CHAPTER 1

INTRODUCTION

Metal joining process has always been a challenge to the technocrats since ages. Joining of metals can be done in the form of temporary or permanent. Temporary joints were performed by using fasteners, couplings etc., permanent joints can be done by using welding, brazing and soldering process. The challenges thrown by these processes are predominant in the reliability of any structure or application. The ability of the joints to withstand the tests imposed by the external agencies call for an extensive investigation by the researchers and scientists. Though many processes are identified for the better joints intended for the specific purpose, the optimisation of process parameters is yet to be achieved. Among the several metal joining process the reliability factor favors Welding. Welding in those days was considered to be suitable for joining similar metals. History of welding dates back to 4th century AD. Joining can be done by applying heat to the surface in between two intimate contact areas, due to this the metal brought to plastic state by applying pressure welding (forge welding) takes place due to solidification. The elements used by the civilizations led to the development of technology. Forge welding was the origin of this joining process when bronze was extensively used by the people. The advancements slowly crept in with the usage of Iron. The Iron pillar in Delhi stands as an example for the welding process practiced in the very early ages. The birth of the scientific age in the early nineteenth century brought in the use of electric current in the welding process. The use of alternating current sources made welding a viable process and subsequent researches took this part of engineering to automation. After the satisfying attempts on the welding processes, people began to ponder on the quality of weldments which gave a lead to invent new methods under different environments. The weld quality has shot up to several folds when welding was carried out in inert environmental conditions. The MIG, TIG and submerged arc welding produced satisfying results. These metal diffusion methods of joining the metals reached its pinnacle when electron beams and laser beams were used to melt the metals intended to be joined.
The productivity of welding these metals and their ability to last long has been extensively studied. The advent of an idea to combine dissimilar metals gave an urge to the scientific community to explore new avenues for task to be accomplished. The constraints are new to the idea of joining dissimilar metals since they differ in their basic physical properties. Their melting point, density, co-efficient of thermal expansion, hardness and strength are varying.

Generally welding is classified as an autogenously branched in which no filler metal is added at the interface. If welding is considered as homogeneous the filler metal is added and is of the same type as parent metal, where as in heterogeneous process, the filler is used but it is of different type from that of the parent metal. In conventional metal joining process like TIG Tungsten inert gas welding, MIG Metal inert gas welding etc. Parameters are to join ferrous and non ferrous metals which are having major drawbacks include large heat affected zone, less bonding strength of distinctive difference in physical and thermal properties of two dissimilar metals. Also defects will occur due to excessive oxidation during melting, solidification cracking is the defect that deteriorates the efficiency of the weld joints. The emission of fumes and toxic substances during welding affect the health of the operators and they have the possibility to suffer from the disorders like irritation on nasal passage, throat, lungs, parkinsons disease, acute and chronic intoxication to operator. Under these circumstances the focus of the researches shifted to the adverse effect of temperature in the weld. The investigations concentrated on the improvement of tensile strength of the weldments, where emerged the new technology called solid state welding of dissimilar metals. The objective of this solid state welding had an implicit idea of joining light weight bimetallic joints. The solid state welding has given a few important methods such as Friction welding, Friction stir welding, Friction surfacing etc. These methods came to the research arena in the middle of the 20th century and became popular among the research enthusiasts in the last decade of the century. In this type of welding process all the process parameters which engaged are mechanical parameters only. Friction incorporated joining techniques are extensively used in the development of precision driven structural components and devices used in the exploration space crafts and the vehicles used in marine navigation.
1.1 CLASSIFICATION OF WELDING PROCESS

All the welding processes can be divided into two major classes (i) Fusion welding and (ii) Solid state welding (Funk 1985, Cary 2002).

Arc welding is the most common method of welding, but these techniques are increasingly giving way to friction welding which has several advantages, namely higher labor productivity and better quality, possibility of joining diverse and poorly weldable metals and alloys, dispensing with high-grade welding materials and highly skilled welders, ecological cleanliness of the process, and so on which shall be discussed later in this chapter.

Figure 1.1 Classification of Welding Process (AWS)
1.2 TYPES OF SOLID STATE WELDING PROCESS

Solid state welding (Friction welding) is a group of welding processes which produces coalescence at temperatures essentially below the melting point of the base materials being joined, without the addition of brazing filler metal.

1.2.1 Friction Welding

In this work continuous direct drive friction welding method was performed to attain the objectives. This type of welding are classified as rotary friction welding as follows.

(a) Inertia friction welding.
(b) Continuous direct drive.

1.2.2 Inertia Friction Welding

Inertia Friction Welding is a variation of friction welding in which the energy required to make the weld supplied primarily by the stored rotational energy of the welding machine.

In Inertia welding, one of the work pieces is connected to a flywheel and the other is restrained from rotating. The fly wheel is accelerated to a predetermined rotational speed, storing the required energy. The drive motor is disengaged and the work pieces are forced together by the friction welding force. This causes the faying surfaces to rub together under pressure. The kinetic energy stored in the rotating flywheel is dissipated as heat through friction at the weld interface as the flywheel speed decreases. An increase in friction welding force (forge force) may be applied before rotation stops. The forge force is maintained for a predetermined time after rotation ceases.
1.2.3 Continuous Direct Drive Friction Welding

In this method instead of flywheel the motor is directly coupled so that there is continuous rotation achieved.

1.3 HISTORY OF THE FRICTION WELDING METHOD

Friction welding is highly economic, with minimum labor and power consumptions and at the same time ensures steady strength characteristics of the welds. Historically speaking, friction welding is an old process but serious developments began in Russia and the United States in the 1950's and later in Great Britain. This technique, proposed by A.I. Chudikov as far back as in 1954 and
developed at the Institute of Welding of Russia (formerly Soviet Union Scientific Research, Planning, Design and Technological Institute of Electric Welding Equipment), is employed both to weld similar and dissimilar metals.

In 1960, the Welding Institute built its first experimental machine which was used to demonstrate the potential of the process for welding bars up to 1 inch diameter.

Rotary friction welding was the first of the friction processes to be developed and used commercially. The mechanical arrangement for component in continuous-drive rotary friction welding involves two cylindrical bars held in-line alignment. One of the components is rotated while the other is advanced into contact under a pre-selected axial pressure. The spindle rotates continues for a specific period of time achieving the sufficient temperature at which metal in the joint zone is in the plastic state. In this condition, the rotating component was stopped while the pressure is either maintained or increased to consolidate the joint.

The metal joining can be achieved by fixing the one of the work piece attached to the driven motor and while other work piece is restrained from rotation. The work piece is rotated at predetermined speed and other one is made to move axially together and an upset pressure coupled frictional force is applied while they make a contact with each other. Due to this, friction developed between the faying surfaces, this continues predetermined time and the rotation is discontinued or stopped by applying the brake force. The forging pressure is made the work piece to make the weld joints.

1954 A. I. Chudikov of U.S.S.R. succeeded in the experiment of friction welding, using a modified lathe and round metal bars. VNIIESO (U.S.S.R. Electric Welding Machine Research Institute) took up the idea and started the research and development from around 1956.

1957 The Institute developed and made public the friction welding machine MST-1. After this announcement, many countries started research and development of the technology for practical applications.
1958 Development in U.S.S.R. entered the stage that the technology was introduced in the production processes.

1958 BWRA (British Welding Research Association) succeeded to produce a prototype of friction welding machine. AMF Corp. of the U.S. also publicized a prototype in the same year.

1960 A work "Friction joining of metals" by VILL of VNIIESO was introduced as a research data in Japan. This triggered ardent investigations and researches on the friction joining.

1960 A machine tool research group brought back useful information from the USSR.

1962 Toyota Industries Corp. developed initially in the country a brake type friction welding machine as mass production equipment.

1964 The Friction Joining Research Conference was founded. It was renamed later as the Society for the Study of Friction Joining and further to the Friction Joining Association, which continues activities to this day.

1973 Izumi started the consignment production of friction welding machines under an agreement with Toyota Industries Corp.

1994 JIS 3607 Standard for the friction joining work of carbon steel was enacted.

1998 Development of a NC controlled phase adjustment friction welding machine for practical applications.

2002 Development of a super fine diameter friction welding machine for practical applications (applicable to drill, sensor shaft, etc.)

2003 Friction welding of Metallic glasses.

2004 Joining of plastics by friction welding.
1.4 MECHANISM OF FRICTION WELDING

In the mechanism of friction welding, the weld joints are being produced at temperature below the melting point of the parent metal. This can be achieved by conversion of mechanical energy into heat energy and viscous plastic deformation energy at interface. This viscous plastic energy in turn produces heat energy through internal viscous dissipation Biljana Savic et al. (2008). The Figure 1.4 shows that the metals are made of up of positive ions ‘floating’ in a ‘sea’ of electrons. When the positive ion clubbed with sea of electrons is made to contact with each other, so that the ions of the two metals are joined to form a bond. Metals having positive ions and sea of electron after bonding form a weld joint. The two joining mechanisms contributing to friction welding, one is diffusion and another is mechanical mixing. The Figure 1.5 shows the cause and effect diagram for the friction welding process to achieve maximum tensile strength. It is a method of solving the problem and to identify the reasons to improve the output parameter based on inputs in a systematic way.
The Figure 1.6 shows the cut section model of friction welded joints it shows the unaffected zone (UZ), PDZ partially deformed zone (PDZ), fully deformed plastic zone (FDPZ), Deformed zone (DZ). Rotational speed plays vital role for creating the different types of grain size. When the input parameters such as frictional pressure, rotational, speed, etc., vary the grain size also varies. The area where finer grain sizes occur on the weld interface is called as FDPZ zone and the elongated grain contained area is called as deformed zone or slightly elongated zone or partially elongated zone.
When there is no change in grain size then it is called as unaffected zone (i.e.) there are no influences on the input welding parameters.
1.5 PROCESS PARAMETERS

After welding due to upset pressure flash will obtain if the flash sticks straight from the joint indicates short weld time and less pressure or speed by this the formation of joints may have crack, if the flash curls backwards on outside diameter it indicates that the weld time and pressure were high. In between these two extremes the correct flash shape would be obtained to get quality weld joints so friction welding parameters are the key to successful weld in proper selection of energy for required combination of metal to be joined. The friction welding parameters can be in two terms (i) Machine variables (ii) Non machine variables

1.5.1 Machine Variables

- Friction pressure.
- Upset pressure.
- Burn off-length
- Speed of rotation.

1.5.1.1 Friction Pressure

It is the pressure applied perpendicular to the weld surface during rubbing, this pressure is calculated by using nominal area of contact at zero amplitude.

1.5.1.2 Upset Pressure

It is the pressure which is usually equal or higher than the pressure during frictional phase and it is applied when the frictional pressure is attained to set a period of time to consolidate the joint.

1.5.1.3 Burn off Length

It is the distance that, one part of the work piece is allowed to forge in to another work piece before the amplitude is decayed or upsetting pressure is applied.

1.5.1.4 Speed of Rotation

The function of the rotational speed is to produce a relative speed at the periphery of the components.
1.5.2 Non Machine Variables

It includes the material type, part configuration (shape and structure) and size (Diameter, Length).

1.6 Advantages

1. Process temperatures are much lower than conventional welding process. This results in avoiding problems which occur with liquid phase, such as alloy segregation, porosity and cracking.

2. Creates narrow heat affected zone.

3. Dissimilar welded joints are produced for an increasing range of materials – aluminum, zinc, lead, copper, magnesium, titanium and steel.

4. No fluxes filler material or shielding gas is required.

5. The process produces lower levels of distortion in the work piece compared to fusion welding.

6. The process is environmental friendly as no splatter and fumes or UV radiations are produced during this process.
7. No special tooling and joint preparation are generally required.

8. Less distortion takes place on the weld joints when compared to fusion welding process.

9. Different materials like steel and ceramic can be joined which cannot be joined by fusion welding process.

1.7 DISADVANTAGES

1. Low melting phases or brittle inter metallic compounds are produced.

2. The softening occurs on the aged alloys.

3. Hardening effects of the material combinations.

1.8 LIMITATIONS

1. Complicated shapes or intricate parts cannot be welded by using this technique.

2. Any one of the component must be cylindrical cross section.

1.9 APPLICATIONS OF FRICTION WELDING

- Machine part production and spare part industry - Cogwheels, piston rods, and hydraulic cylinders, radial pump pistons, shaft with worm screw, crankshafts, drill bits, valves.

- Automotive industry - valves, drive shafts, gear levers, axle fasteners, break spindles, transmission mechanisms, preheat rooms, pipe spindles, banjo axles.

- Aviation and space industry - Repulsion jets, combustion chambers, spindles, turbines, rotors, pipes, fittings, flanges.

- Work set industry - Spiral drills, milling cutters, borer, reamers, cutting tools.

- Electrical, electronics, and chemical industry - Receiver camera for gas analysis, segregation columns for chromatograph, Electrical connectors, continuous solder top, swing contacts, pipe fittings. As the market trends of heavy Industries,
Locomotives, Shipyard Engineering, Aeronautical Engineering, Three dimensional Engineering, Automobile, and in Welding Research Engineering, Bi-Metallic joints are most needed for light, Tough, Strong, Economical corrosion resistant parts and components. All these requirements cannot be fulfilled by one metal or alloy. Joints of Similar and Dissimilar metal combinations are employed in different applications requiring some special combination of various types of mechanical properties such as Hardness, Tensile Strength, Britteness, Malleability etc. and also to save cost incurred towards costly and in sufficient and scanty materials.
1.10 POSSIBLE DEFECTS IN FRICTION WELDING

1.10.1 Lack of Bonding

The main causes for this defect are as follows.

(i) When the rotational speed of the work material is low.

(ii) The contact time between the two work pieces during welding is not sufficient.

(iii) Selection of weld process parameters like friction, upset burn off length etc.,

(iv) Both the contact surface is not proper during machining.
1.10.2 Weld Cracking

These types cracks are two types (i) Macro crack (ii) Micro-fissuring. This types of defect may be due to high upset pressure. These types of defects occur on the following area.

(i) At Thermo-mechanically affected zone (TMAZ).

(ii) Heat affected zone (HAZ).

(iii) At flash.

(iv) Crack inside the weld flash.

(v) Crack at faying surface.

Figure 1.11 (a) Crack at the Sharp Edge Transitional Area to Weld Flash

Figure 1.11 (b) Crack Inside the Weld Flash

Figure 1.11 (c) Internal Cracks on the Faying Interface
The above defects shown in Figure 1.11 (a, b, c) can be minimized by reducing the coarse carbide, forging (or) upset pressure, controlling the weld cycle time, controlling inter-metallic compounds on the weld interface.

### 1.10.3 Non Metallic Inclusion

During forging stage solid non metallic inclusion are snared in the weld region it may be in the form of scale ,rust and by soiled center bore on the raw material to be welded.

### 1.10.4 Intermetallic Phase Accumulation

[Figure 1.11 (d) Non-Metallic Inclusions Entrapped Between the Faying Surfaces]

[Figure 1.11 (e) Inter-Metallic Phases Inside Contact]

[Figure 1.11 (f) Inter-Metallic Phases Along Contact Area]
1.10.5 Inter-metallic Phases along Contact Area

The main reason for this type of defects is selection of various improper process parameters, homogeneity of the metal to be joined, carbides and oxides formation on the bonding zone.

1.11 MATERIAL SELECTION

In this work, two dissimilar materials (i) Ferrous (ii) non ferrous metals of welded joints were investigated which are introduced briefly as follows. Dissimilar aluminum joints are one of the popularly known applications in aviation landing gear assembly, structural industries etc.,

1.11.1 Aluminum Alloys

In 1761 de Morveau proposed the name alumine called as alum and they are used by Greeks and Romans used in medicine as an astringent. Later in 1807 Davy proposed the name aluminum. Aluminum is the second metallic element available in earth crust but does not exist in nature because of high chemical affinity of oxygen. This aluminum alloys make an ideal material for novel application and it has some unique properties like light weight, high strength, low density 2.7 g/mm$^3$ at 20 °C, high reflectivity and high electrical conductivity and thermal conductivity, and excellent corrosion resistance due to a thin surface layer of adherent oxide films that forms when the metal is exposed to air, effectively protecting further oxidation of the metals. The Figure 1.12 shows the general classification of non ferrous metal systems.

1.11.2 Grades of Aluminum Alloy and its Designation

Generally temper designation is varied from alloy designation it has one or more digits used to denote the various heat treatments. In this study wrought aluminum alloy was used and the same tempering treatment is included.

T3 - solution treated and then cold worked, T4- solution treated, T5 - Artificially aged
T6 - Solution treated and artificially aged,
T8 - Solution treated cold worked and then artificially aged.
T9 - Solution treated, artificially age and then cold worked.
Figure 1.12 Alloys and its Constituents Elements

- Non-Ferrous metals
  - Elements
    - Aluminum
    - Chromium
    - Copper
    - Lead
    - Magnesium
    - Manganese
    - Molybdenum
    - Nickel
    - Silver
    - Tin
    - Titanium
    - Zinc
  - Alloys
    - Brass (copper and zinc)
      - Phosphor bronze
      - Gun metal
    - Tin bronze (copper and tin)
    - Aluminum bronze (Copper and Aluminum)
    - Cupro-nickel alloys (copper and nickel)
      - Heat-treatable (wrought)
      - Heat-treatable (cast)
      - Non-heat treatable (wrought)
      - Non-heat treatable (cast)
    - Magnesium alloys
    - Zinc-based ‘die-casting’ alloys
    - Tin-lead alloys
      - Soft soldiers
      - Bearing metals
1.11.3 Classification of Aluminum Alloy

The alloy can be classified as 1xxx to 8xxx. In 1xxx last two digits represents level of purity of alloys. All other alloys 2xxx -8xxx last two digits signify the different alloys in the group.

Aluminum alloys broadly classifieds wrought and cast products. The identification of the alloys is standardized by CEN (European committee) which uses four digits to wrought aluminum alloys. The prefix AW indicates wrought product. These alloys are designated by a four digit number in which first digit indicate the major alloying elements like Zinc, Magnesium, Copper, Manganese etc., and other unwanted impurities are present in are called as trap elements.

AW 1XXX – Commercially Pure Aluminum.
AW 2XXX – Aluminum – Copper Alloys.
AW 3XXX – Aluminum – Manganese Alloys.
AW 4XXX – Aluminum – Silicon Alloys.
AW 5XXX – Aluminum – Magnesium Alloys.
AW 6XXX – Aluminum – Magnesium – Silicon Alloys.
AW 7XXX – Aluminum – Zinc – Magnesium Alloys.
AW 8XXX – Other Elements e.g. Lithium, Iron.
AW 9XXX – No alloy groups assigned.

1.11.4 Precipitation Hardened Alloys

Aluminum alloys are precipitation hardened. It is a thermal treatment process used to improve the yield strength of the materials like aluminum, magnesium, nickel, titanium, and stainless steels. In this present work aluminum alloy of AA7075and AA6061–T6 both of heat treatment alloys which makes use of precipitation which will harden the alloy for precipitation, for achieving this; the aluminum alloy must be heated to a temperature below the melting point. The temperature for the solution treatment depends upon the content of the solute and the usage for different applications. The alloy is then quenched in water to room temperature. Since there is a lack of diffusion no transformation occurs and the
specimen becomes supersaturated solid solution (SSSS). Precipitation occurs to the specimen when it ages to certain temperature for a specific time period. During this process, the supersaturated solid solution decomposes and the regions of concentrated solute become nucleation. This zone will show considerable improvement in strength, called as GP zone. The free energy of the alloy decreases rapidly through the formation of the transition phases to the equilibrium phase. The following Table 1.1 shows general strengthening phases for aluminum matrix. The formation of transition phase to equilibrium phase lowered rapidly because of a reduction in the free energy of the alloy.

**Table 1.1 Common strengthening precipitates in heat treatable aluminum alloys**

<table>
<thead>
<tr>
<th>Phase</th>
<th>Approximate Composition</th>
<th>Typical aging temperature</th>
<th>Alloy Primary Strengthener</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta'$</td>
<td>Al$_2$Cu</td>
<td>175 °C</td>
<td>AlCuMg</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>Al$_2$Cu(Ag,Mg)</td>
<td>200 °C</td>
<td>AlCuMgAg (Cu/Mg~4)</td>
</tr>
<tr>
<td>$\Sigma'$</td>
<td>Al$_2$MgCu</td>
<td>150 °C</td>
<td>AlCuMg</td>
</tr>
<tr>
<td>$\Sigma$</td>
<td>Al$_2$MgCu(Ag)</td>
<td>150 °C</td>
<td>AlCuMgAg (Cu/Mg~1)</td>
</tr>
<tr>
<td>T</td>
<td>Al$_6$CuMg$_4$</td>
<td>190 °C</td>
<td>AlCuMg (Cu/Mg~1/4)</td>
</tr>
<tr>
<td>Z</td>
<td>Al$_3$CuMg(Ag)</td>
<td>200 °C</td>
<td>AlCuMgAg (Cu/Mg~1/4)</td>
</tr>
<tr>
<td>Q</td>
<td>Al$_5$Cu$_2$Mg$_8$Si$_6$</td>
<td>200 °C</td>
<td>AlCuMgSi</td>
</tr>
<tr>
<td>$\beta''$</td>
<td>Mg$_5$Si$_6$</td>
<td>175 °C</td>
<td>AlMgSi</td>
</tr>
<tr>
<td>$\eta'$</td>
<td>Mg Zn</td>
<td>130 °C</td>
<td>AlZnMgCu</td>
</tr>
</tbody>
</table>
1.12 THERMAL TREATMENT OF AGING OF ALUMINUM ALLOYS

There are three types in this thermal treatment process are follows

(i) Solution Treatment

(ii) Maintaining the super saturated solution of alloying elements.

(iii) Precipitating the intermediate phase changes naturally at room temperature and artificially at elevated temperatures.

1.12.1 Solution Heat treatment

To achieve precipitation hardening process it is necessary to create a solid solution with the maximum alloying elements. Depending upon the elemental composition minimum solution temperature is fixed. If the temperature is exceeded it may cause to start the eutectic phase which will defoliate the mechanical properties.

1.12.2 Quenching

Excess vacancies and super saturated solution are to be maintained during this process which is critical. Higher quenching rates shows better properties of strength and toughness. To achieve this selection of quenching medium and temperature should be carefully selected.

1.12.3 Precipitation from Solid Solution

During this stage clusters of solute atoms are formed by meta-stable precipitates, for this precipitation requires fine dispersion of supersaturated solutions. The temperature should be below GP solvus line. This coherent precipitates causes the strengthening mechanism.
Figure 1.13 Temperature Ranges of Binary Aluminum Alloys

Figure 1.14 (a) Solid solution (b) Coherent Zone (c) Semi Coherent Zone (d) In- Coherent Equilibrium Zone. (Hand Book of Aluminum, George E. Totten)
Table 1.2 Correlations between Precipitates and their Formation

<table>
<thead>
<tr>
<th>Interface type</th>
<th>Grain boundary (G)</th>
<th>Dislocation (D)</th>
<th>Vacancy (V)</th>
<th>Homogeneous nucleation (H)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coherent (C)</td>
<td>$G_C$</td>
<td>$D_C$</td>
<td>$V_C$</td>
<td>$H_C$</td>
</tr>
<tr>
<td>Semicohesent (SC)</td>
<td>$G_{SC}$</td>
<td>$D_{SC}$</td>
<td>$V_{SC}$</td>
<td>$H_{SC}$</td>
</tr>
<tr>
<td>Incoherent (IC)</td>
<td>$G_{IC}$</td>
<td>$D_{IC}$</td>
<td>$V_{IC}$</td>
<td>$H_{IC}$</td>
</tr>
</tbody>
</table>

1.12.4 Aging of AA6061-T6

The following changes are happened during different temperature. At temperature 100 °C formations of magnesium and silicon segregates in the matrix lattice. Nucleation of needle like zone on to these segregates start from 200-250 °C. Nucleation of free silicon which rapidly lost its coherency in the temperature range between 240-320 °C and the elemental Composition remains unchanged.

Formation of the coherent B\(_2\) phase is below 450 °C. Formation of semi coherent phase B starts at the same temperature. Formation of equilibrium B phase is above 400 °C. The tempering modes for this aluminum alloy are 530 °C, 160 °C and 170 °C at 8 hrs.

1.12.5 Precipitation Hardening in AA7075 Aluminum Alloy

The Figure 1.15 referred the mechanism of precipitation of AA7075 alloy in binary phase diagram of Aluminum-Zinc in the aluminum-rich region. Since composition of zinc is less than 6 % in the aluminum alloy, it is heated to the temperature above the solvus line. One phase is thermodynamically stable and another region of solid phase dissolves to adverse the effect of the sample treated at 480 °C.
for a specific time period. When the solutionized sample is cooled suddenly below the line the phases alpha and beta are thermodynamically stable and are separated by a phase boundary. The formation of second phase particle grow through thermal fluctuation with time dependence and form more precipitates, once the solution reaches a equilibrium position the precipitation stops. The precipitation of this alloy depletes in alpha phase around 380 °C.

Figure 1.15 Schematic Phase Diagram of Age hardneable Alloy

(ASM Hand Book)

1.13 FERROUS MATERIALS

These materials are having high element proportion of iron which is very strongest and relatively low cost finds major application in locomotives railway lines, highly stressed engine parts where strength to weight ratio is not a primary importance. This can be classified as steel, cast iron and wrought iron. The Figure 1.16 shows the classification of ferrous materials. Steel and cast iron materials were used abundantly as 94% world total consumption of metallic materials. Ferrous metal combination of dissimilar friction weld joints finds more industrial applications and they are shown in Table 1.3.
Table 1.3 Industrial Applications of Dissimilar Steel Welds

<table>
<thead>
<tr>
<th>S.NO</th>
<th>PRODUCT</th>
<th>USER INDUSTRY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>EN19B to EN19B</td>
<td>Front wheel axle in automobiles</td>
</tr>
<tr>
<td>2</td>
<td>EN354 to EN354</td>
<td>Main Shaft in automobiles</td>
</tr>
<tr>
<td>3</td>
<td>SAE 8620 to SAE 8620</td>
<td>Rocker arm shaft</td>
</tr>
<tr>
<td>4</td>
<td>High speed steel to medium carbon</td>
<td>Bimetal drill tools</td>
</tr>
<tr>
<td>5</td>
<td>AISI 316 to EN08</td>
<td>Pumps and nozzles</td>
</tr>
<tr>
<td>6</td>
<td>Tungsten to Copper</td>
<td>Electric power transmission</td>
</tr>
<tr>
<td>7</td>
<td>AISI to Al</td>
<td>Nuclear and cryogenics, chemical</td>
</tr>
</tbody>
</table>

Figure 1.16 Classification of Ferrous Metal
1.13.1 Low Carbon Steel

Steel with low carbon content has properties similar to iron. Low carbon steel has carbon content of 1.5% to 4.5%. Low carbon steels are naturally soft, ductile, it can be worked when either hot or cold and it is readily welded by all methods. They do not harden to any appreciable amount when quenching from a high temperature.

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Figure 1.17 Weldability for Friction Welding Process (AWS Hand Book)
1.13.2 Medium Carbon Steels

These steels are heat-treated after fabrication and used for general machining and forging of parts that require surface hardness and strength. During welding, the weld zone will become hardened if cooled rapidly and must be stress relieved after welding. The feasibility of different material combinations given by AWS 2001 is shown in Figure 1.15.

1.13.3 High Carbon Steel

The range of carbon present in this type of steel is 0.70 to 1.05 %. If these materials are heat treated, it becomes very hard so that it will withstand high shear. It is important that hardness, brittleness and ductility are determined by different carbon content of steels.

1.14 PROBLEM STATEMENT

1.14.1 Justification of Material Selection and Problem Identification

In conventional welding processes, the melting point differences between the two materials to be welded should be very low for a successful weld. But in the case of AISI 316L (melting point around 1363 °C) and EN8 (R) (melting point around 1485 °C), the melting point difference between the two materials is large. Yet, it is possible to weld these two materials by conventional techniques using mild steel as filler material. But in this process, weld decay occurs in the stainless steel regions that degrades the chromium present in it. Since Chromium is the characteristic component in AISI 316L weld, it causes weaker joints and instills poor corrosion resistance. The cooling rate of carbon steels is higher when compared to that of AISI 316L. Carbon steels tends to cool faster and this results in localized stress in the EN8 (R) region, due to these stresses warping or weld misalignment takes place. All the above-mentioned disadvantages can be avoided when AISI 316L and EN8 (R) are welded using friction-welding technique.
A 20% greater solubility of H$_2$ in aluminum exhibits liquid state leading to gas entrapment and porosity in solidified weld. High coefficient of thermal expansion and volume shrinkage during solidification results in severely distorted weld joints or cracks. Welding of AA7075-T6 in arc welding susceptible to stress corrosion cracking and the premature failure. Since the low melting elements are precipitated in the grain boundaries the solidification occurs slowly at the boundaries so that it easily cracks due to shrinkage stress and increase in crack sensitivity. The Al6061–T6 alloys require more heat input during fusion welding to achieve penetration and this will cause increase in distortion in the welded components. For example, in Resistance spot welding it was reported that aluminum has good electrical and heat conductivity which require much heat to melt the metal with high amperage level. (20 kilo Volt-Ampere). To avoid these critical issues continuous direct drive rotary friction welding process are selected to make the weld joints.

1.14.2 Problems in Fusion welding of 7xxx & 6xxx Series Aluminum Alloys

When aluminum is heated above its melting point especially in fusion joining techniques it causes porosity due to absorption of hydrogen (hydrated oxide) susceptibility. Also exposing the weld at the atmosphere will combine with oxygen and form a layer of oxides which will affect the structural integrity of the weld joints. The 7xxx series of aluminum alloys are not suitable for fusion welding technique because of high temperature cracking mechanism, stress corrosion cracking. The 6xxx Al-Mg-Si series base alloys, typically containing around 1% percent magnesium silicide Mg$_2$Si, cannot be arc welded successfully by autogenously. These alloys can be welded with 4xxx series (Al/Si) or 5xxx series (Al/Mg) of filler alloys. Solidification cracking at weld zone and liquation cracking at partially melted zone will occur in these types of alloys. Therefore the problems that occur in fusion joining techniques could be overridden by a solid state metal joining technique. In this research, the feasibility analysis and quality assessment of the weld were done after post weld treatment of dissimilar alloys.
1.15 OBJECTIVES OF THE RESEARCH WORK

The present investigations are carried out having the objectives to improve the weld integrity by choosing suitable process parameters. The key objectives of this research are present as follows.

1. To produce friction welded joints between the material combinations of purely ferrous metals (AISI316L-EN8 (R)) and welds of non-ferrous metals (AA7075-AA6061-T6).

2. To optimise the friction welding parameters such as friction pressure, upset pressure, speed and burn off length with reference to ultimate tensile strength of welded joint.

3. To improve the mechanical properties and to reveal metallurgical characteristics by treating them in cryogenic temperature and critical temperatures which could ascertain prolonged life in the fields of applications pertaining to aerospace, marine, pressure vessel and nuclear power sector.

4. To study the effects of key influencing parameters on the mechanical properties and the macro and microstructural evolution of the joints.

5. To evaluate the quality of the friction welded joints using non-destructive test method.

6. To study the corrosion characteristics on weld joints.

1.16 NEED AND SCOPE OF THE RESEARCH WORK

1. Due to distinctive difference in physical and thermal properties between the dissimilar metals, conventional fusion welding techniques are not promising techniques which affects the weld integrity and mechanical and metallurgical properties.
2. Retained austenite is converted in to a fine matrix of martensite enhance the impact strength.

3. To relieve residual stresses in weld joints, unexpected failures like fatigue fracture could be avoided.

4. To homogenize the crystal Structure to enhance better resistance to plastic deformation.

5. To refine the grain structure to improve the hardness of the materials.

1.16.1 Impact of the Research

The extensive work to be carried out on the material behavior, right from their micro structural study to their evaluation of mechanical properties after subjecting them to several treatments, would certainly result in enriching the knowledge-base which in turn could be transferred to the tender minds. The research thirst can be inculcated in this potential area of metal joining and study of the metals post weld behavior. Opportunities would be created to develop applications, with the data that are to be accumulated in the due course of the work resulting in the involvement of the challenging project works. This work can also bring in new research infrastructures to the department which can further intensify the active research in the field of advanced metal joining techniques associated with post weld treatments in the years to come.

1.17 CRYOGENICS

Application of cold treatment first documented in 1930’s by German companies applied in Jumbo aircraft engines. An experimental analysis was carried out in 1946 by USA. In 1960’s, NASA introduced the cryogenic treatment which can be used for metallic components which response the good results in martensitic, austenitic stainless steel and mild steel.

In recent years major countries make use of cryogenic treatment for the enhancement of potential Mechanical property after the welding process. Cryogenic
treatment is a supplementary one time process which affects the entire cross sectional area of the component. The steels which undergone the cryogenic treatment shows the improvement in uniformity and a refined microstructure with high density. Most of the medium carbon steels and low alloy steels undergo 100% martensitic transformation at room temperature. High carbon and high alloy steels have retained austenite at room temperature. To eliminate the retained austenite the temperature has to be lowered.

This treatment consists of an insulated chamber and the LN2 regulated by a solenoid valve. The regulated the flow of nitrogen is passed to heat exchanger through the bottom of the chambers, the nitrogen gas which effectively reduces the temperature of the welded samples. The temperature inside the chamber is measured in three places with RTDs connected to the digital temperature indicator.

To achieve ultra low temperature at 1 °C/min in deep cryogenic process, it involves conventional hardening and slow cooling down from ambient temperature. After the cooling process soaking process is carried out and allowed to warm and tempered up to room temperature.

1.17.1 Kinetics of Cryogenic Treatment

The applications of cryogenic treatment are based on two theories. The uses of the cryogenic treatment can be identified by x-ray diffraction measurements. One method involves the more nearly complete transformation of retained austenite into martensite. Another involves in the strengthening of the material brought about by the precipitation of submicroscopic carbides. This results in avoiding micro cracks issue and also helps to reduce the internal stresses in the weld joints resulting in improved properties. Due to reducing the vacancies or dislocation, residual stress that develops during welding process is reduced. Also distortion, warping and suspecting of micro cracks can be avoided. The effects of cryogenic treatment includes dimensional stability obtained due to entire molecules of the work part is stabilized.
1.18 Types of Cryogenic Processing

(i) Shallow cryogenic treatment

(ii) Deep Cryogenic treatment

1.18.1 Shallow Cryogenic Treatment or Cold Treatment

The temperature of the component is lowered down to -80 °C. Then the component is soaked for a particular period in solid carbon di-oxide called as dry ice. The transformation is based on the degree of under cooling, the time period and tempering at room condition.

1.18.2 Deep Cryogenic Treatment

The DCT involves lowering the temperature to -192 °C with a cooling rate of 2.5 °C/min i.e from ambient temperature to N2 temperature and then bringing back to the room temperature. After the treatment the austenite traces are seen in the work material, which significantly improves the mechanical properties.

1.19 CRYOGENIC MEDIA

The cryogenic fluid plays a vital role in improving the properties of the welded joints. These liquids are having boiling temperature are below -60 °C. There are two (i) Methanol or Ethanol (ii) Liquid Nitrogen.

1.19.1 Methanol or Ethanol

The dry ice or solid carbon-di-oxide is mixed with ethanol or methanol which can be used as a cooling agent to perform the cryogenic treatment. In this method the temperature is maintained at 60 °C and -110 °C.

1.19.2 Gaseous Nitrogen /Liquid

This liquid nitrogen is a general and most popular cooling agent used for cryogenic treatment. This can be done by two methods
(i) Direct contact liquid nitrogen. (Wet method)

(ii) Dry contact nitrogen.

(i) Direct Contact Liquid Nitrogen

In this method the component is soaked directly in liquid nitrogen at a particular time period. The main disadvantage in this method is there is some generation of thermal shock in the component.

(ii) Dry Contact Nitrogen

In order to eliminate the above disadvantages in direct contact liquid nitrogen method dry contact nitrogen is employed. In this method there is no exposure of component directly to liquid nitrogen. The component is slowly cooled and to the temperature around -196 °C and maintained to a particular time period and then slowly bringing it back to the ambient temperature. This process is called Dry contact nitrogen method.

1.20 CRYOGENIC GASES

These gases have a boiling temperature which is below -100 °C. In this process oxygen, fluorine, hydrogen krypton etc., are combined with nitrogen for processing.

1.20.1 Factors affecting the Cryogenic Treatment

- Rate of cooling.
- Cryogenic soak temperature.
- Duration of Cryogenic soaking.

1.20.1.1 Rate of Cooling Down

Several investigators reported that the cryogenic process is carried out as slow as 3 °C per min starting from ambient temperature to cryogenic temperature.
1.20.1.2 Cryogenic Soak Temperature

Investigation revealed that liquid helium at -286 °C does not show improvement while comparing liquid nitrogen because the percentage of martensite transformation is more in liquid nitrogen.

1.20.1.3 Duration of Cryogenic Soak

It is reported that this type of treatment can be conducted between 6 to 40 hours. Generally 24 hours soaking of materials show good improvement in mechanical properties. More than 24 hours does not have further improvement in their properties.

Figure 1.18 Process Cycle of Cryogenic Treatment
1.21 CRYOGENIC TREATMENT ON STEELS

The following observations were made during cryogenic treatment, complete transformation of retained austenite into Martensite at cryogenic temperature can be achieved. Precipitations of finely dispersed carbides are produced in the Martensite and evenly dispersed resulting in a smooth surface.

It relieves stress and become more corrosion resistant due to the slight smoothening effect on the surfaces. The fine carbides act as hard areas with a low coefficient of friction in the metal that greatly adds to the wear resistance of the metals.

1.21.1 Benefits of Cryogenic Treatment

To relieve stresses in cracking of weld zones in corrosive atmospheres. It improves toughness and hardness of materials, increases electrical conductivity in copper and improves corrosion resistance in chemical, food and oil equipment applications.

Cryogenic treatment stabilizes part dimensions by eliminating the possibility of spontaneous transformation of retained austenite to martensite during fabrication. 

Cryogenic treatment stabilizes part dimensions by eliminating sudden transformation of retained Austenite to martensite during fabrication process.

1.21.2 Application of Cryogenic Treatment

(a) In Welding

During welding process internal stresses were developed within the metals. By cryogenic treatment the metal is brought to a relaxed state by relieving the stresses, stability of the metal is less susceptible to micro cracking in the weld zone.

(b) In Sports

Improve performance of golf balls, tennis rackets, fish hooks and rifle barrels.
(c) In Tool design

In centre drawing dies the efficiency is increased by 3 times in the life of carbide dies.

(d) In Electrical Parts

The cryogenic treatment improves conductivity in aluminum and copper electrical parts.

1.22 HEAT TREATMENT

To attain desired serviceability of the component, by increasing the strength, hardness etc., the welded joints can be treated by several methods due to this the phase transformation occurs and microstructure of the component is modified which influences the properties of the metals.

The main process variable of the heat treatment process is

(i) Temperature  (ii) Holding time (iii) Heating rate (iv) Cooling rate

1.22.1 Process

(i) Hardening (ii) Annealing (iii) Normalizing (iv) Tempering

(i) Hardening

Steel is heated till austenitic range and it is held in that temperature until carbon gets dissolved and then cooled rapidly. Due to the insufficient time of cooling the amount of carbon escaping is limited and gets dissipated in the lattice structure. This restricts the dislocation in the movement even when the stress is applied.

(ii) Annealing

To improve toughness and regain its ductility annealing is carried out. Annealing also relieves residual stresses in the component. The cooling can be done very slowly at 10 °C /hour. It can be done in controlled atmosphere.
(iii) Normalizing

This process is used to control the excessive softness of the weld joint. Fine pearlite is produced by the process of decomposing of austenite as ferrite and carbide at low temperature. The component is heated till the austenite phase and it is cooled through the medium of air.

(iv) Tempering

Tempering is the process done to reduce brittleness because of the presence of martensite phase. Steel is heated to lower critical temperature and soaked for an hour and cooled slowly. Whenever there is an increase in tempering temperature lowers the hardness.

![Figure 1.19 Annealing process](image-url)
1.23 EFFECTS OF ALLOYING ELEMENT IN STEELS

(i) Addition of carbon and phosphorus will increase the strength; excess of these alloying elements show a drastic decrease in weld ability, ductility and toughness.

(ii) Manganese considered as a de-gasifiers to increases surface quality.

(iii) Chromium forms chromium carbides which improve edge holding capacity.

(iv) Addition of nickel present in low alloy steel will be more beneficial to strength properties.

(v) Addition of hydrogen and Oxygen cause brittleness, decreases ductility and toughness of steel.

(vi) Amount of copper content add advantages in low temperature notch. When copper insists in precipitation hardening which promotes the ultimate tensile strength, hardness and toughness.

(vii) Decrease in impact toughness of the steel can be reduced by adding less amount of nitrogen.
1.24 EFFECTS OF ALLOYING ELEMENT IN ALUMINUM ALLOYS

1.24.1 Magnesium-Manganese

Increasing this alloy in wrought product results in high strength in the work-hardened condition, high resistance to corrosion, and good welding characteristics. Fabrication is difficult by increasing elemental compositions either magnesium or manganese. Also increase the tendency toward cracking during hot rolling, particularly if traces of sodium are present.

1.24.2 Magnesium- Silicon

This alloying elements were present in a AA6xxx group which can be a maximum contents is 1.5%. The maximum solubility of this alloying element is 1.85% and this decreases with temperature. Age hardening forms by Guinier-Preston zones and a very fine precipitate were obtained.

1.24.3 Zinc

Zinc offers high tensile strength in wrought aluminum alloys but hot cracking and there is stress-corrosion cracking is the main problem in these alloy. Aluminum-zinc alloys containing other elements offer the best combination of ultimate tensile properties in wrought aluminum alloys.

1.24.3.1 Zinc-Magnesium

The addition of magnesium to the aluminum-zinc alloys develops more strength to the alloying system, especially in the range of 3 to 7%, 5% Zn. Magnesium and zinc form MgZn$_2$, produces a higher response to heat treatment than in the binary aluminum-zinc system. Strength can be increased to wrought aluminum alloys by adding magnesium. By increasing the composition of MgZn$_2$, concentration from 0.5 to 12% in cold-water quenching increases the tensile and yield strengths. The addition of magnesium required to form MgZn$_2$, further increases the tensile strength.
1.25 RESEARCH METHODOLOGY (PERSPECTIVE IN THE RESEARCH PROBLEM)

To accomplish the objective of this research, a methodology was developed. The methodology was essentially a real type weld joint approach to improve the mechanical properties. The first task was to make a weld joint in continuous friction welding process by applying the parameters using Taguchi orthogonal array. Taguchi relation was used to optimize the parameters. The parameters were considered by making the trial and error method and by using literature review. In order to validate the results the samples were subjected to room temperature. The tests like tensile testing were evaluated by Universal testing machine using ASTM –standard E8-307. Micro Vickers Hardness of the different zone of weld joints were measured by inverted metallurgical microscope, Microstructure of the weld joints were studied by inverted metallurgical microscope (Wolpert Wilson Instrument with a load range 10mf-2Kgf.
Mechanical Characteristics & Metallurgical characteristics at room temperature

Selection of material AA7075 AA6061-T6 & EN8 AISI316L

Selection of parameters pilot study

Experimental design based on Taguchi L9 orthogonal array

Friction welding

Process optimisation

Thermal & Structural analysis using quick field

Mechanical Characteristics & Metallurgical characteristics at room temperature

Selection of samples for PWHT based on T.S (low, medium, high)
Figure 1.21 Flow Chart for Methodology of Work
Once the testing was completed at room temperature the samples were selected based on tensile strength for post weld heat treatment and cryogenic treatment. For heat treating the specimen was treated at 485 °C and then it was annealed to room temperature. To carry out cryogenic treatment cryo freezer is used, liquid nitrogen was as a freezer for 2 and 4 hours. Corrosion studies were done on base metal and welded joints by using potentio-dynamic polarization method and impedance spectroscopy method comprising of potentiostat. Finally, the results were compared with different treatment by varied temperatures at different time periods.

1.26 ORGANISATION OF CHAPTERS

**Chapter 1** starts from introduction that comprises of process description of process parameters, and the feasibility of joining the dissimilar materials, application, advantages, and justification of material selection, problem statement, need, scope and objective of this study.

**Chapter 2** presents literature survey of similar and dissimilar weld joints (Ferrous and non ferrous metals). Mechanical, metallurgical, impact and corrosion studies on welded joints. Taguchi optimisation techniques, simulation studies on weld joints are detailed. Post weld studies on similar and dissimilar materials in different welding methods are conclave in this chapter.

**Chapter 3** explores the experimental work and procedures which includes the property of the materials, selection of parameters and its working limits, fabrication of welded joints, and temperature measurements for simulation of structural and thermal analysis using quick field software.

**Chapter 4** reports results and discussion in mechanical testing (Tensile, hardness, impact) destructive and non destructive testing (radiography technique), metallurgical characterization of the friction welding joints at room temperature.

**Chapter 5** includes results and discussion on the mechanical, metallurgical and corrosion tests conducted at room temperature, post weld treated samples. The
samples were taken from the outcome of experimental design done with L9 orthogonal array focused on tensile strength (Low, Medium, High Tensile strength).

**Chapters 6** describe optimisation and analysis which was done by Taguchi technique at 95% confidence level using MINITAB 14. The developed model validated using the normal probability plot, predicted versus actual tensile strength plot, 2D surface plots, contour plot on various process parameters involved in the experiments.

**Chapter 7** interprets the conclusions of the overall investigations, and the recommendations for future work are enumerated.