Chapter 1

Introduction

1.1 Aluminium Alloy

Aluminium is the most abundant metal available in the earth's crust. Steel was the most used metal in 19th century; but Aluminium has become a strong competitor for steel in engineering applications. Aluminium has many attractive properties compared to steel. It is economical and versatile to use. That is one of the main reasons it is used a lot in the aerospace, automobile and other industries. The most attractive properties of aluminium and its alloys which make them suitable for a wide variety of applications, are their light weight, appearance, fabricability, strength and corrosion resistance. The most important property of aluminium is its ability to change its properties in a very versatile manner; it is amazing how much the properties can change from the pure aluminium metal to its most complicate alloys. There are more than a couple of hundreds of aluminium alloys and many are being modified from them. Aluminium alloys have very low density compared to steel; it has almost one thirds the density of steel. Properly treated, alloys of aluminium can resist the oxidation process which steel cannot resist; it can also resist corrosion by water, salt and other factors [1].

1.2 Characteristics of Aluminium Alloys

The unique combination of properties provided by aluminium and its alloys make aluminium one of the most versatile, economical, and attractive metallic materials for a broad range of uses from soft, highly ductile wrapping foil to the most demanding engineering applications. Aluminium has a density of only 2.7 g/cm^3, approximately one third as much as steel ($7.83 g/cm^3$). Aluminium resists the kind of progressive oxidation that causes steel to rust away. The exposed surface of aluminium combines with oxygen to form an inert aluminium oxide film only a few ten-millionths of an inch thick, which blocks further oxidation. If the protective layer of aluminium is scratched, it will instantly reseal itself [2].

Aluminium can resist corrosion by water, salt, and other environmental factors, and by a wide range of other chemical and physical agents. Aluminium surface can be highly reflective and hence radiant energy, visible light, radiant heat, and electromagnetic waves are efficiently reflected by it. Aluminium typically displays excellent electrical and thermal conductivity and is about 50% to 60% that of copper. Aluminium is non-ferromagnetic, a property of importance in the electrical and electronics industries. It is non-pyrophoric, which is important in applications involving handling or exposure of inflammable or explosive materials. Aluminium is non-toxic and is routinely used in containers for food and beverages [3]. One of the most important characteristics of aluminium is its machinability and workability. It can be cast by any known method, rolled to any desired thickness, stamped, drawn, spun, hammered, forged, and extruded to almost any conceivable shape. Due to the exciting range of properties of aluminium and aluminium alloys, this group of metals is extensively used for wide range of industrial applications. Aluminium and its alloys can be ranked next to steel, in terms of industrial applications. In many of these applications, welding is used as a method of fabrication [4].

1.3 General Classification of Aluminium Alloys

Pure aluminium is readily alloyed with many other metals to produce a wide range of physical and mechanical properties. There is an international accord recognizing the aluminium association wrought alloy designation system. The alloy designation system is briefly described below [5].

- First digit - Principle alloying element(s).
- Second digit - Variation of initial alloy
- Third and fourth digits - Individual alloy variations
    - 1xxx – Pure Al (99.00%)
    - 2xxx – Al-Cu Alloys
    - 3xxx – Al-Mn Alloys
    - 4xxx – Al-Si Alloys
    - 5xxx – Al-Mg Alloys
    - 6xxx – Al-Mg- Si Alloys
    - 7xxx – Al-Zn-Mg Alloys
    - 8xxx – Al + Other Elements

The means by which the alloying elements aid to strengthen aluminium are used as the basis to classify aluminium alloys into two categories: non-heat treatable and heat treatable.

1.3.1 Non–heat treatable aluminium alloys

The initial strength of the non-heat treatable aluminium alloys depends primarily upon the hardening effect and effect of alloying elements such as silicon, iron, manganese and magnesium. These elements increase the strength either in dispersed phase or by solid solution strengthening. The non- heat treatable alloys are mainly found in the 1xxx, 3xxx, 4xxx and 5xxx alloy series. The strength of all the non-heat treatable alloys may be improved by strain hardening [6].

1.3.2 Heat–treatable aluminium alloys (age hardenable aluminium alloys)

The initial strength of aluminium alloys in this group depends upon the alloy composition, just as the non heat-treatable alloys. Heat treatable aluminium alloys develop their properties by solution heat-treating and quenching, followed by either natural or artificial aging. Cold working may add additional strength. The heat-treatable alloys are found primarily in the 2xxx, 6xxx and 7xxx alloy series [7].

1.4 Welding of Aluminium Alloys

There are many different methods available for joining aluminium and its alloys. The selection of the method depends on many factors such as geometry and the material of the parts to be joined, required strength of the joint, permanent or dismountable joint, number of parts to be joined, the aesthetic appeal of the joint and the service conditions such as moisture, temperature, inert atmosphere and corrosion.

Welding is one of the most used methods for aluminium. Most alloys of aluminium are easily weldable. Metal inert gas (MIG) and Tungsten inert gas (TIG) are the welding processes which are used the most, but there are some problems associated with this welding processes like porosity, lack of fusion due to oxide layers, incomplete penetration, cracks, inclusions and undercut, but they can be joined by other methods such as resistance welding, friction welding, stud welding and laser welding. While welding, many physical and chemical changes occur such as oxide formation, dissolution of hydrogen in molten aluminium and lack of colour change when heated [8].

The formation of oxides of aluminium is because of its strong affinity to oxygen. Aluminium oxidizes very quickly after it has been exposed to oxygen. Aluminium oxide forms if the metal is joined using fusion welding processes, and as aluminium oxide has a high melting point than the metal and its alloys it results in incomplete fusion. Aluminium oxide is an electrical insulator and if it is thick enough it is capable of preventing the arc which starts the welding process. So special methods such as inert gas welding, or use of fluxes is necessary if aluminium has to be welded using the fusion welding processes.

Hydrogen has high solubility in liquid aluminium when the weld pool is at high temperature and when the metal is still in liquid state, it absorbs lots of hydrogen which has very low solubility in the solid state of the metal. The trapped hydrogen cannot escape and forms porosity in the weld. All the sources of hydrogen has to be eliminated (in order to get sound welds), such as lubricants on base metal or the filler material, moisture on the surface of base metal or condensations inside the welding equipment if it uses water cooling and moisture in the shielding inert gases. These precautions require considerable pretreatment of the work piece to be welded and the welding equipment [9].

Hot cracking is also a problem of major concern when welding aluminium. It occurs due to the high thermal expansion of aluminium, large change in the volume of the metal upon melting and solidification and its wide range of solidification temperatures. The heat treatable alloys have greater amounts of alloying elements so the weld crack sensitivity is of concern. The thermal expansion of aluminium is twice that of steel. In fusion welding process melting and cooling occurs very fast, which is the reason for residual stress concentrations [10].

Weldability of some aluminium alloys is an issue with the fusion welding processes. The 2000 series, 5000 series, 6000 series and 7000 series of aluminium alloys have different weldabilities. The 2000 series of aluminium alloys have poor weldability generally because of the copper content, which causes hot cracking and poor solidification microstructure and porosity in the fusion zone. So the fusion welding processes are not very suitable for these alloys. The 5000 series of aluminium alloys with more than 3% of Mg content is susceptible to cracking due to stress concentration in corrosive environments, so high Mg alloys of 5000 series of aluminium should not be exposed to corrosive environments. All the 6000 series of aluminium are readily weldable but are sometimes susceptible to hot cracking under certain conditions. The 7000 series of aluminium alloys are both weldable and non-weldable depending on the chemical composition of the alloy [11].

Alloys with low Zn-Mg and Cu content are readily weldable and they have the special ability of recovering the strength lost in the HAZ after some weeks of storage after the weld. Alloys with high Zn-Mg and Cu content have a high tendency to hot crack after welding. All the 7000 series of aluminium have the sensitivity to stress concentration cracking [12]. All these problems associated with the welding of these different alloys of aluminium has lead to the development of solid state welding processes like friction stir welding technique which is an upgraded version of the friction welding processes. This process has many advantages associated with it, and it can weld many aluminium alloys such as 2000 and 7000 series which are difficult to weld by fusion welding processes. The advantages of the friction stir welding processes are low distortion even in long welds, no fuse, no porosity, no spatter, low shrinkage, can operate in all positions, energy efficient and excellent mechanical properties as proven by the fatigue, tension and bend tests.

1.5 Aluminium Alloys Chosen for this Investigation

In this research work, AA7075-T651 have been chosen for this investigation. Aerospace aluminium alloys of the 7XXX series are high strength materials which are generally heat treated in order to provide an optimum balance between strength, toughness, and stress corrosion cracking resistance. They are precipitation strengthened alloys with the primary strengthening precipitates being the 'η', Mg_2Zn phase [13]. As for essentially all precipitation hardening aluminium alloys, the heat treatment of the base metal is roughly as follows: a solution heat treatment followed by rapid quenching produces a supersaturated solid solution. The solid solution is decomposed during an aging treatment which is comprised of one or more steps of holding the material at a temperature less than the solution treatment temperature. The resulting microstructure exhibits an optimized distribution of fine precipitates. The temperature histories associated with any type of welding operation will modify the "optimized" microstructure to varying extents depending on the type of welding and the specific parameters (heat input, welding speed) applied. It should be noted that many precipitation hardening alloys contain a greater level of alloying elements than can be brought into solid solution: in many 7XXX series alloys, this fact, coupled with the presence of low-melting phases, can result in the phenomenon of local melting at temperatures well below the bulk solidus.

In all cases, welding is the primary joining method which has always represented a great challenge for designers and technologists. As a matter of fact, lots of difficulties are associated with this kind of joint process, mainly related to the presence of a tenacious oxide layer, high thermal conductivity, high coefficient of thermal expansion, solidification shrinkage and, above all, high solubility of hydrogen, and other gases, in the molten state [14]. Further problems occur when attention is focused on heat-treatable alloys, since heat, provided by the welding process, is responsible for the decay of mechanical properties, due to phase transformations and softening.

Fusion welding of precipitation hardenable aluminium alloys produces a fusion zone consisting of as-cast coarse microstructure with solute gradients across the dendrite boundaries. In addition, strengthening precipitates are dissolved during fusion welding when welded in solution treated and aged (STA) condition. These microstructural changes often lead to a significant deterioration in the weld strength. Post weld aging to restore mechanical properties is not effective because of solute loss in the matrix introduced by the solute segregation. Solution treatment and aging is needed to effectively improve the weld properties, but post weld solution treatment is not practicable due to distortion problems [15] Weld fusion zone of these aluminium alloys typically exhibit coarse columnar grains because of the prevailing thermal conditions during weld metal solidification. This often results in inferior weld mechanical properties and poor resistance to hot cracking. While it is thus highly desirable to control solidification structure in welds, such control is often very difficult because of the higher temperatures and higher thermal gradients in welds in relation to castings and the epitaxial nature of the growth process [16].

1.6 Friction Stir Welding (FSW)

Friction Stir Welding (FSW) is a relatively new method of joining materials. The process was invented by Wayne Thomas et al., of “The Welding Institute (TWI)” and patented in 1991 [17]. It is most often used to join metals with low melting points such as aluminium and copper. It is also used to join steel and titanium. It is a solid state welding process that offers many advantages over fusion welding processes. The FSW process utilizes a rotating non-consumable tool to perform the welding process. In its simplest form the rotating tool consists of a small pin (or probe) underneath a larger shoulder.

This welding process uses three mechanical operations to join the parent metals of the work piece. The first operation is heat generation. As the rotating tool makes contact with the work piece, heat is generated. The generated heat is from both plastic deformation of the parent metals and friction between the tool and the work piece. This heat can soften the work piece in preparation for the deforming and then joining of the parent metals. The second operation utilized in the welding process is plastic deformation. As the tool rotates and travels through the work piece it plastically deforms the parent metals that define the work piece. During the welding process the pin portion of the tool is plunged into the work piece and travels along the faying surface. As the pin rotates within the work piece it shears a thin layer of the material. The shearing action causes the plastic deformation. The deformed material is rotated around to the backside of the pin. The third operation is forging. In this third operation the shoulder of the tool is used to forge together the two plastically deformed parent metals that have been rotated around to the pin's backside [18]. Forging pressure is created by firmly holding the tool in the work piece with a sufficient axial force. The plastic deformation and subsequent forging action bonds the parent metals without the need for a filler material, shielding gas or cooling fluids. Figure 1.1 illustrates the schematic representation of FSW process.

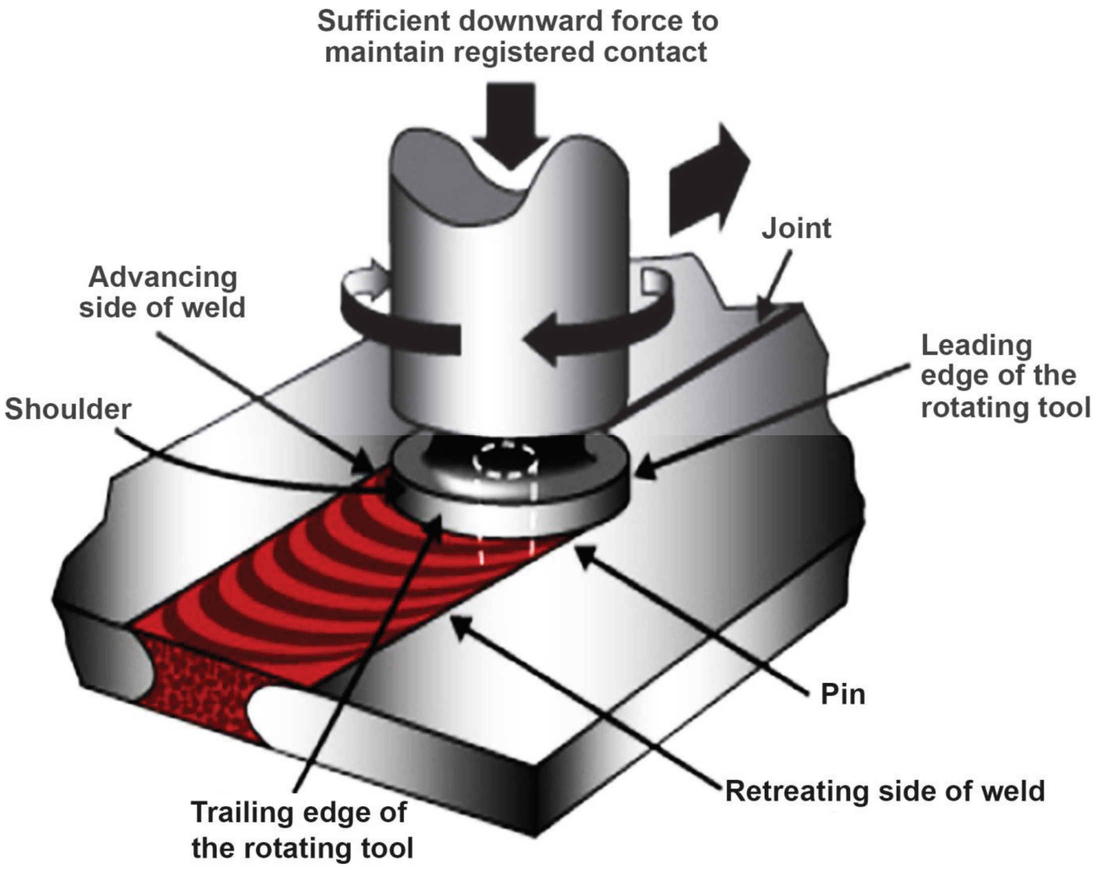
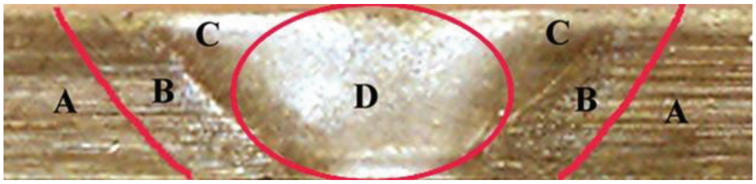


Fig. 1.1.Illustration of the FSW process (*Ref-TWI*, 2005).



(A = Unaffected Base Metal; B = Heat Affected Zone (HAZ); C = Thermo-Mechanically Affected Zone (TMAZ); D = Friction Stir Processed (FSP) zone)

Fig. 1.2 Different regions of FSW joint

There are several advantages of FSW when compared to fusion welding methods such as arc and resistance welding. Since FSW is a solid state process, the temperature of the metal does not reach its melting point. Thus porosity problems associated with the solidification of the metal are not encountered. In addition, greater weld joint strength is achieved with FSW. The solid state process plastically deforms the work piece which allows the resulting joint to retain a large portion of its parent metal strength. Experimental data reported [19] shows optimized tool design and process parameters can produce weld joints with 97% of the parent metal's tensile strength. The plastic deformation and forging action make the grain structure of the resulting weld much finer than its parent metal. This finer grain structure contributes to the increased tensile strength of the weld joint.

A friction stir welded joint can be defined by four regions. These regions can be seen in Figure 1.2. The area marked (a) is the portion of the parent metal that was unaffected by the welding process. Region (b) is referred to as the heat affected zone (HAZ). Although no plastic deformation took place in this region, heat from the welding process has changed the localized mechanical properties of the parent metal but the grain structure remains the same as that of the parent metal. The tool's shoulder did not traverse over this region. Region (c) is the thermo-mechanically affected zone (TMAZ). This region's mechanical properties have been affected by strain and elevated temperatures due to the nearby proximity of the welding tool's shoulder and pin. The microstructure has been altered slightly, but it is still similar to the microstructure of the parent metal. The weld nugget is the region of fine grained microstructure where severe plastic deformation occurred. This is called both the friction stir processed (FSP) zone and the dynamically recrystallized zone (DRX). This region is approximately the size of the pin because the rotating pin passed through this zone during the welding process. It is marked as region (d) in Figure 1.2. The severe plastic deformation of the parent metal and resulting fine grain structure is due to the shearing action of the rotating pin and the forging action of the shoulder. As can be seen in Figure 1.2 the grain structure of this region is much smaller when compared to the HAZ and the unaffected area of the parent metal. Elangovan and Balasubramanian (2008 and 2007) concluded that the welding speed and the pin profile influences the formation of the fine grained microstructure, because of the refined grain structures, seldom does joint failure begin in the weld nugget [20, 21].

1.7 Outline of the Thesis

In this research work, an attempt was made to study the effect of post weld heat treatment on mechanical and metallurgical properties of friction stir welded AA 7075-T651 aluminium alloy. Indigenously designed and computer numerical controlled FSW machine was used to fabricate the joints. A detailed literature survey was made and the important information relevant to the present investigation are critically reviewed. The motivation to carry out this research work and scope and objectives of the present investigation are presented in Chapter II. The details pertaining to various experimental works carried out in this investigation are explained in Chapter III. Friction stir welded joints were characterized using optical microscope, scanning electron microscope, transmission electron microscope and micro-hardness testing machine and the results are presented in Chapter IV. Tensile properties of friction stir welded joints were evaluated using Universal Tensile Testing Machine and the effect of post weld heat treatment on tensile properties of the joints is discussed in Chapter V. Fatigue behaviour of friction stir welded joints were evaluated using servo-hydraulic controlled fatigue testing machine (INSTRON, UK) and the influences of post weld heat treatment on fatigue (S-N) behaviour of the joints are analysed in Chapter VI. Fatigue crack growth behaviour of friction stir welded joints were evaluated using servo-hydraulic controlled fatigue testing machine and the effect of post weld heat treatment on fatigue crack growth behaviour of the joints are analysed in Chapter VII. Effect of post weld heat treatment on fracture toughness of the joints are analysed in Chapter VIII. Important conclusions derived from this investigation and suggestions for further research are presented in Chapter IX.