1. INTRODUCTION

1.1 INTRODUCTION OF THE FSW TECHNIQUE

In today’s modern world there are different welding techniques to join metals. They range from the conventional oxyacetylene torch welding to laser welding. The two types of welding can be divided as fusion welding and pressure welding.

The fusion welding process involves bonding of the metal in the molten stage and may need a filler material if required such as a consumable electrode or a spool of wire. Some processes may also need an inert ambience in order to avoid oxidation of the molten metal. A flux material or an inert gas shield in the weld zone protects weld pool to avoid defects. Examples of fusion welding are metal inert gas welding (MIG), tungsten inert gas welding (TIG) and laser welding. There are many disadvantages in the welding techniques where the metal is heated to its melting temperatures and let it solidify to form the joint. The melting and solidification causes the mechanical properties of the weld in some cases to deteriorate such as low tensile strength, fatigue strength and ductility. The disadvantages also include porosity, oxidation, microsegregation, hot cracking and other microstructural defects in the joint. The process also limits the combination of the metals that can be joined because of the different thermal coefficients of expansion.
The solid state welding is the process where coalescence is produced at temperatures below the melting temperatures of the base metal without any need for the filler material or any inert ambience in many cases. Examples of solid state welding are friction welding, explosion welding, forge welding, hot pressure welding and ultrasonic welding. The three important parameters time, temperature and pressure individually or in combinations produce the joint in the base metal. As the metal in solid state welding does not reach its melting temperatures, there are fewer defects caused due to the melting and solidification of the metal. In solid state welding the metals being joined retain their original properties as melting does not occur in the joint and the heat affected zone (HAZ) is also very small compared to fusion welding techniques where most of the deterioration of the strength and ductility begins. Dissimilar metals can be joined with ease compared to fusion welding.

Friction stir welding (FSW) is an advanced friction welding process. The conventional friction welding is done by moving the parts to be joined relative to each other along a common interface also applying compressive forces across the joint. The frictional heat generated at the interface due to rubbing softens the metal and the soft metal gets extruded due to the compressive forces and the joint forms in the clear material, the relative motion is stopped and compressive forces are increased to form a sound weld before the weld is allowed to cool.
Friction stir welding is also a solid state welding processes, this remarkable upgradation of friction welding was invented in 1991 in The Welding Institute (TWI) [1]. The process starts with clamping the plates to be welded to a backing plate so that the plates do not fly away during the welding process. A rotating wear resistant tool is plunged on the interface between the plates to a predetermined depth and moves forward in the interface between the plates to form the weld. The advantages of FSW technique is that it is environment friendly, energy efficient, there is no necessity for gas shielding for welding aluminium. Mechanical properties as proven by fatigue, tensile tests are excellent. There is no fume, no porosity, no spatter and low shrinkage of the metal. Joining dissimilar and previously unweldable metals can be attempted by this unique process.

1.2 ALUMINIUM ALLOYS AND WELDING OF ALUMINUM ALLOYS
Aluminium is the most abundant metal available in the earths crust. Steel was the most used metal in 19th century but Aluminium has become a strong competitor for steel in engineering applications. Aluminium has many attractive properties compared to steel as it is attractive and versatile to use. It is used extensively in aerospace, automobile and other industries. The most attractive properties of aluminium and its alloys which make them suitable for a wide variety of applications are their light weight, appearance, fabricability, strength and corrosion resistance.
The most important property of aluminum is its ability to change its properties in a very versatile manner, it is amazing how much the properties can change from the pure aluminum metal to its most complicate alloys. There are more than a couple of hundreds alloys of aluminum alloys and many are being modified from them internationally. Aluminium alloys have very low density compared to steel. It has almost one thirds the density of steel. Properly treated alloys of aluminum can resist the oxidation process which steel can not resist, it can also resist corrosion by water, salt and other factors.

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

Most alloys of aluminum 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, and laser welding. When welding many physical and chemical changes occur such as oxide formation, dissolution of hydrogen in molten aluminum and lack of color change when heated.
1.3 WELD DEFECTS USING CONVENTIONAL PROCESSES

Because of a history of thermal cycling and micro structural changes, a welded joint may develop certain discontinuities. Welding discontinuities can also be caused by inadequate or careless application of established welding technologies or substandard operator training. The major discontinuities that affect weld quality are described below.

1.3.1 Porosity

Trapped gases released during melting of the weld area and trapped gases during solidification, chemical reactions during welding, or contaminants, cause porosity in welds. Most welded joints contain some porosity, which is generally spherical in shape or in the form of elongated pockets. The distribution of porosity in the weld zone may be random, or it may be concentrated in a certain region. Porosity in welds can be reduced by the following methods:

- Proper selection of electrodes and filler metals.
- Improving welding techniques, such as preheating the weld area or increasing the rate of heat input.
- Proper cleaning and preventing contaminants from entering the weld zone.
- Slowing the welding speed to allow time for gas to escape.
1.3.2 Slag inclusions

Slag inclusions are compounds such as oxides, fluxes, and electrode-coating materials that are trapped in the weld zone. If shielding gases are not effective during welding, contamination from the environment may also contribute to such inclusions. Welding conditions are important, and with proper techniques the molten slag will float to the surface of the molten weld metal and not be entrapped. Slag inclusions may be prevented by:

- Cleaning the weld-bead surface before the next layer is deposited by using a hand or power wire brush.
- Providing adequate shielding gas.
- Redesigning the joint to permit sufficient space for proper manipulation of the puddle of molten weld metal.

1.3.3. Incomplete fusion and penetration

Incomplete fusion (or lack of fusion) produces poor weld beads, such as those shown in Figure 1.1.

Figure 1.1 Examples of various discontinuities in fusion welds.
A better weld can be obtained by:

- Raising the temperature of the base metal.
- Cleaning the weld area prior to welding.
- Changing the joint design and type of electrode.
- Providing adequate shielding gas.

Incomplete weld occurs when the depth of the welded joint is insufficient. Penetration can be improved by:

- Increasing the heat input.
- Lowering travel speed during welding.
- Changing the joint design.
- Ensuring that surfaces to be joined fit properly.

1.3.4 Weld profile

Weld profile is important not only because of its effects on the strength and appearance of the weld, but also because it can indicate incomplete fusion or the presence of slag inclusions in multiple-layer welds. Underfilling results when the joint is not filled with the proper amount of weld metal as shown in Figure 1.2. Undercutting results from melting away the base metal and subsequently generating a groove in the shape of a recess or notch.

Unless it is not deep or sharp, an undercut can act as a stress raiser and reduce the fatigue strength of the joint and may lead to premature failure. Overlap is a surface discontinuity generally caused by poor welding practice and selection of the wrong materials. A proper weld is shown in Figure 1.5.
1.3.5 Cracks

Cracks may occur in various locations and direction in the weld area. The types of cracks are typically longitudinal, transverse, crater, and toe cracks as shown in Figure 1.3. These cracks generally result from a combination of the following factors:

- Temperature gradients that cause thermal stresses in the weld zone. Variations in the composition of the weld zone that cause different contractions.
- Embitterment of grain boundaries by segregation of elements, such as sulfur, to the grain boundaries as the solid-liquid boundary moves when the weld metal begins to solidify.
- Hydrogen embitterment.
- Inability of the weld metal to contract during cooling is a situation similar to hot tears that develops in castings and related to excessive restraint of the work piece.
Cracks in welded joints caused by thermal stresses that develop during solidification and contraction of the weld bead and the welded structure. (a) crater cracks. (b) Various types of cracks in butt and T joints.

Cracks are classified as hot or cold cracks. Hot cracks occur while the joint is still at elevated temperatures. Cold cracks develop after the weld metal has solidified. Some crack prevention measures are:

1. Change the joint design to minimize stresses from shrinkage during cooling.
2. Change welding-process parameters, procedures, and sequence.
3. Preheat components being welded.
4. Avoid rapid cooling of the components after welding.

**1.3.6 Lamellar tears**

In describing the anisotropy of plastically deformed metals, it is stated that because of the alignment of nonmetallic impurities and inclusions (stringers), the work piece is weaker when tested in its thickness direction.
This condition is particularly evident in rolled plates and structural shapes. In welding such components, lamellar tears may develop because of shrinkage of the members or by changing the joint design to make the weld bead penetrate the wearer member more deeply.

### 1.3.7 Surface damage

During welding, some of the metal may spatter and be deposited as small droplets on adjacent surfaces. In arc welding possess, the electrode may inadvertently contact the parts being welded at places not in the weld zone (arc strikes). Such surface discontinuities may be objectionable for reasons of appearance or subsequent use of the welded part. If severe, these discontinuities may adversely affect the properties of the welded structure, particularly for notch-sensitive metals. Using proper welding techniques and procedures is important in avoiding surface damage.

### 1.4 NEW PROCESSES

The Primary incentive for welding process development is the need to improve the total cost effectiveness of joining operations. Recently, concerns over the safety of the welding environment and the potential shortage of skilled technicians and operator in many countries have become important considerations.
The use of new joining techniques such as Friction Stir Welding appears to be increasing since it does not involve melting. The application of these processes has in the past been restricted, but with the increased recognition of the benefits of automation and the requirement for high-integrity joints in newer materials it is envisaged that the use of these techniques will grow.

This is a new process originally intended for welding of aerospace alloys, especially aluminum extrusions. Whereas in conventional friction welding, heating of interfaces is achieved through friction by rubbing two surfaces, in the FSW process, a third body is rubbed against the two surfaces to be joined in the form of a small rotating non-consumable tool that is plunged into the joint. The contact pressure causes frictional heating. The probe at the tip of the rotating tool forces heating and mixing or stirring of the material in the joint.

1.5 SCOPE OF WORK

Friction stir welding being a novel process and facilitates welding of plate to plate joints required for several applications. This process is chosen for applying to welding of AA 6082-T6 (Al-Mg-Si alloy) of 5mm thickness. This alloy finds use for structural and other industrial applications.
Since tool geometry and interaction of tool with base metal is important for getting good quality welds, different tool geometries were designed and manufactured. Since mechanism of bonding involves efficient movement of plasticized material around tool profile, the joints were investigated thoroughly for defects under varying conditions of process parameters.

The optimization of process parameters was carried out using design of experiments approach and the joint properties were evaluated by conducting tensile, hardness tests. Also the quality of the joints was confirmed by macro and microstructural investigation. A detailed analysis was carried out and finally the best welding conditions and best tool profile to get defect free welds was recommended.

The results will be of immense use for applying to other aluminium alloys and to other joint designs apart from the present material under investigation.