1.0 Introduction

Aluminium, the second most plentiful metallic element on earth, became an economic competitor in engineering applications as recently as the end of the 19th century. The emergence of three important industrial developments would, by demanding material characteristics consistent with the unique qualities of aluminium and its alloys, greatly benefit growth in the production and use of the new metal. Electrification would require immense quantities of light-weight conductive metal for long-distance transmission and for construction of the towers needed to support the overhead network of cables which deliver electrical energy from sites of power generation. Aluminium industry works for the structurally reliable, strong, and fracture-resistant parts for airframes, engines, and ultimately, for missile bodies, fuel cells, and satellite components.

The properties of aluminium that make this metal and its alloys the most economical and attractive for a wide variety of uses are its appearance, light weight, fabric ability, physical properties, mechanical properties, and corrosion resistance. Aluminium has a density of only 2.7 g/cm³, approximately one-third as much as steel (7.83 g/cm³), copper (8.93 g/cm³), or brass (8.53 g/cm³). It can display excellent corrosion resistance in most environments, including atmosphere, water (including salt water), petrochemicals, and many chemical systems. Aluminium typically displays excellent electrical and thermal conductivity, but specific alloys have been developed with high degrees of electrical resistivity. These alloys are useful, for example, in high-torque electric motors. Aluminium is often selected for its electrical
Aluminium is non ferromagnetic, a property of importance in the electrical and electronics industries. Aluminium is also nontoxic and is routinely used in containers for foods and beverages. Some aluminium alloys exceed structural steel in strength. However, pure aluminium and certain aluminium alloys are noted for extremely low strength and hardness [Elwin 1992].

1.1 Aluminium alloys designations

It is convenient to divide aluminium alloys into two major categories: casting compositions and wrought compositions. A further differentiation for each category is based on the primary mechanism of property development. Many alloys respond to thermal treatment based on phase solubilities. These treatments include solution heat treatment, quenching and precipitation, or age hardening. For either casting or wrought alloys, such alloys are described as heat treatable. Some casting alloys are essentially not heat treatable and are used only in as-cast or in thermally modified conditions unrelated to solution or precipitation effects. Cast and wrought alloy nomenclatures have been developed. The Aluminium Association system is most widely recognized in the United States for their alloy identification system which employs different nomenclatures for wrought and cast alloys [Metal hand book 1979].

For wrought alloys a four-digit system is used to produce a list of wrought composition families as follows:

- 1xxx Controlled unalloyed (pure) compositions.
- 2xxx Alloys in which copper is the principal alloying element, though other elements, notably magnesium, may be specified.
- 3xxx Alloys in which manganese is the principal alloying element.
- 4xxx Alloys in which silicon is the principal alloying element.
- 5xxx Alloys in which magnesium is the principal alloying element.
- 6xxx Alloys in which magnesium and silicon are the principal alloying elements.
- 7xxx Alloys in which zinc is the principal alloying element, but other elements such as copper, magnesium, chromium, and zirconium may be specified.
- 8xxx Alloys including tin and some lithium compositions.

Casting compositions are described by a three-digit system followed by a decimal value. The decimal .0 in all cases pertains to casting alloy limits. Decimals .1 and .2 stands for ingot compositions, which after melting and processing should result in chemistries conforming to casting specification requirements. Alloy families for casting compositions are:

- 1xx.x Controlled unalloyed (pure) compositions, especially for rotor manufacture
- 2xx.x Alloys in which copper is the principal alloying element, but other alloying elements may be specified.
- 3xx.x Alloys in which silicon is the principal alloying element, but other alloying elements such as copper and magnesium are specified
- 4xx.x Alloys in which silicon is the principal alloying element
- 5xx.x Alloys in which magnesium is the principal alloying element
- 6xx.x Unused
- 7xx.x Alloys in which zinc is the principal alloying element, but other alloying elements such as copper and magnesium may be specified
- 8xx.x Alloys in which tin is the principal alloying element

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1.2 Heat treatable and non heat treatable aluminium alloys

Heat-Treatable and Non-Heat-Treatable are the two basic types of aluminium alloys. They are both widely used in welding fabrication and have somewhat different characteristics associated with their chemical and metallurgical structure and their reactions during the arc welding process.

1.2.1 Non-heat-treatable aluminium alloys

The strength of these alloys is initially produced by alloying the aluminium with addition of other elements. These alloys consist of the pure aluminium alloys (1xxx series), manganese alloys (3xxx series), silicon alloys (4xxx series) and magnesium alloys (5xxx series). A further increase in strength of these alloys is obtained through various degrees of cold working or strain hardening. Cold working or strain hardening is accomplished by rolling, drawing through dies, stretching or similar operations where area reduction is obtained. Regulating the amount of total reduction in area of the material controls its final properties. Material which has been subjected to a strain-hardening temper, may also be given a final, elevated temperature treatment called “stabilizing”, to ensure that the final mechanical properties do not change over time [Cross and Kohn 1993, Alhazza 2010].

1.2.2 Heat treatable aluminium alloys

The initial strength of these alloys is also produced by the addition of alloying elements to pure aluminium. These elements include copper (2xxx series), magnesium and silicon, which are able to form the compound magnesium silicate
(6xxx series), and zinc (7xxx series). When present in a given alloy, singly or in various combinations, these elements exhibit increasing solid solubility in aluminium as the temperature increases. Because of this reaction, it is possible to produce significant additional strengthening to the heat-treatable alloys by subjecting them to an elevated thermal treatment, quenching and when applicable, precipitation heat-treatment also known as artificial ageing.

1.3 Wrought aluminium and aluminium alloy designation system

A four-digit numerical designation system is used to identify wrought aluminium and aluminium alloys. As shown below, the first digit of the four-digit designation indicates the group: For the 2xxx through 7xxx series, the alloy group is determined by the alloying element present in the greatest mean percentage. An exception is the 6xxx series alloys in which the proportions of magnesium and silicon available to form magnesium silicide ($\text{Mg}_2\text{Si}$) are predominant. Another exception is made in those cases in which the alloy qualifies as a modification of a previously registered alloy. If the greatest mean percentage is the same for more than one element, the choice of group is in order of group sequence: copper, manganese, silicon, magnesium, magnesium silicate, zinc, or others [Joseph and Benedyk 2009].

1.3.1 1xxx Series

Aluminium of 99.00% or higher purity has many applications, especially in the electrical and chemical fields. These grades of aluminium are characterized by excellent corrosion resistance, high thermal and electrical conductivities, low mechanical properties and excellent workability. Moderate increases in strength may be obtained by strain hardening. Iron and silicon are the major impurities. Typical uses include chemical equipment, reflectors, heat exchangers, electrical conductors and capacitors, packaging foil, architectural applications and decorative trim.
1.3.2 2xxx Series

Copper is the principal alloying element in 2xxx series alloys, often with magnesium as a secondary addition. These alloys require solution heat treatment to obtain optimum properties; in the solution heat-treated condition, mechanical properties are similar to and sometimes exceed, those of low-carbon steel. In some instances, precipitation heat treatment (ageing) is employed to further increase mechanical properties. The alloys in the 2xxx series do not have as good corrosion resistance as most other aluminium alloys and under certain conditions they may be subject to inter granular corrosion. Therefore, these alloys in the form of sheet are usually clad with high-purity aluminium or with a magnesium-silicon alloy of the 6xxx series, which provides galvanic protection of the core material and thus greatly increases resistance to corrosion. Alloys in the 2xxx series are particularly well suited for parts and structures requiring high strength-to-weight ratios and are commonly used to make truck and aircraft wheels, truck suspension parts, aircraft fuselage and wing skins and structural parts.

1.3.3 3xxx Series

Manganese is the major alloying element of 3xxx series alloys. These alloys generally are non-heat treatable but have about 20% more strength than 1xxx series alloys. Because only a limited percentage of manganese (up to about 1.5%) can be effectively added to aluminium, manganese is used as major element in only a few alloys. However, three of them 3003, 3004, and 3105 are widely used as general-purpose alloys for moderate-strength applications requiring good workability. These applications include beverage cans, cooking utensils, heat exchangers, storage tanks, awnings, furniture, highway signs, roofing, siding, and other architectural applications.
1.3.4 4xxx Series

The major alloying element in 4xxx series alloys is silicon, which can be added in sufficient quantities (up to 12%) to cause substantial lowering of the melting range without producing brittleness. For this reason, aluminium silicon alloys are used in welding wire and as brazing alloys for joining aluminium, where a lower melting range than that of the base metal is required. Most alloys in this series are non-heat treatable, but when used in welding heat-treatable alloys, they pick up some of the alloying constituents of the latter and so respond to heat treatment to a limited extent. Alloy 4032 has a low coefficient of thermal expansion and high wear resistance, and thus is well suited to production of forged engine pistons.

1.3.5 5xxx Series

The major alloying element in 5xxx series alloys is magnesium. When it is used as a major alloying element or with manganese, the result is a moderate-to-high-strength work-hardenable alloy. Magnesium is considerably more effective than manganese as a hardener, about 0.8% Mg being equal to 1.25% Mn, and it can be added in considerably higher quantities. Alloys in this series possess good welding characteristics and good resistance to corrosion in marine atmospheres. However, certain limitations should be placed on the amount of cold work and the safe operating temperatures permissible for the higher-magnesium alloys (over about 3.5% for operating temperatures above about 65 °C) to avoid susceptibility to stress-corrosion cracking. Uses include architectural, ornamental and decorative trim; cans and can ends; household appliances; streetlight standards; boats and ships, cryogenic tanks; crane parts and automotive structures.
1.3.6 6xxx Series

Alloys in the 6xxx series contain silicon and magnesium approximately in the proportions required for formation of magnesium silicide (Mg$_2$Si), thus making them heat treatable. 6xxx series alloys have good formability, weldability, machinability, and corrosion resistance, with medium strength. Alloys in this heat-treatable group may be formed in the T4 temper (solution heat treated but not precipitation heat treated) and strengthened after forming to full T6 properties by precipitation heat treatment. Uses include architectural applications, bicycle frames, transportation equipment, bridge railings, and welded structures.

1.3.7 7xxx Series

Zinc, in amounts of 1 to 8% is the major alloying element in 7xxx series alloys and when coupled with a smaller percentage of magnesium results in heat-treatable alloys of moderate to very high strength. Usually other elements, such as copper and chromium, are also added in small quantities. 7xxx series alloys are used in airframe structures, mobile equipment and other highly stressed parts. Higher strength 7xxx alloys exhibit reduced resistance to stress corrosion cracking and are often utilized in a slightly over aged temper to provide better combinations of strength, corrosion resistance and fracture toughness [Davis 1994].

1.4 Alloy and temper designation systems for aluminium and aluminium alloys

The temper designation system used in the United States for aluminium and aluminium alloys is used for all product forms (both wrought and cast), with the exception of ingot. The system is based on the sequences of mechanical or thermal treatments, or both, used to produce the various tempers. The temper designation
follows the alloy designation and is separated from it by a hyphen. Basic temper designations consist of individual capital letters. Major subdivisions of basic tempers, where required, are indicated by one or more digits following the letter. These digits designate specific sequences of treatments that produce specific combinations of characteristics in the product. Variations in treatment conditions within major subdivisions are identified by additional digits. The conditions during heat treatment (such as time, temperature, and quenching rate) used to produce a given temper in one alloy may differ from those employed to produce the same temper in another alloy [Gilbert and Elwin 2004, Mathers 2002].

The basic temper designations are as follows

- F as-Fabricated
- O Annealed
- H Strain-hardened (wrought products only)
- W Solution heat-treated
- T Solution heat treated

1.5 System for heat-treatable alloys

The temper designation system for wrought and cast products that are strengthened by heat treatment employs the W and T designations. The W designation denotes an unstable temper, whereas the T designation denotes a stable temper other than F, O, or H. The T is followed by a number from 1 to 10, each number indicating a specific sequence of basic treatments [Davis 1993].

The T1 designation is used for the products that are not cold worked after an elevated-temperature shaping process such as casting or extrusion and for which mechanical properties have been stabilized by room-temperature ageing.
T2 designation applies to the products that are cold worked specifically to improve strength after cooling from a hot-working process such as rolling or extrusion and for which the mechanical properties have been stabilized by room-temperature ageing. It also applies to the products in which the effects of cold work, imparted by flattening or straightening, are accounted for in specified property limits.

T3 designation applies to products that are cold worked specifically to improve strength after solution heat treatment and for which mechanical properties have been stabilized by room-temperature ageing. It also applies to products in which the effects of cold work, imparted by flattening or straightening, are accounted for in specified property limits.

T4 designation explains the products that are not cold worked after solution heat treatment and for which mechanical properties have been stabilized by room-temperature ageing. If the products are flattened or straightened, the effects of the cold work imparted by flattening or straightening are not accounted for in specified property limits.

T5 designation covers the products that are not cold worked after an elevated-temperature shaping process such as casting or extrusion and for which mechanical properties have been substantially improved by precipitation heat treatment. If the products are flattened or straightened after cooling from the shaping process, the effects of the cold work imparted by flattening or straightening are not accounted for in specified property limits.

T6 designation signifies products that are not cold worked after solution heat treatment and for which mechanical properties or dimensional stability, or both, have been substantially improved by precipitation heat treatment. If the products are
flattened or straightened, the effects of the cold work imparted by flattening or straightening are not accounted for in specified property limits.

T7 applies to wrought products that have been precipitation heat treated beyond the point of maximum strength to provide some special characteristic, such as enhanced resistance to stress-corrosion cracking or exfoliation corrosion. It applies to cast products that are artificially aged after solution heat treatment to provide dimensional and strength stability.

T8 designation applies to products that are cold worked specifically to improve strength after solution heat treatment and for which mechanical properties, dimensional stability, or both, have been substantially improved by precipitation heat treatment. The effects of cold work, including any cold work imparted by flattening or straightening, are accounted for in specified property limits.

T9 is comprises the products that are cold worked specifically to improve strength after they have been precipitation heat treated.

T10 identifies products that are cold worked specifically to improve strength after cooling from a hot-working process such as rolling or extrusion and for which mechanical properties have been substantially improved by precipitation heat treatment. The effects of cold work, including any cold work imparted by flattening or straightening, are accounted for in specified property limits [Aluminium standards and data 1988; Aydin et al., 2009].

1.6 6000 series alloys

The 6000 series of alloys is also commonly encountered in marine construction. In this series, the primary alloying elements are magnesium and silicon, which are added so that magnesium silicate will be formed in the aluminium [George and Mackinzie 2003]. The most common alloy seen in marine construction is 6082,
along with 6061, a slightly weaker version which is popular in the North American civil engineering market. The 6000-series alloys are not as corrosion resistant as the 5000-series, but are much easier to extrude, making them attractive for producing structural shapes or integrated plate-stiffener combinations. The metallurgy of this alloy is significantly different than the 5000 series, with heat treatment increasing the strength of the alloy. When produced, this alloy is heated to a high temperature so that the alloying elements are in solution. Then, the metal is quenched rapidly to a low temperature, leaving the magnesium silicate trapped in a super-saturated solution. The magnesium Silicate will then precipitate from the aluminium which results in a stronger microstructure. When this precipitation occurs naturally over time it is referred to as natural ageing. Alternatively, the quenched material can be raised to an elevated temperature for a short period of time, allowing a more rapid precipitation to occur. This process is referred to as artificial ageing. By controlling the temperature and exposure time, the size of the precipitates can be controlled, allowing an alloy with optimum strength properties to be obtained [Heinz et al., 2000]. This results in an increase in strength, but a corresponding reduction in ductility. If the alloy is exposed to an elevated temperature for too long a time, the precipitates will grow in size, and the strength of the alloy will be reduced but its ductility increased. This is known as over-ageing. Thermal welding of these alloys typically produces a significant drop in strength, as the added heat will over-age the metal. Heat-treatment tempers are indicated by the letter T followed by one or more letters. The common temper for 6082 or 6061 in the marine market is T6, which indicates an alloy that has been quenched and artificially aged. T4 is a weaker form that has only been quenched, with no ageing.
Aluminium alloy 6082 is a medium strength alloy with excellent corrosion resistance. It has the highest strength of the 6000 series alloys. Alloy 6082 is known as a structural alloy. In plate form, Aluminium alloy 6082 is the alloy most commonly used for machining. The addition of a large amount of manganese controls the grain structure which in turn results in a stronger alloy. Aluminium alloy 6082 is typically used in: High stress applications, Trusses, Bridges, Cranes, Transport applications, Ore skips, Beer barrels, Milk churns

1.7 Welding of aluminium alloys

Aluminium is light in weight, yet some of its alloys have strengths exceeding mild steel. It retains good ductility at sub-zero temperature, has high resistance to corrosion and is non toxic. Pure aluminium melts at 660 °C and aluminium alloys have an approximate melting range of from 482 to 660 °C, depending upon the alloys. There is no colour change in aluminium when heated to the welding temperature range. High thermal conductivity (as compared to steel) necessitates a high rate of heat input for fusion welding [Pandey et al., 2002, Idowu et al. 2009]. Thick section may require preheating. During resistance spot welding, aluminium’s high thermal and electrical conductivity require high current, shorter weld time, more precise control of welding variables than when welding steel. Aluminium and its alloys rapidly develop a tenacious, refractory film when exposed to air.

1.8 What makes aluminium different

The main characteristics of aluminium, which influence welding, are hydrogen solubility, aluminium oxides, thermal conductivity, thermal expansion and solidification shrinkage, and non discoloration. It is a lack of understanding in the cleaning aspects that has kept many fabricators away from the welding of aluminium.
1.8.1 Hydrogen solubility

One needs to understand that moisture or hydrocarbons on the surface might decompose beneath the arc and release hydrogen. Hydrogen is extremely soluble in molten aluminium, so, when the weld freezes the hydrogen gets trapped in the weld itself. That is the main source of porosity in aluminium welds. From the standpoint of cleanliness, any sources of moisture have to be removed from the surface. Once this is done, the main source of porosity in aluminium welds is eliminated. The cleanliness of the filler metal is another consideration. The importance of storage and handling of the filler metal is often underestimated. The filler metal is handled just like a plate.

1.8.2 Aluminium oxides

The oxides, in a sense, can be even more of a problem. Aluminium oxides melt at about 2066 °C or about three times the melting point of the aluminium alloys itself. It is obvious in welding that the base metal will be melted long before the oxide. In the welding of non heat treatable aluminium alloys, the natural oxides can be broken up by the inert arc. However in welding heat treatable alloys that have been taken up to a high temperature to give them a certain thermal treatment, a much thicker oxide will form than is present in the non heat treatable alloys.

1.8.3 High thermal conductivity

The thermal conductivity of aluminium is about six times than that of steel. If the aluminium is welded too slowly, the heat travels ahead of the arc and will force the operator to make continual adjustments to current and travel speed. Even though most aluminium alloys melt in the 565 °C to 648 °C range, the high thermal conductivity of aluminium necessitates that a more intense heat may be employed than that used in welding steel. Welding is carried out with higher heat input and at a faster rate than that used for steel. Conductivity is also important when weld
procedures are being set and welder’s qualification is being carried out. It can affect the mechanical properties. Larger or longer test pieces are to be used in order to provide an adequate heat sink or to avoid overheating.

1.8.4 Thermal expansion

Thermal expansion is about twice that of steel. Of particular concern here is the greater expansion in thinner materials. Solidification shrinkage in aluminium weld metal is about 6% by volume and it can be the main cause for distortion, especially in thicker welds. To compensate, the weld passes have to be balanced, particularly in fillet welds. Unlike steel aluminium does not change colour when it is heated up. In welding the metal, the operator has to get in position where he can see the molten pool and the end of the electrode tip if expects to make good welds. Aluminium surface is also highly reflective. As such, the welders require protection against radiation.

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, 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. MIG and TIG are the welding processes which are used the most, but there are some problems associated with this welding process 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 [Mandal 2005].

1.9 **Weldability of aluminium alloy**

Weldability of some aluminium alloys is an issue with the fusion welding processes. The 2000 series, 4000 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 cooper content which causes hot cracking and poor solidification in the microstructure and porosity in the fusion zone. The 2000 series are heat treatable and possess good combination of high strength, toughness and also exhibit good weldability in specific cases. The specific number of series (2219 and 2048) is readily welded and so is used for aerospace application. Alloy 2195 is a new Li bearing alloy for space applications that provides very high modulus of elasticity along with high strength and weldability. The most widely used 4000 series alloy (4032) is medium strength, heat treatable alloy used principally for forging applications such as aircraft pistons. Alloy 4043 on the other hand is one of the most widely used filler alloy for gas metal arc welding and TIG welding of 6000 series alloy which is used for structural and automotive applications. For the same reason, other variations of 4000 series are used for cladding on brazing sheet [Cross 1993]. 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 at high temperatures to avoid stress corrosion cracking. All the 6000 series of aluminium are readily weldable but are sometimes susceptible to hot cracking under certain conditions. The 6000 series materials possess good weldability provided adequate filler metal is fed into the joint. A problem can be that fabricators
do not open the joint sufficiently to get enough filler metal in there to avoid cracking. Using 4000 series filler metal it is the best to allow about 50% dilution of the filler into the weld metal composition. The 7000 series of aluminium is both weldable and non-weldable depending on the chemical composition of the alloy. 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 the welding of the alloy. Alloys with high Zn-Mg and Cu content are highly susceptible to hot crack after welding. All the 7000 series of aluminium have the sensitivity to stress concentration cracking [Martukanitz 1993, Devis 1994]. All these problems associated with the welding of these different alloys of aluminium have led to the development of solid state welding processes like Friction Stir Welding technique, an upgraded version of the friction welding processes. This process has many advantages associated with it and can weld many aluminium alloys such as 6000 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, very energy efficient and excellent mechanical properties as proven by the fatigue, tension and bend tests.

1.10 Introduction of friction stir welding process

Friction stir welding (FSW) was invented at The Welding Institute (TWI) of UK in 1991 as a solid-state joining technique, and it was initially applied to aluminium alloys [Thomas et al. 1991]. A non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and traversed along the line of joint. The parts have to be suitably clamped rigidly on a backing bar to prevent the abutting joint faces from being forced apart. The length of the pin is slightly less than the required weld depth. The plunging
is stopped when the tool shoulder touches the surface of the job. The tool shoulder should be in intimate contact with the work surface. The function of tool is heating of work-piece, and movement of material to produce the joint. The heating is accomplished by friction between the tool and the work-piece and plastic deformation of work-piece. The localized heating softens the material around the pin and combination of tool rotation and translation leads to movement of material from the front of the pin to the back of the pin. Because of various geometrical features of the tool, the material movement around the pin can be quite complex [Boz and Kurt, 2004]. Here a substantial forging force is applied by the tool to consolidate the plasticized metal behind the tool. The welding of the material is facilitated by severe plastic deformation in the solid state involving dynamic recrystallization of the base material. As the tool is moved along the seam the desired joint is created. The schematic view of the operation is shown in Figure 1.1 [Singh 2011]

![Figure: 1.1: Schematic drawing of friction stir welding](image)

There are two different modes of material flow involved in friction stir welding called pin driven and shoulder driven flow [Lohwasser 2009]. These two driven material merges together at the rear side of the pin to form a defect free weld. The pin driven material flow occurs during the interaction of base metal with tool pin
in the weld cavity. The shape of the cavity depends on the outer most pin profile. The 
material transfer in the pin driven region takes place layer by layer. When the tool is 
traversed, the material at the leading edge flows through retreating side to trailing 
edge. This material periodically fills the space created in the trailing edge. The 
shoulder deflects the pin driven material from retreating side to advancing side. This 
occurs by the sliding action of the tool shoulder surface on the pin driven material. As 
the shoulder interaction increases, material is deflected back to the weld cavity. Thus 
the material flow is layer wise in pin driven region, and it is bulk in shoulder driven 
region. When the material escapes out of the weld cavity due to insufficient axial 
pressure, it results in flash formation.

The FSW process can be thought to consist of three phases: the plunge 
phase, where the weld is initiated; the main phase, where the weld is made; and the 
termination phase, where the welding tool is withdrawn from the workpiece. The 
plunge phase consists of inserting the rotating welding tool into the joint, typically 
accomplished by commanding the welding system to drive the total pin axially into 
the work-piece at a specific rate. Frictional heating and pressure, at the end of the pin, 
induce work-piece material to displace, forming a ring of expelled, plastically 
deformed material around the pin as the pin enters the work-pieces. As the tool is 
plunged into the joint, heat is generated into the surrounding material. Once the 
welding tool is plunged into the work-piece, it rotates at several hundred rpm and heat 
is generated between welding tool and work-piece to reach a higher temperature.

Once the welding tool begins to travel along the joint, friction and plastic work produce heat to maintain sufficient softening in the work-piece to permit material flow around the pin. Heat from the welding process conducts within the 
work-piece, serving to precondition the material in front of the tool, producing
softening from recovery of work hardening and averaging in materials such as aluminium. This metallurgical alteration may be slight, such as in when welds are made at very high travel speed, or it may dramatically soften the work-piece. Simultaneously, this material is pulled around the welding tool and deposited behind it in a way that prevents the formation of voids.

As the welding tool arrives at the end of the joint, forward motion of the tool is typically stopped and the tool is withdrawn from the work-piece, leaving a keyhole at the end of the weld. The end of the weld is generally not usable and must be trimmed away.

1.11 Process parameter of FSW

While the general principles of the effect of process variables on the friction stir welding process have much in common with other welding processes, there are many factors which can affect output response. The main process variables in friction stir welding are listed as follows:

- Tool rotational speed
- Welding speed
- Shoulder diameter
- Pin diameter and profile
- Axial force
- Tilt angle
- Work piece material
- Shoulder and pin material

All these variables may affect the characteristics of the weld joint significantly. Tool rotation speed is the rotation speed of friction stir welding tool and can be directly related to the frictional heat generation [Oertelt et al., 2001]. The term
welding speed is preferred to transverse speed, which is the rate of travel of tool along the joint line. Tool rotational speed and welding speed decide whether enough heat input is being supplied to weld so as to favourably affect the weld characteristics. Forces are important parameters parts of friction stir welding technology. The force applied parallel to the axis of rotation of the tool (Z-direction) is the downward forces and forces applied parallel to the welding direction (X-direction) is the transverse forces. The force developed in a direction perpendicular to both X and Z force is side force (Y-direction). Insufficient and excessive downward force produce defects in the weld. The defect free weld is decided by the use of proper tool design.

Tool consists of three parts, these are shoulder diameter, pin and shank. Pin having small diameter and plunged into the work piece materials completely. The pin is responsible for proper stirring of the material and transportation of plasticized material from the leading edge of the tool to trailing edge of the tool [Rai et al., 2011]. Shoulder is part of the tool which produces most of heat due to its rubbing with work piece surface. Shoulder generates the frictional heat and also prevents the escape of the plasticized material from the upper surface of the work piece. The side of the weld, where the direction of the velocity vector of the tool and traverse direction are same that side is called the advancing side of the weld, and when the direction of the velocity vector is opposite to the traverse direction, it is called the retreating side.

All these variables act to determine the outcome of the welding process. The main interest in studying the effect of the process variables lies in understanding the effect of the process on joint properties, including static mechanical and metallurgical properties, with the goal of maximizing productivity, performance and reproducibility. The welding process affects these joint properties primarily through
heat generation and dissipation, so primary attention should be given to the effect of the welding process variables on heat generation and related outcomes [Pouget and Reynolds 2008; Rodrigues et al., 2009]. Other areas of study include the effect of process parameters on material flow, defect formation, process forces, grain size, etc.

The material flow during FSW is complicated and the understanding of deformation process is limited. It is important to point out that there are many factors that can influence the material flow during FSW. These factors include tool geometry (pin and shoulder design, relative dimensions of pin and shoulder), welding parameters (tool rotation rate and direction, i.e., clockwise or counterclockwise, traverse speed, plunge depth, spindle angle), material types, workpiece temperature, etc. It is very likely that the material flow within the nugget during FSW consists of several independent deformation processes.

Figure 1.2: (a) Metal flow patterns and (b) metallurgical processing zones developed during friction stir welding (Mishra R.S., 2005)

1.12 **Welding tools used for friction stir welding (FSW)**

Many of the advances made in friction stir welding have been enabled by the development of new welding tools. The welding tool design, including both its
geometry and the material from which it is made, is critical to the successful use of the process. Welding tool geometry development led to the first sound welds made in aluminium alloys, and this field of study has led to higher weld production speeds, higher workpiece thickness, improved joint property, new materials and new welding equipment. Welding tool material development has enabled welding of high melting point materials, such as titanium, steel, and copper, and has improved productivity in aluminium welding.

New welding tool features have been developed with, for the goal of reducing process forces, increasing the robustness of the process, or simplifying welding control. Different features are used by different practitioners of FSW, depending on the materials being welded and the process performance goals required. FSW practitioners needing to weld at higher travel speeds or with deeper weld penetration may adopt variations to the original tool design [Zhoua et al., 2006]. Tool steel materials are generally acceptable for the FSW of aluminium alloys. However, much like the situation today with welding tool geometry, even for welding aluminium alloys there is no accepted standard tool material.

### 1.13 Micro structural terminology

The solid-state nature of the FSW process, combined with its unusual tool and asymmetric nature, results in a highly characteristic microstructure. Some regions are common to all forms of welding whereas some are unique to the technique. Figure 1.3 shows the various regions formed in friction stir welded joints.
Unaffected Material or Parent Metal (A): This is the material remote from the weld, which is neither deformed, nor affected by the heat in terms of microstructure or mechanical properties.

Heat-Affected Zone (HAZ) (B): It is common to all welding processes. As indicated by the name, this region is subjected to a thermal cycle but is not deformed during welding. The temperatures are lower than those in the TMAZ but may still have a significant effect if the microstructure is thermally unstable. In fact, in age-hardened aluminium alloys this region commonly exhibits the poorest mechanical properties.

Thermo-Mechanically Affected Zone (TMAZ) (C): It occurs on either side of the stir zone. In this region the strain and temperature are lower and the effect of welding on the microstructure is correspondingly smaller. Unlike the stir zone the microstructure is recognizably that of the parent material, albeit significantly deformed and rotated. Although the term TMAZ technically refers to the entire deformed region it is often used to describe any region not already covered by the terms stir zone and flow arm.

Stir Zone (Nugget, Dynamically Recrystallised Zone) (D): It is a region of heavily deformed material that roughly corresponds to the location of the pin during welding. The grains within the stir zone are roughly equiaxed and often an
order of magnitude smaller than the grains in the parent material.

1.14 Advantages of FSW process over the conventional welding process

The key benefits of this newly developed welding process are to increase joint efficiency and range of alloys that can be welded. Friction stir welding permits welding opportunities relative to dissimilar alloys and difficult weld material. Composite materials can also be welded with this process. Other advantages are as follows.

1.14.1 Improved weldability

Since FSW is a solid state process, weldability in certain materials can be improved. Some aluminium alloys or material forms, such as castings, are difficult or impossible to weld by traditional arc welding processes due to the formation of brittle phases and cracking. [Ouyang and Kovacevic 2002].

1.14.2 Reduced distortion

The low temperature is achieved in FSW as compared to arc welding processes. It generally leads to reduced longitudinal and transverse distortion. But in FSW weldments residual stresses are developed. Reduced distortion makes possible new methods of construction significantly affecting the total cost of manufacturing.

1.14.3 Improved appearance

The root side of conventional friction stir welds has been shown to be extremely smooth and flat in a variety of materials and thicknesses. After painting, the root side of the joint becomes virtually invisible. This has played a role in justification of the use of the process over other joining processes in commercial shipbuilding, in aircraft manufacture and in-the production of food trays.
1.14.4 Elimination of under matched-filler metal

In some materials there are no available filler metals for arc welding that match the strength of the base metal. However, FSW is an autogenous welding process, preventing the need for filler metals resulting in improved joint strength and/or ductility, also leads to cost avoidance by eliminating the wire feeding system.

1.14.5 Green technology

FSW is considered to be the most significant development in metal joining in a decade and is a “green” technology due to its energy efficiency, environment friendliness, and versatility. As compared to the conventional welding methods, FSW consumes considerably less energy. No cover gas or flux is used, thereby making the process environmentally friendly. The joining does not involve any use of filler metal and therefore any aluminium alloy can be joined without concern for the compatibility of composition, which is an issue in fusion welding. [Murr et al., 1998; Li et al., 1999; Panday et al., 2003].

1.15 Limitations of FSW

One of the main limitations of the FSW is that the joint is not self supporting and must be properly restrained. The other limitation of the FSW as follows:

- Key hole at the end of the work piece
- The cost of the friction stir welding machine is very high.
- Backing bar required

1.16 Joint geometries

A variety of joint geometries are possible with FSW; however, there are certain limitations and requirements that are unique to the process. The process has been used to manufacture of butt welds, overlap welds, T-sections, fillets, and corner
welds. For each of these weld joint geometries specific tool design are required. Longitudinal butt welds and circumferential lap welds of aluminium alloys successfully welded with this process.

### 1.17 Application of FSW

#### 1.17.1 Ship building and marine industries

In the shipbuilding and marine industry several companies use the FSW process for the production of commercial applications. The process is suitable for the following applications:

- Panels for freeze, decks, oil rig panels, bulkheads and floors
- Helicopter landing platforms, offshore accommodations
- Marine and transport structures
- Aluminium extrusions, patrol vessels

#### 1.17.2 Aerospace industry

Aerospace industry is welding prototype parts by friction stir welding. This process offers significant benefits as compare to the riveting. Large tanks for satellite launch vehicles are being fabricated by friction stir welding process from high strength aluminium alloys [Pacchione and Lohwasser 2004]. The friction stir welding process can be considered for:

- Fuel tanks for spacecraft
- Cargo air craft, aircraft fuselages and wings, military and scientific rockets

#### 1.17.3 Railway

Friction stir welded structures are now used in the trains. The commercial production of high speed trains made from aluminium extrusions which may be joined by FSW successfully running. Modern railway carriage is increasingly
produced from longitudinal aluminium extrusion with integrated stiffeners. The railway vehicles industry makes increasing use of friction stir welding. The railway industry includes the following applications:

- High speed trains, railway tankers, goods wagons,
- Trams, underground carriages, rolling stock

1.17.4 Automotive

Friction stir welding and its variant friction stir spot welding used in the production of aluminium automotive components. The applications of FSW are as follows:

- Tanks, suspensions and pistons
- Tailored blanks, wheel rims, chassis cradles, doors, bonnets
- Houses the fuel tanks, truck bodies, mobile cranes

1.17.5 Other industry sectors

Friction stir welding used in the various industry sectors outside of the transportation industry. Friction stir welding now being used to welding of materials with higher melting point and also can be used to welding of dissimilar materials. The friction stir welding includes the application as follows:

- Aluminium bridges, motor and loudspeaker housing, heat sinks
- Heating, ventilating and air conditioning units
- Window frames and aluminium pipe lines
- Vacuum vessels, panels and components of food industry