Chapter 2: Literature review

2.1 Introduction

In this chapter, the introduction of stainless steel including its history of development and their types have been discussed. The mechanical and physical properties of different kinds of stainless steel are also discussed. Different types of welding operations used for ferritic stainless steel have been described in detail. The literature review of the GMAW, GTAW and FSW of AISI 409 have been done. Also, the literature review about the FSP of aluminium alloys, magnesium alloys, carbon steels, and stainless steels has been done. Finally, the research gap was found based on the literature review.

2.2 Stainless steel

Stainless steels are high alloyed steels, which contain a minimum of 10.5 weight % chromium. It is mandatory to form a hard and tenacious layer of chromium oxide on the surface of the steel so that the material is prevented from corrosion as well as heat [3]. It is one of the most commonly used engineering materials [48].

The chemical composition of the stainless steel decides the type of phases present in that steel. The phase transformation and phase stability during the heating or cooling cycle can be understood using the appropriate phase diagrams for these Fe- Cr, Fe- Cr- C and Fe- Cr- Ni systems. However, other alloying elements present also affect the amount and type of phases present. Apart from chromium and iron, other alloying elements like nickel, molybdenum, silicon, niobium, aluminium, vanadium, titanium, tantalum, tungsten, carbon, nitrogen, sulphur, phosphorus, copper, etc. are present in several grades of stainless steel. The corrosion resistance is provided by several elements like Cr, Mo and Nb; however, Cr is the main element that is primarily used to make the steel corrosion resistance. The corrosion resistance and good mechanical properties have made stainless steel a popular material for several engineering applications, and it is globally one of the most widely used materials. The worldwide production of stainless steels is currently (year 2019) 52.2 million tons and has been increased by 2.09 times in the last 11 years [49].

2.3 History of stainless steel

It is still a matter of discussion regarding the development of stainless steel because several authors have different opinions on this topic. However, generally, it is believed that Harry Brearley, born in Sheffield, England invented stainless steel [50]. He set up the 'Brown Firth Laboratories', which the two leading Sheffield companies financed. In 1912, he started developing a material to resolve the problem of a small arms manufacturer facing the problem of erosion of the material inside the gun barrels due to the action of the heat of the discharge gases. It means that in the initial periods, the problem was related to the 'erosion' of the material, not 'corrosion'. Therefore, due to the high melting temperature of chromium, it was selected, and it was decided to mix it in the melts. Chromium was mixed in different percentages of 6 to 15 % with varying contents of carbon. The first trustworthy stainless steel produced on 13th August 1913 consisted of 0.24 % carbon and 12.8 % chromium. To check the grain structure of the developed material, etching of the material by nitric acid-based etchant was performed. Surprisingly, it was found that the material did not etched, which was the indicator of its increasing corrosion resistance property. To confirm this observation, the material was tried to get etched in different etchants like lemon acids, vinegar, etc. However, in all of these conditions, the developed material was found to resist corrosion. Therefore, Brearley named this material' rustless steel'. Later on, Ernest Stuart called this material 'stainless steel' after failing to stain this material with vinegar. The stainless steel developed by Brearley possessed some limitations, such as it could only be supplied in hardened and tempered condition, making it hard to work.

Within a year of Brearley's discovery, in Germany, Krupp was experimenting to develop a material by adding nickel to the melt. The developed material by Krupp was more resistant to acids and was softer and more ductile, and therefore easier to work.

Just before the First World War, the "400" series of martensitic and "300" series of austenitic stainless steels were developed from these two inventions. However, there was no significant development in this direction from the start of the First World War till 1919 due to the destructive effect of war. In the early 1920s, various materials such as 20/6, 17/7 and 15/11 stainless steels were developed with different chromium and nickel combinations. Dr W.H. Hatfield, who was Brearley's successor at the Brown Firth Laboratories, developed the 18/8 stainless steel (18% chromium, 8% nickel) in 1924. This 18/8 is also called 304 and still dominates the market over other grades of stainless steels.

Most grades of the stainless steels that are frequently used today were developed from 1920 to 1935. Other grades of stainless steel, such as 17/4 PH (precipitation hardening) grades, were developed after World War II. Duplex stainless steels have been used since the 1970s onwards and were developed to meet challenging application requirements. Till date, about 100 grades of stainless steel have been developed and made commercially available [51].

2.4 Types of stainless steel

Stainless steels are generally divided according to dominant phases like austenite, ferrite and martensite in their microstructure. Based on this criterion, stainless steels can be subdivided into five types, as shown in Figure **(2.1**).

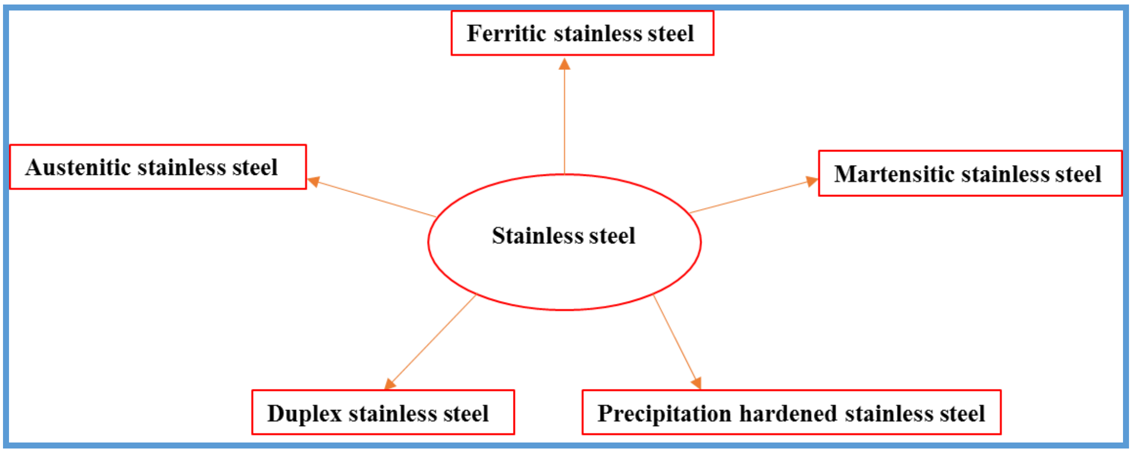

Figure 2.1 Types of stainless steel.

These different types have been discussed in more detail in the following sections.

2.4.1 Martensitic stainless steel

In these grades of stainless steel, the dominant phase is martensite which is formed from austenite during sufficient rapid cooling. These steels possess lower corrosion resistance than other types of stainless steels due to the lower chromium percentage (between 11.5 to 14 %). They are based on the Fe-Cr-C system and possess a wide range of yield strength from 275 MPa in annealed condition to 1900 MPa in the quenched and tempered condition. The strength of these steels generally changes with the amount of carbon present in them (which varies in a wide range of percentages from 0.05 to 1.20 %). These steels are used for applications where a combination of high strength, hardness and corrosion resistance under normal atmospheric conditions is desired, like steam piping, cutlery, surgical instruments, gears, shafts, large hydro turbines, and turbine blades of steam, gas and jet engines [52].

Due to the lower chromium percentage and the lesser amount of alloying elements, these steels are less expensive than the other stainless steels. Due to the formation of untempered martensite during cooling after welding, these steels possessed the least weldability among the stainless steels.

2.4.2 Duplex stainless steel

As evident from its name, these steels consist of two phases (generally ferrite and austenite) in near equal proportions. They possess a combination of superior corrosion resistance and strength. Austenitic stainless steel can be replaced by these steels for applications where pitting corrosion and stress corrosion cracking are the main problems. They are costlier than austenitic stainless steel due to the difficulty in their processing. These steels have superior mechanical strength than austenitic stainless steel with good toughness and ductility; however, impact properties at low temperatures are not good [53]. Therefore, these steels are used between 280^0 C to -40^0 C. They are much better than structural steels with superior corrosion resistance, comparable strength and comparable thermal expansion coefficient. It is widely used in oil , and gas pipelines and pressure vessels [54].

2.4.3 Precipitation hardened stainless steel

These stainless steels are characterised by the precipitation reactions under moderate heating, which follows quenching and form fine precipitates that impart sufficient steel strength. The precipitation hardened steels are sub-classified into martensitic, semi austenitic and austenitic, depending upon the predominant microstructural phases present. They possess high strength, almost equal to the 1520 MPa in some grades, along with good toughness and ductility. The corrosion resistance is nearly identical to that of austenitic stainless steels. These steels have a good combination of mechanical strength and corrosion resistance. It has good machinability in the annealed condition, but its machining is challenging after hardening heat treatment. Hence, they are more expensive than the other stainless steels, and their use is limited.

2.4.4 Austenitic stainless steel

Austenite is the main phase present in austenitic stainless steels because of the dominance of austenite stabilising elements like nickel. The addition of nickel improves the toughness of the steel at low temperatures by reducing the ductile to brittle transition temperatures. Also, the weldability and formability of the material are enhanced by the addition of nickel. Other elements like carbon, nitrogen and copper are also added to stabilise the austenite phase at room temperature. Carbon also improves strength at high temperatures, and nitrogen increases the strength at ambient temperature and low temperatures. Therefore, a combination of strength with good ductility and toughness is found in these steels. These steels are based on the Fe-Cr-Ni system and are widely used because of their good corrosion resistance in most environments and their strength equivalent to mild steel. It can be used in cryogenic conditions due to its good impact properties at lower temperatures [55]. It can also be used at high temperatures (up to 760ºC); however, the strength and oxidation resistance at such high temperatures gets reduced. The heat treatment process cannot harden these steels; however, it is possible to strengthen them by cold working. They possess good corrosion resistance at ambient conditions and high temperatures, increasing their range of applications [56, 57]. Due to good formability, weldability, durability, strength, and good corrosion resistance, these steels are used in a wide range of applications such as structural support, kitchen equipment, architectural goods, medical products, and heat treating baskets [58-61]. This steel's worldwide market share is more than two-thirds of all type of stainless steels [62, 63].

These steels are more expensive than low chromium and medium chromium ferritic stainless steel due to nickel, a costly element. These steels have shown low corrosion resistance in chloride environments like sea-water and extremely caustic mediums. These mediums accelerate the pitting corrosion, crevice corrosion, and stress corrosion cracking in these steels due to sufficient nickel in them [64].

2.4.5 Ferritic stainless steel

In ferritic stainless steel, the ferrite phase is dominating over another phase due to ferrite stabilising elements like chromium, molybdenum, silicon, niobium, aluminium, vanadium, tungsten [65]. These stainless steels are also based on the Fe-Cr-C system and have been further elaborated in the later part of the thesis.

Ferritic stainless steel has better crevice corrosion, pitting corrosion and stress corrosion cracking in chloride environments [66, 67]. Therefore, they are preferred over austenitic stainless steel in the chloride environment because austenitic stainless steels have poor corrosion resistance in the chloride environment.

2.4.5.1 Classification of ferritic stainless steel

The classification of ferritic stainless steels has been carried out by several authors using two basis. The first basis of classification is the percentage of chromium element and other alloying elements. On this basis, ferritic stainless steel has been classified into five groups. The second basis of classification percentage of the chromium element only. When classifying, based on the percentage of chromium only, ferritic stainless steels are generally subdivided into three types.

A. Classification of ferritic stainless steels based on chromium, carbon and the stabilising elements present.

Ferritic stainless steels are generally classified into five groups based on the percentage of chromium, carbon and stabilising elements like Mo, Nb and Ti, as shown in Figure 2.2 [68].

	Standard Ferritic Grade			Special Ferritic Grade	
	Group 1	**Group 2**	**Group 3**	**Group 4**	**Group 5**
Chromium wt. %	10-14	14-18	14-18 stabilized	10-18 +Mo	18-30
Market Share	30%	48%	13%	7%	2%
Specific Examples	Types 409, 410, 420	Type 430	Types 430Ti, 441, with stabilization elements, Ti, Nb, Mo	Types 434, 436, 444 Mo>0.5 wt%	Types 445, 445J1, 445J2, 447

Figure 2.2 Different grades of ferritic stainless steel.

From the above figure, it can be seen that group 1, 2 and 3 comes under the standard ferritic grade, while group 4 and 5 comes under the special ferritic grade. Group 1 consists of 409, 410 and 420 grades of stainless steel, and it contributes 30% share of the ferritic stainless steel market. The chromium content in this steel group is the lowest (10 to 14 weight %) among all other groups. Grade 430 steel is the main grade of Group 2 (14 to 18 weight% of chromium), and it has the maximum market share (48%) of the ferritic stainless steel. Group 3 possess the same range of chromium percentage as group 2 in addition to the stabilising elements (Ti, Nb and Mo). Grade 430 Ti and grade 441 is the main grade of this group. In group 4, the chromium lies between 10 to 18 weight % and Mo greater than 0.5 weight %. This group consists of 434, 436, and 444 grade of steel and its market share is 7%. The range of chromium in group 5 is maximum (18 to 30 weight %), and its market share is least (only 2%) among all other groups of ferritic stainless steel. Grade 445 and 447 are the primary grade of this group.

Each group possess certain similarity in the properties of their grades. On moving from group 1 to 2, the range of chromium percentage is increased; therefore, the corrosion resistance is also increased. Group 2 and 3 possess the same range of chromium percentages; therefore, both groups' corrosion resistance is nearly the same. However, the stabilising elements present in group 3 makes this group less sensitisation. Group 4 has better pitting corrosion resistance due to the presence of Mo. Group 5 possess a maximum percentage of chromium than other groups; therefore, it possesses excellent corrosion resistance than the other groups.

These different groups of ferritic stainless steel have different corrosion resistance, physical and mechanical property. The details about the applications and properties of these groups are discussed below.

(A.1). Group 1: 10-14% Cr (such as 405/409/409L/410L)

This group consists of ferritic stainless steel having the least chromium content among the ferritic stainless steel group. Due to the lower chromium content, their corrosion resistance is lower; therefore, these steels are ideal for those applications where corrosion resistance is not of prime importance, and slight rusting can be accepted during application. However, the corrosion resistance is much superior when compared with plain carbon steels. The cost of stainless steel in this group is the lowest due to the lower percentage of costly alloying elements like Cr and the absence of Ni. Therefore, it offers a cost advantage over other groups of ferritic stainless steel. Type 409 was initially used for automotive exhaust system silencers (exterior parts in non-severe corrosive environments). Later on, its application became vaster, and manufacturing of various parts of the exhaust systems like catalytic converter, exhaust manifold, tailpipe, etc., was also carried out using this 409 stainless steel. Other than its application in the automotive industry, it is also used in many other industries for different applications like food and dairy industry, electronic industry, heat exchanger, pressure vessels, thermostat, paddle wheel, washing machine drums, roof support structure and various others [69]. Type 410L is often used for containers, buses and coaches and, recently, LCD monitors frames.

(A.2). Group 2: 14-18% Cr (such as 430)

Group 2 stainless steel is most widely used among these groups in various industrial and domestic applications. This group possesses better corrosion resistance than group 1 due to its higher chromium content (which is approximately the same as those present in austenitic grade 304). In many applications like indoor application, this group is suitable and can replace grade 304. However, this group is more costly than group 1 due to the higher amount of alloying elements. Among the applications of group 2, the highest share is contributed by AISI 430 ferritic stainless steel. Its typical chemical composition is 16-18% Cr and 0.12 % C by weight. Since the carbon is an austenite stabiliser and is present in an appreciable amount, which causes martensite formation occurs during welding. The formation of martensite results in reduction in ductility. Therefore, the carbon content is reduced to a lower value, typically in the range of 0.02 to 0.05%, particularly in the thin sheet that needs to be welded during application. Type 430 is often used in household utensils, dishwashers, pots, pans and decorative panels.

(A.3). Group 3: 14-18% Cr + stabilization elements (Ti, Nb and Mo) (such as 430Ti and 441)

In this group of ferritic stainless steel, Ti, Nb and Mo are added in the stainless steels, which form their carbides and nitrides, thus, preventing the formation of chromium carbides and nitrides. These alloying elements show more affinity towards carbon and easily form carbides and nitrides than chromium, reducing the sensitisation tendency of these ferritic stainless steels. The formation of carbides also reduces the content of carbon from the bulk material, that causes reduction in the stability of the austenite phase and ultimately reduces the martensite phase formation. The carbides of these elements like NbC, TiC, ZrC have a different stabilising tendency and different stabilisation temperatures. Other properties like drawability, pitting corrosion resistance, high-temperature strength and creep resistance may be improved by adding alloying elements. Some examples of group 3 are types 430Ti, 439, 441, etc.

This group possesses better weldability and formability than group 2 (430 grade) and the weldability and formability is comparable to that of 304 austenitic grade. These materials are used for various applications such as sinks, heat exchanger tubes, exhaust systems and washing machines.

(A.4). Group 4: 10-18% Cr and Mo content higher than 0.5% (such as 434, 436, 444, etc.)

In this grade, Mo is mainly added as the stabilising elements to improve the corrosion resistance especially pitting corrosion resistance. The corrosion resistance of various grades in this group varies significantly since it depends on chromium percentage. The amount of chromium in this group can vary from 10% to 18%. The material which possessed lower chromium content has lower corrosion resistance. However, in this group, Cr content is generally found between 17-18%. Pitting Resistance Equivalent (PRE) number is shown in equation **(2.1**) which shows the relative contribution of Cr and Mo element towards the pitting corrosion resistance in chloride environment.

$$PRE = \%Cr + 3.3*\%Mo \quad \textbf{(2.1)}$$

From the above equation, it can be easily inferred that Mo is 3.3 times more effective than chromium in preventing pitting corrosion.

The corrosion resistance of some grades like 444, etc., is comparable to that of austenitic grade 316. Since Mo is also a ferrite stabilising element, this element and other ferrite stabilising elements result in a fully ferritic microstructure. When this material is used at high temperatures for a longer duration, it becomes brittle in nature due to the precipitation of various carbides and the formation of different brittle phases like χ and σ phases.

These stainless steels are widely used to manufacture hot water tanks, solar water heaters, exhaust systems, electric kettle, microwave oven elements, automotive trim and outdoor panels, etc.

(A.5). Group 5: Cr content higher than 18% and not belonging to other groups (such as 445,446, 447, etc.)

This group consists of materials with a higher amount of Cr and other alloying elements like Mo, Ni, etc. Due to the higher amount of Cr element, corrosion resistance possessed by these stainless steels is excellent. However, the formation of brittle phases may occur due to high amounts of Cr content when subjected to high temperature. Therefore, special precaution has to be taken during welding of materials of this group. To increase the material's toughness, nickel is also added, but simultaneously, Ni also increases the kinetics of the precipitation phenomenon of carbides of different elements. Another major drawback of adding Ni element is that it enhances stress corrosion cracking in the chloride environment. Several difficulties have been identified during the production of materials of this group which again increase its production cost. Considering the cost factor, these are used in specialised applications like high-temperature applications in severe corrosion environments, nuclear power station condensers, sea-water exchanger tubes, and exhaust applications.

B. Classification based on the amount of chromium percentage only

Some authors do another classification based on the amount of chromium element only, i.e. high, medium and low Cr ferritic stainless steel.

(B.1). High chromium ferritic stainless steels (Cr > 25%)

These materials are developed for applications in more aggressive environments such as chemical processing, pulp and paper industries, refineries and high-efficiency furnaces. High chromium grades have far more corrosion resistance than the austenitic stainless steels, but it is more costlier and difficult to fabricate. It also possesses 475º C embrittlement that is why its application is limited to 400^0C. The weldability is also poor due to the formation of embrittling phases.

(B.2). Medium chromium ferritic stainless steel (Cr 16 to 18%)

These materials are also used in automotive exhaust components but costlier than low chromium ferritic stainless steel. Its corrosion resistance property is also better than that of low chromium grade.

(B.3). Low chromium ferritic stainless steel (like 409) (Cr 10.5 to 12.5%)

Low chromium ferritic stainless steel is widely used in those products where the requirement of general corrosion resistance is superior to carbon steels like automotive exhaust components (i.e. muffler, exhaust tubing, catalytic converter and tail pipe), heat exchanger, pressure vessels, in food and dairy industries, thermostat, paddle wheel, washing machine drums, and roof support structure, etc.

Low chromium grade AISI 409 stainless steel is an attractive material for automotive industries and other industries. It has four subcategories, i.e. UNS 40900, UNS 40910, UNS 40920 and UNS 40930, depending upon the variation in the composition of carbon and titanium elements. To improve the weldability and to reduce the formation of martensite, lower amount of carbon is necessary. To improve the weldability further, titanium and niobium are added to form the carbides or nitrides by combining with carbon and nitrogen, which can reduce the formation of martensite and improve the stability of the ferrite phase but then also the formation of martensite cannot be eliminated.

Welding is an important manufacturing process to join this low chromium ferritic stainless steel material to make any component. Different types of welding are used like GMAW, GTAW, resistance welding, EBW and LBW. Among these types of welding processes, GMAW is widely used in industries due to their high welding speed, cleaner weld, and ability to weld thin and thicker plates along with good mechanical strength of the welded component.

2.5 Mechanical and physical properties

2.5.1 Crystal structure

The crystallographic structure of the ferritic stainless steel is body centred cubic (BCC). Compared with the austenitic grade, which is of face-centred cubic (FCC) crystal structure, it possessed a lower capacity to accumulate the alloying elements, i.e. two atoms per unit cell. The type of crystallographic orientation affects the material's physical and mechanical properties, including magnetic property, ductile to brittle transition temperature, plasticity and deformation, thermal expansion and conductivity, texturing, and grain orientation. Its BCC structure possesses no defined slip planes and hence possessed lower formability, limiting its applications in some cases [70-73].

2.5.2 Physical properties

Ferritic stainless steels are ferromagnetic materials due to their BCC crystal structure. They possess higher thermal conductivity and a lower coefficient of thermal expansion than the austenitic grades, which results in lower distortion in the welded plate or when heated compared to that of distortion in the welded plate of austenitic grades [74, 75].

2.5.3 Mechanical properties

Ferritic stainless steels have higher yield strength than the austenitic grades but lower ultimate tensile strength and lower ductility. That higher yield strength results in the lower formability of ferritic stainless steel grades [76]. But drawing operation can be easily performed by the ferritic stainless steel grade materials since it possessed higher values of Limited Drawing Ratio (LDR) compared to the austenitic grades [77]. LDR is an essential parameter for the deep drawing process. It is defined as the ratio of maximum blank diameter that is to be deep drawn into a cylinder of diameter in one step to the diameter of the cylinder.

2.6 Welding of ferritic grades

Complex designed components cannot be manufactured by casting or any other forming process. In that case, welding is a critical process to make that component. Also, welding possesses many other advantages over other techniques. There are different types of welding processes like electric resistance welding, EBW, LBW, friction welding and electric arc welding, which are used to join the ferritic stainless steels [78-97].

2.6.1 Electric resistance welding

It is one type of welding process in which electric resistance offered by the material generates the heat that melts the material, and after removing the current, welding of two materials takes place due to solidification. In this process, two materials are brought in contact, either to form a lap joint or butt joint, and the electrode serves two purposes: first, hold the material, and the second is to flow the electric current. This process uses direct current as well as alternating current.

Since this process depends upon the conversion of electrical energy to thermal energy. Equation **(2.2**) is used to find out the heat generated in this process

$$H = I^2RT \tag{2.2}$$

Where,

H' is the generated heat (joule)

'I' is the electric current (ampere)

'R' is the electric resistance (Ohm)

'T' is the time of current flow (second)

The main advantage of this process is that it is straightforward to operate, and another is no use of filler material. Along with these advantages, this process can weld at a very high speed and can be performed without using a shielding environment and doesn't require any filler material. The limited thickness of the material to weld is considered as the main limitation of this process.

2.6.1.1 Types of electric resistance welding

There are various types of this process:

(a) Spot welding

It is one of the simplest types of electric resistance welding. In this process, the welding happens at one point at one time. Electrode copper is used to make contact by applying the force and simultaneously applying the electric current through the copper electrode to provide the heat required for welding.

(b) Seam welding

The series of continuous spot welding is known as seam welding. In this process, the electrodes of wheel shape are used instead of rod-shaped as used in the spot welding process. As in spot welding type, these electrodes apply force and electricity to the workpieces.

(c) Projection welding

It is similar to spot welding, with two main differences, first is in the shape of the electrode, and the second is the shape of one of the workpieces, i.e. projections on one workpiece. After applying the electric current, the weld occurs at the projected points.

(d) Flash butt welding

In this process, the workpieces are brought into contact and then electric current is applied. Due to the electric resistance offered by the air gap between them, heat is generated. Thus the temperature of both the material increases. Upon achieving sufficient temperature, both workpieces are forced against each other, and thus the forge welding occurs.

Electric resistance welding is widely used in the automotive industry, pipe and tubing industry, pressure vessel industry, etc.

2.6.2 Electron beam welding

In this type of welding, the electron beam is used to generate the heat required for welding. Electron is generated from the electron gun, accelerated during its motion towards the workpiece by applying the magnetic field. When the high velocity of electrons strikes the workpiece, the kinetic energy converts into the thermal energy that is very high to melt the material, and welding occurs. Since the electron may distract from its path by colliding with the molecules of the air present within its path, that is why, this welding is performed in the vacuum chamber. Also, due to welding occurring in the vacuum environment, there are no impurities in the welded region, which improves its weld strength. This process is highly automated, and movement of the workpiece inside the vacuum chamber is done by automatic clamping tools, jigs and fixtures. Due to this automation, this process is very precise and highly repeatable.

This process possesses good welding strength and small heat affected zone due to its capability to heat the material to a confined region, which is why it is used in several industries. This process is also used to join dissimilar material and refractory material, which the conventional welding processes cannot join.

2.6.3 Laser beam welding

Like electron beam welding, this process is highly automated and precise with minimum heat affected zone. This process utilises a laser beam to generate the heat for the welding process. The depth to width ratio of the welds is high as in the electron beam welding process. Due to its capability to perform welding operation at high speed, the weldment possesses a high cooling rate. In some materials, like high carbon steel, due to the high rate of cooling, excess formation of martensite phases occurs, resulting in the cracking of the welded component. A vacuum environment is not required for this process as in electron beam welding. This process is used in the automotive industry on a large scale. It can weld carbon steels, HSLA steels, stainless steel, aluminium and titanium [98-100].

2.6.4 Friction welding

It uses mechanical friction as the source of heat generation [101-104]. In this process, two materials are brought into contact, keeping one of the material fixed. Two types of motion are given to another material, first, which causes the frictional heat, and the second is traversing towards the static material. As the frictional heat increases and plastic deformation starts, along with the simultaneous movement of another material. After achieving sufficient temperature, the motion is stopped, and axial force is applied, resulting in bonding. Due to the rubbing action between the materials, impurities in the form of scale, dirt, etc., are removed from the surfaces, which indicates that minimum surface preparation is required to carry out this welding process. This process is used for metals as well as thermoplastics.

2.6.4.1 Types of friction welding used for metals

Depending upon the relative motion between these two materials, this process has been categorised into two types for the metals [105]:

2.6.4.1.1 Rotary friction welding

In this process, one material is rotated and traverse towards the other fixed material. This process is limited to weld cylindrical shaped materials only. However, different shapes can also be welded but with much difficulty, but at least one material must be cylindrical. It is widely used to join the drill bits to its shank and various other similar applications.

2.6.4.1.2 Linear friction welding

One material is fixed while another is vibrated. Due to vibration between these two materials, the frictional heat is generated. When both materials are sufficiently heated, the vibration is stopped, and force is applied to form the joints. This process offers the advantage that materials of any shape can be readily welded. The weld metals produced by this welding process are also stronger than the weld metals produced by rotary friction welding.

2.6.4.2 Types of friction welding used for thermoplastics

2.6.4.2.1 Linear vibration welding

As the name suggests, the vibration is applied to generate the heat required for welding two materials in this process.

2.6.4.2.2 Orbital friction welding

In this process, both materials are kept in contact under pressure. The relative motion between two materials occurs in a circle of tiny size, which generates frictional heat.

2.6.5 Electric arc welding

It is a type of fusion welding process in which the base metal to be joined is melted using the heat generated by the electric arc. After welding, the solidification of the liquid metal takes place, and thus, joining happens. This process may use either direct current (DC) or alternating current (AC) to generate the electric arc depending upon the type of base metal to be joined and the type of welding process.

In this process, the filler material may be or may not be used, depending upon the thickness of the material and type of process. In the welding of thinner sections (up to 2mm), the use of filler material is not required, while in the thicker sections (greater than 2 mm), filler material is mandatory. Some welding processes in which the filler material is added externally offer the advantage over the other welding processes in the choice of use of filler wire. In some processes like GTAW, the filler material may be used or may not be, while in other processes like GMAW, filler wire must be used.

Due to the production of intense heating during the welding process, gases like oxygen, hydrogen, nitrogen, etc., that are present in the surrounding environment tends to react with the molten metal and form oxides and other embrittling phases in the weld metal region, which deteriorates the properties of the welded joint. Therefore proper shielding of the weld metal is necessary to avoid the contact of surrounding gases with the molten weld pool. Different welding processes use different methods to protect the molten weld pool. The shielding gases such as helium, argon, carbon dioxide, and their mixtures with the oxygen or nitrogen is used in GTAW, GMAW, plasma arc welding

(PAW), etc. while the other process like shielded metal arc welding (SMAW), flux cored arc welding (FCAW) and submerged arc welding (SAW) is using the flux coated on the electrode, flux within the electrode, and granular flux respectively to protect the molten weld pool. These fluxes serve various other purposes along with the generation of shielding environment around the molten weld pool.

There are four types of welding processes depending upon the method of arrangement of welding gun, wire feeding system and controlling of the whole welding process. These are manual welding, semi-automatic welding, mechanised welding and automated welding. In manual welding, all the work including wire feeding and holding of the welding torch and other operations, are performed manually. In the semi-automatic type of welding, the feeding of the electrode occurs automatically, and the welding torch is held manually. In mechanised welding, both the feeding of the electrode and the movement of the welding torch occurs automatically, but the welding parameters can be varied during the welding operation. In the automatic welding type, all the welding process parameter can be controlled and manually adjusted between the welding operations but not during the welding operations. In this type, manual intervention is not permissible during the welding operation. The welder's job is only to start and stop the welding operation.

GMAW and GTAW are two electric arc welding methods that are widely used for ferritic stainless steel. In the GMAW process, the consumable electrode is in the form of a spool and continuously fed through a welding torch to the base metal. While in the GTAW process, a non-consumable electrode (tungsten, tungsten-thorium and graphite) is used. Both processes have some advantages and some limitations over one another. That is why the selection of types of welding processes depends upon the requirements. Spatters are formed during the GMAW process, while the GTAW process produces spatter free weld. Thus, GTAW possesses cleaner welds compared to that of the GMAW process. Faster welding can be achieved with the GMAW process. Also, GMAW is easy to operate than to operate GTAW machine. GMAW process serves one other advantage over the GTAW process is that GMAW can weld the materials of a wide range of thicknesses, i.e. thinner as well as thicker materials, while GTAW is usually used to weld only thinner sections.

These different types of welding processes are used according to the applications of the material and types of grades, but electric arc welding is a widely used process among them due to its lower capital investment and high welding speed with good quality of welded plate. There are different types of electric arc welding process like GMAW, GTAW and various others. Among these processes, the GMAW process offers many advantages over other processes such as GMAW possessed the capability to join different thickness of the material, higher welding speed, good control over the process parameters and possessed better mechanical properties of the weldment.

Welding of ferritic stainless steel can be done using filler wire or without any filler wire depending upon the thickness of the plate and types of the welding process. Different grades of filler wire, like ferritic grade (such as ER409Cb) and austenitic grade (such as ER308L, ER309L and ER316L) are used to join the ferritic stainless steel grade materials. The type of filler wire is selected depending upon the chemical composition of the material and to obtain certain specific properties of the welded component for the applications.

2.7 Welding of ferritic stainless steel AISI 409 (SS409)

Different welding processes such as GMAW, GTAW, LBW, EBW, FSW, and PAW are used to join stainless steel AISI 409 (SS409) materials. The type of welding processes used depends upon the thickness of the material, productivity, application, mechanical properties, corrosion properties, economy and other factors.

2.7.1 Gas tungsten arc welding of SS409

The advantages and limitations of the gas tungsten arc welding (GTAW) process have been described earlier. The major advantage of this welding process is that it produces cleaner welds than other welding processes, whereas the main limitation is that it can weld only the thinner section in one pass. Various researches have been carried out, some of which is described below.

The limitation of reduced depth of penetration in the GTAW process can be reduced to some extent by using activated fluxes instead of only shielding gas. This type of welding process is known as Activated TIG (A-TIG) welding. In this type of welding process, a thin layer of flux comprising mixtures of oxides, fluorides and chlorides is applied in the area to be welded. Venkatesan et al. [106] investigated the effect of ternary fluxes on the depth of penetration in A-TIG welding of AISI 409 ferritic stainless steel plate. In this study, the combination of three types of fluxes viz, SiO_2, TiO_2 and Cr_2O_3, were used to perform the welding operation. The combination of these fluxes was optimised to get deeper penetration. Two fold increase in depth of penetration was found by using this flux combination over conventional TIG welding.

The main limitation associated with the GTAW process is the slow welding speed. Researchers tend to reduce this problem to improve productivity. In this order, Feng et al. [107] experimented to obtain the feasibility to increase welding speed in high speed TIG welding process. In this study, the defects associated with this high speed welding process was analysed. It was found that the maximum backward velocity of the lateral channel increased the undercut defect on increasing the welding speed. However, initially on increasing the welding speed up to a certain extent, the undercut defect was not detected, but on increasing the welding speed further, the undercut defects became more serious. This increase in the undercut defect on increasing the welding speed tends to deteriorate the mechanical properties of the weldments. Therefore, the welding speed cannot be increased beyond a certain limit. Along with the undercut defect, the one other defect known as humping, is also associated with high speed welding. According to these findings, to obtain sound welds in GTAW process, the welding speed cannot be increased beyond a certain limit. However, the problem such as undercut and humping related to the high speed of welding is reduced or nearly entirely omitted using tandem high speed welding instead of high speed welding only. In this type of welding, an assistant arc is generated, which follow the main arc to prevent the backflow of molten metal in the liquid channel. This prevention of backflow of molten metal tends to reduce the undercut or humping problem. Qin et al. [108] experimented on a high speed tandem GTAW process of thin ferritic stainless steel 409 L plate of 1.5 mm thickness. In this study, the welding speed was varied up to 3.0 m/min and no defects in the form of undercut or humping were observed. At the same heat input, on comparing the mechanical properties obtained by using this high speed tandem welding process and a process used without tandem, it was observed that high speed tandem welding gives better mechanical properties with fine microstructure of welded joint than the other.

Spot welding is an important type of welding process used in various industries mainly in automobile industries at a large scale. Due to the presence of stress concentration at the weld spot, the mechanical properties of the weld joints are reduced. To minimise this stress concentration and to achieve weld joints of better quality, a new technique of joining known as weld bonding is used, in which the two materials which are to be joined, is first joined by using adhesive bonding and then welding is performed at that spot. Different types of welding processes can be used, such as LBW, metal inert gas welding (MIG), FSW, ultrasonic welding (USW), PAW and resistance spot welding (RSW). Kumar et al. [109] carried out an investigation to study the effect of input process parameters, i.e. welding current, weld time and gas flow rate in TIG spot weld bonding of 409L ferritic stainless steel on weld penetration, bead width and tensile shear strength of the weld bonds using design of experiment (DOE) approach. It was observed that weld time most significantly affected the weld performance followed by welding current and gas flow rate. The excessive grain coarsening of the heat affected zone was also observed along with the finer grain size of the weld metal region. The tensile testing results showed failure of weld bond in two ways, namely interfacial failure and button pull out failure. It was observed that the button pullout failure, which is the more preferred failure mode in tensile shear testing of weld, was occurred when the welding current and weld time was high.

The welding process parameters involved in the welding process plays a significant role in determining the microstructure of the welded joints and hence, mechanical and other related properties of the welded joints. Ranjbarnodeh et al. [110] investigated the effect of welding process parameters in the GTAW process on the microstructural transformation of the heat affected zone of AISI409 ferritic stainless steel. In this study, three samples were prepared using different combinations of welding speed and welding current having constant welding voltage. The study was mainly focused to find the effect of welding process parameters on texture distribution, local misorientation, and grain size distribution of the HAZ. These microstructural characteristics were investigated by using electron backscattered diffraction (EBSD). This investigation found that the heat affected zone possesses complete recrystallisation followed by severe grain growth. The number of low-angle grain boundaries was decreased within the heat affected zone. The heat input was the main factor responsible for the severe grain growth of the heat affected zone.

2.7.2 Friction stir welding of SS409

Friction stir welding (FSW) is a type of solid state welding process which was invented by The Welding Institute (TWI), U.K., in 1991 [111]. In this welding process, the base materials which are to be joined, are placed on the bed of the machine in butt or lap position and a non-consumable rotating tool is traversed over the interested line of joining from one location to the other. The non-consumable rotating tool consists of two parts, the upper one is tool shank, and lower one is tool pin. The length of the tool pin is generally less than the thickness of the base material to be joined or nearly equal to thickness of the base material to be joined. At the starting stage of the welding operation, the lower portion, i.e. tool pin, comes into contact with the base material. Friction between the material and the tool pin results in the heat generation at both the base material and the tool pin, leading to plastic deformation of the base material. Thus, the material becomes softened at the starting point, which helps to penetrate the tool easily into the base material. After full insertion of the tool pin into the base material, the lower portion of the shank, which is known as shoulder, comes into contact with the base material, which also produces frictional heat. Thus more plastic deformation takes place after full insertion of the tool material into the base material. After that, the tool is traversed along the adjoining line to perform the welding operation.

This welding process possess some advantages over other types of welding processes such as lesser heat input is involved in this welding process as compared to the other types of welding processes, especially fusion welding processes, which tends to reduce the problems associated with the fusion welding processes such as excessive residual stress, grain coarsening of the weld metal region as well as heat affected zone, porosity, etc.

Along with these advantages, FSW possesses some disadvantages also, such as non-consumable rotating tool material is much costlier, which increases the production cost of the welded material. The selection of tool material among different types of available tool materials depends on the base material's mechanical properties to be welded, especially hardness. The harder base material requires harder tool material also, and the cost of the tool material is increased in proportion to their hardness. The second limitation is that the tool material degrades very fast due to excessive heating, and that requires frequent changing of the tools, which adds some more cost to the welding process. The third limitation is that welding of thicker materials (except of softer materials like some softer grades of aluminium and magnesium) is very difficult due to the limitation of the tool material properties and cost associated with the tool material.

This welding process is newly developed, and much research is still needed to make this welding process popular among industries by reducing the problems associated with this welding process. Various researchers have carried out their investigation in different areas of this welding process, some of which are described below.

Ahmed et al. [112] studied the effect of FSW process parameters (rotation rate and traverse speed) on the microstructural evolution of friction stir welded ferritic stainless steel AISI 409. It was found from this study that on increasing the traverse speed at constant rotation speed, both the yield strength and the ultimate tensile strength along with the ductility was decreased, whereas on increasing the constant rotation speed at traverse speed, there was no major effect on the ultimate tensile strength, but the yield strength and ductility were decreased. This decrease in the yield strength, ultimate tensile strength, along with the ductility of the welded joints, was attributed to the grain size reduction in the stir zone, which increase hardness of the stir zone and the weld metal, that is why, the tensile failure happened outside the weld region in the weaker section. It was also found that this zone consists of different fractions of different phases (bainitic/ferritic microstructure) at different locations along the thickness of the stir zone due to the thermo-mechanical deformation occurring in the stir zone.

Cho et al. [18] carried out the metallography study of the friction stir welded ferritic stainless steel AISI 409. It was found that the welds produced were of high quality with defect free welds. The stir zone possessed very fine grain size with increased fraction of low angle grain boundaries as compared to that in the base material. This finer grain and fraction of low angle grain boundary were further increased on increasing the plunging depth.

Ahn et al. [113] studied microstructures and friction stir welded 409L stainless steel properties using a Si_3N_4 tool material. It was found that the stir zone possessed equiaxed grains due to dynamic recrystallisation. The mechanical properties of the weld were found similar to that of the base metal. The pitting corrosion and intergranular corrosion of the weld were found similar to that of the base metal.

Lakshminarayanan et al. [114] developed the empirical relationships between the mechanical properties (tensile strength and impact toughness) and the welding process parameters (RS, welding speed and tool SD) of the friction stir welded AISI 409M ferritic stainless steel joints. This study found that the welding speed has the greatest influence on tensile strength and impact toughness, followed by RS and tool SD.

2.7.3 Gas metal arc welding of SS409

This welding process possesses many features, as described earlier. In the manufacturing of components of SS409, the most widely used welding process is gas metal arc welding (GMAW). Therefore, several researchers have carried out different studies on the GMAW of SS409, which will be discussed in the following few paragraphs.

The different process parameters affect the quality of the welded plate. The shielding gas composition is one of the important process parameters that can change the chemical reactions taking place in the molten weld pool, which can change the weldment properties. A detailed study of the effects of type of shielding gases on the microstructure of the weld and mechanical properties of 409L ferritic stainless steel has been carried out by Feghhi et al. [115]**.** In this study, the four different compositions of shielding gas (Ar, Ar +20% He, Ar + 12% CO_2, and Ar + 25% CO_2) were used. After performing welding operation, non-destructive testing of the welded plates has been carried out along with the metallography and mechanical testing (hardness and tensile tests). The results of the work carried out demonstrated that the welding of specimens using Ar + 25% CO_2 and Ar + 12% CO_2 specimens possessed the highest strength and hardness values in the fusion zone, and it was due to the formation of martensite around the ferrite grains. A similar study has also been done by Mukherjee et al. [116]**.** In this study, the influence of different gas mixtures of (Ar+CO_2) on the microstructure and mechanical properties in GMAW of modified 409M ferritic stainless steel has been investigated. The result showed that on increasing CO_2 content, the grain size of weld metal and heat affected zone decreased, and hardness and toughness of weld metal increased.

The ferritic stainless steel SS409 can be welded with the same grade of material known as similar welding. It can also be welded with different grade of material, known as dissimilar welding. Many advantages and challenges are associated with the dissimilar welding. The main advantage of dissimilar welding is that it reduces the cost of the component to be manufactured because it eliminates the necessity of manufacturing the whole component by using the same material. The whole component may be manufactured using more than one material, and to join different materials, dissimilar welding is used. In this way, the unnecessary costly material can be replaced by less expensive material, which reduces the manufacturing cost of the component. The main challenges in dissimilar welding are that the different materials possess different properties such as the coefficient of thermal expansion, thermal conductivity, and melting point, which can result in residual stress in the weldment, intermetallic compounds brittle in nature. These challenges may deteriorate the welding strength and other properties; therefore the dissimilar welding must be performed cautiously. Ghosh et al. [14] investigated the dissimilar welding of AISI 409 ferritic stainless steel to AISI 316L austenitic stainless steel by using grey based Taguchi method. In this study, welding was conducted as per the L9 orthogonal array of the Taguchi method using the GMAW process with 316L as filler wire. The welding current, gas flow rate and nozzle to plate distance were used as the input parameters, and each parameter possessed three levels. It was found that among these three parameters, gas flow rate contributes the most on percentage contribution to the overall objective/grey relational grade, whereas nozzle to plate distance contributes the least.

In the GMAW process, as the welding current is varied, then the behaviour of transferring molten drops from the electrode into the molten weld pool is changed, which can alter the mechanical properties as well as other properties of the weldments. In the GMAW process, there are four modes (short circuit transfer, globular transfer, spray transfer and pulse mode transfer) by which the metal can be transferred. Each mode possesses some advantages and limitations; therefore, the selection of mode of metal transfer depends upon various factors. Mukherjee et al. [117] studied the effect of different heat input at two different modes of metal transfer (i.e. pulse mode at 0.5 kJ/mm and 0.9 kJ/mm and spray mode at 0.5 kJ/mm), using austenitic filler wire (i.e. 308 L).

This study found that the micro-hardness of welded joints and toughness of weld metals was significantly more in the case of pulse mode metal transfer than that achieved in the case of spray mode metal transfer for particular heat input. It was also depicted significant enhancement in grain structure with the higher heat input conditions due to the lower cooling rate associated with the high heat input, which provides sufficient time for grain coarsening. This grain coarsening in the WMZ and HAZ was the major challenge in welding ferritic stainless steel such as SS409 because the mechanical properties deteriorated on grain coarsening. This grain coarsening in the WMZ becomes more challenging in the autogenous welding and homogeneous welding because, in these types of welding, any pinning sites in the form of different phases such as austenite, martensite and other precipitates are absent or present in very small amount which does not prevent the grain growth of the ferrite grains. However, the problem associated with the grain coarsening of the WMZ is somewhat reduced by using heterogeneous welding with the use of filler materials of different grades such as austenitic type filler (e.g. ER304L, ER308L, ER316L). But the problem associated with the grain coarsening of the heat affected zone still remains the same, and it can be generally controlled by decreasing the heat input. The reduction in the heat input for welding is possible only to a certain extent, but it has been observed by various researchers that even with the lowest heat input, the heat affected zone possess coarser grains than the other regions. Therefore, the other technique has to be investigated to refine these coarser grains of the heat affected zone so that the mechanical properties of the welded plate can be improved.

2.8 Friction stir processing

Grain size is an important factor in deciding mechanical properties, including hardness, yield strength, creep, fatigue, and ductile to brittle transition temperature of any material [118-121]. Generally, it was found that the mechanical properties are improved on refining the grains [122-125]. Various grain refining techniques (such as rapid solidification, by vibration and stirring during solidification, the addition of grain refiner, severe plastic deformation and so on) are used in practice to refine the grains [126-133]. Friction stir processing (FSP) is one type of severe plastic deformation techniques [134-139].

The basic working principle of FSP is same as that of the FSW process [140-143]. The first main difference between these two processes is that in the FSW process, two materials are joined, whereas in FSP, there is no joining of any material; instead, this operation is performed only on single plate to modify the microstructural features and properties of the interested region of that single plate. The same machine performs the FSW and FSP operation. The second main difference between these two processes is that in the FSW process, the length of the tool pin is almost the same as that of the thickness of the materials to be joined, but in the FSP operation, the length of the tool pin is equal to the required depth of modification of the material [144]. Thus, the tool wear rate is much lower in the FSP than that in the FSW process.

Basic terminology used in FSP is advancing side, retreating side, processed region, flash and processing direction has been shown in Figure 2.3.

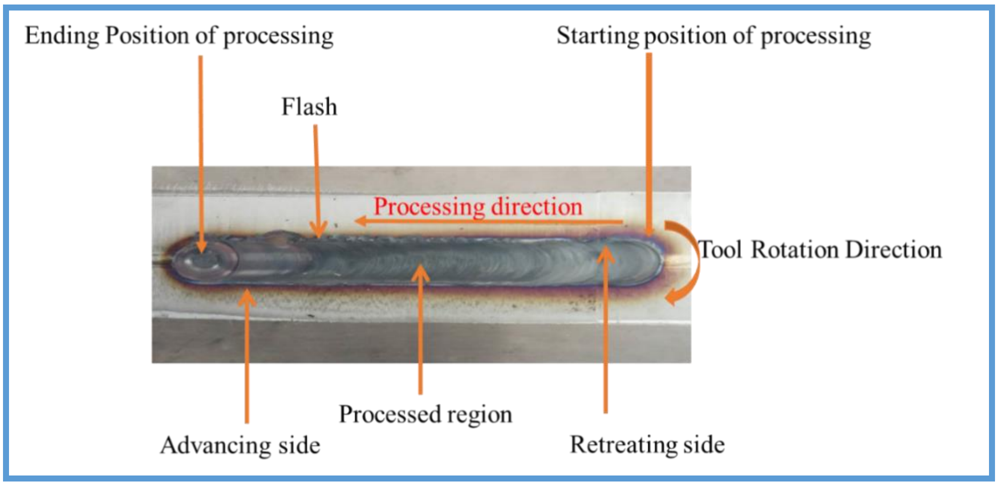

Figure 2.3 Terminology used in FSP.

The plastically deformed material which is expelled out during the FSP operation is known as flash. Various researchers considered it as a defect; therefore, the generation of flash should be minimum in a good quality of friction stir processed plate. The construction and working of the FSP are described in more detail in chapter 3, and here the main focus is on the findings from the studies carried out by various researchers.

No literature has been found on the FSP of AISI 409; instead of that, various literatures have been found on the FSP of various other materials such as aluminium alloys, magnesium alloys, copper alloys, stainless steels other than AISI 409, carbon steels, etc. Therefore, the findings obtained from these studies can be extrapolated to obtain the basic idea of changes in the microstructural and mechanical properties on FSP of AISI 409 material.

2.8.1 Friction stir processing of aluminium and its alloys

Aluminium is the first material on which the FSW as well as FSP have been done. Cavaliere and Squillace [145] investigated the effect of FSP on the mechanical and microstructural properties of 7075 aluminium alloy. It was found that the stirred zone possessed equiaxed fine recrystallised grain structure, whereas the thermo-mechanically affected zone (TMAZ) possessed partially recrystallised grain structure. An exciting result has been found that the microhardness is minimum in the centre of the processed region, and on further moving on either side of the centre, the hardness was found to increase, and after a certain distance, this hardness started to decrease. Tensile testing has also been performed to compare the tensile properties of the base metal and friction stir processed plate. In the case of friction stir processed plate fractured away from the centre in the heat affected zone, the tensile specimens indicated that the plate after processing became stronger than the base metal.

To investigate the effect of FSP on the microstructural and corrosion properties, Surekha et al. [146] performed FSP on AA2219 aluminium alloy to a depth of 2 mm in a 5 mm plate. It was found that the stir zone possessed fine alpha-aluminium grains, along with the reduction and dissolution of both the eutectic phase ($CuAl_2$) and the strengthening precipitates ($CuAl_2$). Various types of corrosion tests were carried out, such as Anodic polarisation and electrochemical impedance tests in 3.5 % NaCl, Salt spray and immersion tests. In each test, the friction stir processed plate's corrosion resistance was found superior compared to the base metal, attributed to the dissolution of ($CuAl_2$) particles. It was also found that the corrosion resistance of the processed alloy was increased with the number of passes.

Yadav and Bauri [147] studied the change in commercially pure aluminium's microstructure and mechanical properties after FSP. It was found from this study that the initially coarser grain size of the base material is refined into the finer grains of 3 micron in a single pass. Due to this grain refinement, it was also found that the yield strength of the material was improved by a factor of 2.4 after FSP with little loss of ductility. The improvement in the hardness was also found by 34%.

To investigate the effect of different media on the microstructure, surface chemistry and corrosion resistance of aluminium alloy AA7075, FSP has been carried out in the water and air medium by Pang et al. [148]. From this investigation, it was found that FSP conducted in the air when tested in a 0.5M NaCl solution showed better results, i.e. corrosion rate was reduced. On the other hand, the FSP conducted in water when tested in a 0.5M NaCl solution showed the detrimental result, having no influence on the pitting potential but increasing the corrosion rate. It was due to the enrichment of copper at the surface, which tends to increase the surface area available for the cathodic reaction. It was also found that for the long term exposure of the processed samples in both the mediums, the corrosion rate was increased.

A lot of research work on the FSP of aluminium alloys have been carried out by various researchers in different areas. The extensive survey on this is beyond the scope of the present work.

2.8.2 Friction stir processing of magnesium and its alloys

Magnesium alloys are gaining popularity among various industries, especially in the transport industry due to their lightweight than aluminium and steel with excellent strength and rigidity at room temperature. However, the formability of magnesium alloys is poor at room temperature due to its HCP lattice, which limits its widespread utilisation. To improve the properties of these alloys, FSP is one of the most effective technique. Various researchers have carried out various studies on the FSP of different grades of magnesium alloys, some of which are discussed below.

The possibility of modification in the microstructure and mechanical properties of commercial AZ31 magnesium alloy by using FSP was investigated by Darras et al. [111]. This study found that the FSP leads to finer grain size of the stir zone along with the more homogenised grain structure, which improved the mechanical properties.

It is well known that the grain size is one of the most important factors which decides the most of the properties of the material. FSP can obtain the modification in the grain size. A detailed study has been carried out to examine the impact of the FSP on the microstructure, texture and residual stress of AZ31B magnesium alloy by Woo et al. [149]. In this study, the comparative analysis of results was carried out between the FSP operation 'with shoulder and tool pin' in one case and 'with shoulder and no tool pin' in another case. In both cases, it was found that the stir zone possessed finer grains than the other zones. The effect of the grain refinement in the stir zone did not contribute any significant changes in the hardness and chemical composition, whereas, on the other hand, grain refinement in the stir zone contribute significant changes in the tensile yield strength, texture, and residual stresses. A significant reduction in the yield strength has been observed in the first case, while it was not observed in the second case. A significant variation has been observed in the spatial texture in the first case, whereas in the second case, it was not so. The residual stress has been found to decrease near the stir zone in the first case, whereas it was not found in the second case.

Cavaliere et al. [150] carried out a study on the superplastic behaviour of friction stir processed AZ91 magnesium alloy produced by high pressure die cast. It was found that after FSP, the tensile properties like strength and ductility of the material at room temperature was improved due to the very fine grain size of the stirred zone as compared to the unstirred zone. At high temperatures, the strength was found to decrease, but ductility was increased. On increasing the strain rates, the flow stress was decreased.

Feng and Ma [36] investigated to establish the procedure to enhance the mechanical properties of AZ91 casting. From this investigation, it was found that the coarser network like eutectic β-$Mg_{17}Al_{12}$ phase distributed at grain boundaries was significantly broken and dissolved into the matrix on performing FSP, which lead to refinement of grains and thereby, tensile properties of casting was improved considerably by FSP.

Since at room temperature, the formability of the magnesium is poor. Therefore, to improve the ductility of the material at room temperature, the grain size should be significantly reduced below 1 micron, which is known as ultrafine grains. To achieve ultrafine grains, FSP of AZ31 Mg-Al-Zn alloy equipped with a rapid heat sink has been done by Chang et al. [151]. This study found that the ultrafine grains were successfully achieved, and the mean hardness of the UFG regions increased twice.

2.8.3 Friction stir processing of carbon steels

Carbon steels are widely used in industries due to their strength, hardness and stiffness; however, some properties such as tribological properties, corrosion properties, etc., of carbon steel are poor, which limits the use of this material. These properties can be further improved by various techniques such as heat treatment, surface coating such as chemical vapour deposition (CVD), physical vapour deposition (PVD), thermal spray, mechanical treatment such as shot peening, etc. Among these different kinds of techniques, FSP is one of the techniques which has the potential to change the properties of the material.

To process a small area by using FSP, a single pass is adequate. Whereas to process a larger area, multipass processing is necessary. Aldajah et al. [152] investigated the impact of single-pass FSP, and multi-pass FSP applied to high carbon steel (AISI 1080) on its friction and wear performance. A significant increase in surface hardness was found on performing FSP due to the transformation of pearlite into the martensite, which leads to considerable improvement in the friction and wear behaviour of the steel as measured by unidirectional sliding ball-on-flat testing.

The impact toughness is one of the important mechanical properties. The effect of FSP on the impact toughness of low carbon steel via Charpy impact test at different temperatures was investigated by Sekban et al. [153]. In this investigation, the grain size of the processed region was found finer as compared to the originally coarse-grained structure due to both large deformation and simultaneous dynamic recrystallisation. This grain refinement after FSP leads to an increase in the tensile strength with a slight decrease in the ductility values. The ductile to brittle transition temperature was decreased, i.e. impact toughness was improved on refining the grain size due to FSP.

There are various process parameters used in FSP such as RS of tool spindle, traversed speed of the tool (PS), tilt angle given to the tool spindle (tool tilt angle), SD, tool pin length, tool pin diameter and tool pin shape, depth up to which the tool shoulder is plunged in the workpiece (depth of plunge in –Z axis), etc. which affect the soundness of the processed material. These process parameters are discussed in detail in chapter 3. The effect of tool pin shape (cylindrical, conical, square and triangular pin) on the microstructural evolutions and tribological characteristics of friction stir processed ST14 structural steel was investigated by Amirafshar and Pouraliakbar [154]. Defect free processing has been obtained by all shapes of tool pin. From the mechanical and tribological point of view, the square tool pin shape was found best tool pin shape among different tool pins.

The feasibility of the use of FSP for the processing of mild steel to enhance its surface hardness has been explored by Grewal et al. [155]. Grain refinement of the steel surface was obtained by using FSP, along with the evolution of various phases. Improvement in the microhardness of the steel has been obtained by 50 to 80% with that of the un-processed steel.

An attempt to achieve ultrafine dual-phase structure with superior mechanical property in friction stir processed plain low carbon steel has been done by Xue et al. [156]. In this study, the FSP under rapid water cooling has been done at 400 RPM of RS and 50 mm/min of travel speed. Ultrafine grains have been obtained, which enhances the tensile strength. This work confirmed the strategy to prepare high strength low carbon steels.

Aktarer and Kucukomeroglu [157] carried out a study to investigate microstructural alteration and the main mechanical properties of high-strength low-alloy (HSLA) steels (EN 10149-2 /S315MC) after FSP. Refining of the grains, as well as considerable increase in both hardness and strength values, were observed. The increase in the yield and tensile strength after FSP was about 30% and 34%, respectively.

2.8.4 Friction stir processing of stainless steels

One major advantage of stainless steel that it possesses over the carbon steels is its higher corrosion resistance, but, generally, all other properties of it, such as mechanical properties and tribological properties, are inferior or superior to that of the carbon steels depending upon the alloying elements. To improve these properties, various research works have been carried out by using FSP.

Hajian et al. [158] carried out a study to enhance the cavitation erosion resistance of AISI 316 L stainless steel by using FSP. Cavitation erosion is one of the major surface damaging factors in hydraulic systems such as ship propellers, pump impellers, hydro-turbines, etc. Cavitation erosion is the erosion of surfaces by the cavitation phenomenon produced due to the high differences in the pressure at the localised region. From this study, it was found that the original coarser grains were refined. The study has been performed at different process parameters, which lead to different grain sizes. Depending upon this range of grain sizes, the refinement of grains enhanced the cavitation erosion phenomenon by a factor of 3-6.

Dodds et al. [159] carried out a work in which the tribological properties of the AISI 420 martensitic stainless steel was improved by using FSP. In this work, the microstructure, hardness and wear resistance of the friction stir processed material were compared with the properties of conventionally hardened AISI 420 martensitic stainless steel. Austenite to martensite transformation has been observed in the friction stir processed AISI 420 martensitic stainless steel. Still, the microstructure was different from those which was obtained with the conventional heat treated material. The microhardness and tribological properties were found more in friction stir processed AISI

420 martensitic stainless steel than the microhardness and tribological properties of conventional heat treated material.

The effect of FSP on microstructural evolution and mechanical properties of AISI 201 stainless steel was investigated by Cui et al. [160]. It was found from the study that the grain size of the stir zone is result of the competition between continuous recrystallisation (CDRX) and discontinuous recrystallisation (DDRX). The process parameters affect the grain size, δ-ferrite content, density of dislocations and sub-structures in the stir zone. Inhomogeneous finer grains was observed on the advancing side due to mixed CDRX and DDRX. It was established that the DDRX possess better refinement action than the CDRX. All the tensile samples were fractured at the retreating side, which indicated that the advancing side was stronger than the retreating side. The tensile strength of the processed samples was found to be slightly lower than the tensile strength of the base metal. However, the hardness of the stir zone was more.

Tinubu et al. [161] carried out extensive work to understand the effect of FSP on the wear behaviour and wear mechanisms of A-286 stainless steel, Fe–Ni–Cr based austenitic, precipitation hardened alloy in high frequency reciprocating sliding test. The properties of this alloy were compared between two different conditions of alloy, the first was as rolled (AR) + aged and the second was FSP + aged. During the wear testing, it was observed that the particle size of the abraded material was coarser in the case of AR + aged, while in the case of FSP + aged, much finer-scale microabrasion took place. The coarser abraded particles resulted into the more wear debris which increased the wear rate in the case of AR + aged, while the opposite result was obtained in the case of FSP + aged material. Thus, it was established from this work that the FSP can enhance the tribological properties of the material.

2.9 Literature gap

After carrying out an exhaustive literature survey on the fusion welding (such as GMAW) of AISI 409L, it was found that the grain growth of the heat affected zone occurred, which tends to deteriorate the mechanical and other properties of the weldments. On the other hand, from literature survey on the FSP, it was concluded that the FSP could enhance the mechanical and other properties of the material. It was also found from the exhaustive literature survey on the FSW that this welding process has some limitations, in which one most important limitation is related to the cost of the tool material and inability to weld thicker plates. But, in the case of FSP, the length of the tool pin is smaller than the thickness of the material; therefore, this process can be applied to the material of any thickness. In the FSP, the length of the tool pin should be equal to the depth of the material up to which the material is required to improve the mechanical and other properties. Therefore by using this process, the limitations associated with the FSW is somewhat reduced.

To weld thicker plates as well as to reduce the cost of the tool material, an alternative approach is that, first the plates should be joined by using any fusion welding process as described above and then, the problems associated with the grain coarsening of the heat affected zone should be reduced by using the FSP operation. In this way, the thicker plates can be joined with good mechanical and other properties.

No literature has been found to use both technique in the joining of AISI 409L by using GMAW and FSP. Therefore, there is some research gap to use both the technique (GMAW and FSP) in the joining of AISI 409L, which may lead to better mechanical properties of the welded plates.