferritic stainless steels are used in applications with different severity of corrosive environment, i.e. grades with a higher percentage of chromium are used in more severe corrosive environment and vice-versa. Various components are manufactured by this ferritic stainless steel material in different industries like different parts of exhaust systems (exhaust manifold, catalytic converter, exhaust pipes, muffler, and tailpipe), head light, brake discs and decorative trim in automotive industry, washing machine drums, roofing (school roof, gymnasium roof, airport roof), siding and railway wagons for coal and iron ore, heat exchanger (moisture separator reheater welded tubes, feedwater heater welded tubes, condenser welded tubes), pressure vessels, food and dairy industry (fermentation and storage tank, bakery oven, conveyer toaster, gas cooking equipment, refrigerator, heated merchandiser, restaurant trolley), chemical processing, pulp and paper industries, refineries and high efficiency furnaces, kitchen equipments (cutlery, coffee server, microwave oven, gas cooking top, pressure cooker, dishwasher), sugar industry (conveyor system, slate carrier, slate carrier, crystallizer and diffuser) [17-25]. Their worldwide market share is about 20 to 25% of all the stainless steel produced.

The components manufactured for different applications from ferritic stainless steels require joining. Welding is the most common process among the different types of joining process. Different types of welding process such as resistance welding, gas tungsten arc welding (GTAW) or tungsten inert gas (TIG) welding, gas metal arc welding (GMAW) or metal inert gas (MIG) welding, electron beam welding (EBW) and laser beam welding (LBW) are commonly used. GMAW process is very widely used in industries among the welding processes due to its high welding speed, high arc efficiency, capacity to weld varying thickness of plates, and its capability to produce clean welding with good mechanical properties. The process can weld both ferrous and non-ferrous alloys. GMAW is widely used in several industries like automotive, robotic, railways, shipbuilding, aircraft engine manufacturing, general and heavy electrical engineering works [26]. It is also used to manufacture pressure vessels, tanks, pipes and domestic equipment.

GMAW was initially developed in 1948 by Battelle Memorial Institute (U.S.A.) in order to welding of Al and other nonferrous alloys, which was further improved by various researchers in subsequent years [27]. In the GMAW process, an arc is generated between the consumable electrode and the base material being welded. The electrode also provides the filler material and is automatically fed into the molten weld pool in accordance with the welding process parameters set by the welder [28]. The composition of the electrode is usually similar to that of the base metal but at times may be different. During the initial days of GMAW, only inert gases like argon and helium were used as the shielding gas to protect the molten weld pool from atmospheric contamination, but later, other active gases were also tried and were found suitable for welding a few ferrous alloys. Active gases that are popularly used include carbon dioxide and nitrogen along with mixtures of these gases with other active and inert gases.

GMAW is popularly used for welding of different grades of stainless steels, including ferritic stainless steel, using argon as the shielding gas. During welding of ferritic stainless steel, the electrode used may be of ferritic grade or of austenitic grade. When the selected electrode is of ferritic stainless steel grade, then the formation of ferrite phases dominates over any other phases like austenite and martensite during solidification. Due to the very small amount/ absence of other phases in the weld, the growth of the grains is not restricted by any other phases which results into coarser grains in the weld metal zone (WMZ) [29]. But when the electrode is of austenitic stainless steel grade, then austenite and martensite phases are formed during the solidification process, which restricts the growth of the ferrite phases and results in finer grains in the WMZ

[30]. In the heat affected zone (HAZ) of the ferritic stainless steel, where the composition of the base material remains the same, coarser grains are always present when compared to the base metal irrespective of the type of electrode material. This coarse grained region is adjacent to the fusion boundary on both of its sides.

The grain coarsening of the HAZ is responsible for making this region as the weakest region of the weldment. According to the Hall-Petch equation, the yield strength is inversely proportional to the grain size [31]. This region of HAZ having coarse grains has poor strength as well as low impact energy. Hence the joint efficiency of the weldment is usually well below 100%. The mechanical properties of the welded component can be enhanced by reducing the grain size in the HAZ by some means. The technique used should be such that it does not bring about any significant change to the weldment.

Friction stir processing (FSP) is a novel technique that locally modifies the material's surface to improve its mechanical and surface properties [32-34]. The process of FSP is a variant of the friction stir welding (FSW) process. This welding process is used to join two materials; however, the FSP is not used to weld the plates, but instead, it only modifies the surface of one single plate [35-38]. However, the machine used is same for both processes. To perform FSP, a cylindrical tool of a certain diameter and having specific shapes of the pin (like triangular, square, hexagonal, round, tapered, etc., with or without threading) is used. The pin of the rotating tool is inserted up to the depth to which processing of the material is to be carried out. The base material is firmly clamped and after the insertion of tool pin, the FSP tool is traversed along the desired path. The heat is generated due to the friction rubbing between the rotating tool and the base material, which increases the temperature of the material and helps to plasticize the material. The movement of the plasticized material occurs from the front of the tool to the backward of the tool. The heat generation along with the movement of the plasticized material results into the dynamic recrystallization phenomenon, which refines the grain significantly if the heat and flow of the material are properly controlled [39-42].

In this experiment, GMAW of ferritic stainless steel AISI 409L has been done using austenitic stainless steel grade electrodes ER304L at different welding parameters. The metallographic study and mechanical characterisation, i.e. hardness, tensile testing and Charpy impact testing of the welded samples, have been carried out. The sample which possessed good combination of mechanical properties was selected for FSP to refine the grains of different regions of the welded plate. In this study, shoulder diameter (i.e. 15 mm and 20 mm) and the three different ratio of rotational speed (RS) to processing speed (PS) (i.e. 6, 9 and 12) was taken as processing parameter. The variation of grain size, hardness, and tensile strength of the fiction stir processed plate has been analysed with the shoulder diameter and the ratio of RS to PS. The residual stress of different regions of the welded plate sample S7 and friction stir processed plate sample A has also been found.

Assessment of the quality of the welded and processed components can be done by two methods, i.e. destructive testing technique and non-destructive testing technique. Metallographic study, hardness testing, tensile testing and impact testing are major destructive testing techniques to find the quality of the welded and processed components. During manufacturing or in-service period, the non-destructive testing technique is used to check the quality by maintaining the integrity of the components. Magnetic Barkhausen noise (MBN) and Magnetic hysteresis loop (MHL) analysis technique are one of the most important non-destructive testing which are frequently used to characterize the ferromagnetic materials [43-45]. The ferromagnetic material like ferritic stainless steel possesses magnetic domains which are randomly oriented in the absence of any magnetising field, producing no net field. But, when the magnetic field is applied, these magnetic domains start to orient in the direction of the applied magnetic field producing some amount of net magnetisation within the material. This net magnetisation depends upon various factors such as intensity of the magnetic field, magnetising frequency, pinning sites in the form of grain boundaries, phases, precipitates, etc. and other factors [46, 47]. The magnetic response of the material in the MBN analysis technique is represented in the form of root mean square (RMS) value, and number of pulses while in the MHL technique, magnetic response of the material is determined in terms of average maximum flux density, remanence, coercivity and coreloss.

The MBN and MHL techniques were also used to characterize the welded and processed component at different values of magnetic field intensity and magnetising frequency.

1.2 Objectives of the current research work

AISI 409L ferritic stainless steel is widely used in various industries, and GMAW is one of the most commonly used welding technique that used for welding of this material. However, the mechanical properties of the welded joints are poor, mainly because of the grain growth in the HAZ. In this work, GMAW of ferritic stainless steel was carried out, and the process parameters were optimised to achieve the best possible mechanical properties. The mechanical properties were further improved by performing friction stir processing on the welded joint. The present work attempts to provide a method to effectively mitigate the inherent problems present in GMAW of ferritic stainless steel.

This research work has been carried out to achieve the following specific objectives:-

1. To find the range of process parameters at which defects free welds could be obtained during gas metal arc welding of 409L stainless steel.
2. To study the effect of heat input on the mechanical properties of the welds obtained in gas metal arc welded 409L ferritic stainless steel and to optimize the process parameters for best mechanical properties.
3. To develop the methodology to successfully perform friction stir processing (FSP) on welded plates and to find the range of process parameters at which FSP could be successfully carried on SS409L welded plates.
4. To study the effect of FSP process parameters on mechanical and metallurgical properties obtained after performing FSP on welded plates.
5. To establish the suitability of MBN analysis technique to characterize SS409L plates after gas metal arc welding and after performing friction stir processing.

1.3 Format of the thesis

Chapter 1 Introduction

A brief introduction to ferritic stainless steel particularly AISI409L, its uses in industries, the problems associated with the GMAW of AISI 409L and how FSP has a potential to reduce these problem has been dealt in this chapter. The advantage of the MBN analysis technique has also discussed briefly. The objectives of the current research work have also been described along with the format of the thesis.

Chapter 2 Literature review

In this chapter, the various types of stainless steel available for engineering applications and their properties have been discussed in detail. Different types of welding processes used for welding ferritic grade stainless steels have been discussed. The classification of ferritic stainless steel and in particular, the importance of AISI 409 ferritic stainless steel is mentioned from the industrial point of view. The previous research work carried out by various researchers on fusion welding particularly GMAW of AISI 409 stainless steel have been discussed thoroughly. Literature review of works carried out on in the area of FSP of aluminium, magnesium, carbon steels in general and stainless steels in particular have been presented in this chapter. In the last section, the gap in research work is also highlighted.

Chapter 3 Experimentation

This chapter describes the details of GMAW, FSP and various characterisations carried out in this work. For the ease of readability, this chapter has been divided into two parts. The first part describes the details of experimentation carried out on GMAW of AISI 409L. The experimental setup used, the process parameter selection and optimization of process along with final welding experiments has been reported. The second part of this chapter deals with the FSP of the gas metal arc welded plate and details the FSP setup, selection of process parameters, tool material and tool design.

Lastly, the characterisation of the base materials, welded plates and plates that have been obtained after welding and FSP using both the destructive testing technique and non-destructive testing technique have been described. In this work, the destructive testing technique involved metallographic study, microhardness, tensile testing, Charpy impact testing and residual stress testing of the welded plate as well as of the processed plates. The chemical composition of the weld metal have also been estimated. While the non-destructive testing technique involved radiographic testing and MBN analysis.

Chapter 4 Results and discussion

This chapter is also divided into two parts. In the first part, the results obtained while testing plates obtained after GMAW of AISI409L have been reported. This includes the results of visual examination, X-ray radiography, mechanical testing and MBN analysis. Relationship between the percentage dilution and heat input, welding current, welding voltage, and welding speed have been discussed in detail. The results of metallography study, microhardness of the weld metal and HAZ of different welded samples have discussed in detail. The mechanical properties of the GMAW welds has been reported as obtained from the tensile testing and Charpy impact testing. Longitudinal residual stress of different regions of the one welded plate has been discussed. One welded sample has been characterized using the MBN analysis technique to study the magnetic response of the different regions of the welded plate at different magnetising field intensity and magnetising frequency.

In the second part of this chapter, the results obtained from the various test performed after FSP of previously welded plates have been discussed. The test results include metallographic study, microhardness testing, tensile testing, Charpy impact testing, residual stress testing and MBN analysis.

Chapter 5 Conclusions

In this chapter, the important conclusions obtained from this research has been summarized.

Chapter 6 Scope for future work

Based on the results obtained from this research work, the possible areas in which this work can be further explored is given in this chapter.