CHAPTER 1
INTRODUCTION

1.1 Friction stir welding process

Friction stir welding (FSW) is a relatively new and promising solid state joining process developed and patented by The Welding Institute (TWI), Cambridge, U.K.[1]. Figure 1.1 shows the schematic drawing of FSW process. The work piece is placed on a backup plate and clamped rigidly by a fixture to prevent lateral movement during FSW. A specially designed frustum shaped tool with a pin extending from the shoulder is rotated with a speed of several hundreds rpm and slowly plunged into the joint line. The pin usually has a diameter one-third of the shoulder and typically has a length slight less than the thickness of the work piece. The pin is forced into the work piece at the joint until the shoulder contact the surface of the work piece (figure 1.2 a). As the tool descends further, its surface friction with work piece creates additional heat and plasticizes a cylindrical metal column around the inserted pin and the immediate material under the shoulder. The weld usually thins the parent metal by about 3-6 % of original thickness. The work piece to be joined and the tool are moved relative to each other such that the tool tracks along the weld interface. The rotating tool provides the ‘stir’ action, plasticizing metal within a narrow zone while transporting metal from the leading face of the pin to the trailing edges. As the tool passes, the weld cools, thereby joining the two plates together (figure 1.2 b). On tool extraction a hole is left as the tool is withdrawn from the work piece (figure 1.2 c).
Figure 1.1 Schematic drawing of friction stir welding

(a)

(b)

(c)

Figure 1.2 Description of the three main stages of FSW (a) plunge phase (b) translational and rotational motion of the tool through the plates (c) tool extraction
The process was developed initially for aluminum alloys but since then FSW was found suitable for joining large number of materials like magnesium, copper, brass, titanium and steel. Another important aspect is the possibility to join materials with very different mechanical and physical properties such as aluminum-steel [2], aluminum magnesium[3], and aluminum-copper [4-5]. Welding of aluminum and its alloys has always represented a great challenge for designers and technologists. Lot of difficulties are associated with this fusion joining process, mainly related to presence of a tenacious oxide layer, higher thermal conductivity, high coefficient of thermal expansion, solidification shrinkage and above all solubility of hydrogen and other gases in molten state. There is core demand of aircraft industries to substitute the traditional joining technologies with low cost and high efficiency ones such as FSW. FSW technology is expected to replace the fastener, riveted and arc welding joining methods for large scale production applications. FSW offers ease of handling, high levels of repeatability thus creating very homogenous welds. Its applicability to aluminum alloys, in particular dissimilar alloys or those considered unweldable by conventional welding, makes it as an attractive method for the transportation sector [6]. A serious problem with fusion welding is the complete alteration of microstructure and loss of mechanical properties. Being a solid state process, FSW has potential to avoid significant changes in micro structure and mechanical properties. FSW can produce superior mechanical properties when compared to the typical electric arc welding process and therefore has gained considerable research interest and is considered as one of the most encouraging design challenge for future. The quality of the welds produced and reproducibility of this fully automated process have provided the impetus for many industries to use it in production. Nevertheless, many aspects of the process are still poorly understood and require further study, for example, the temperature field in the nugget and side region. FSW has many advantages over traditional welding processes [7-8] including the following:

- The welding procedure is relatively simple with no consumables or filler material.
- It does not require shielding gas, no arc formation and no fumes.
- Welds can be made in a single pass with no specialized joint preparation.
- Superficial oxide generation is not deterrent for the process and no particular cleaning operations are needed before welding.
• The procedure is machine tool technology based which can be automated and carried out in all positions.
• Lower residual stress and distortion of the base metal is achieved.
• Reduced need for human skill.
• The surface appearance approaches that of a roughly machined surface, which reduces production costs in further processing and finishing.
• Parent metal chemistry is retained without any gross segregation of alloying elements.
• Process is solid phase with process temperature regimes much lower than in fusion techniques, thus avoiding problems which can occur in solid phase, such as porosity and cracking.

There are also certain disadvantages associated with the process which include:
• It is necessary to clamp the work piece with suitable jigs and fixture so that there is no lateral movement of the work piece.
• An end hole is left as the tool is withdrawn from the work piece.
• Moderate welding speed compared with some fusion welding processes.
• Its application is limited to certain type of joints eg. lap and butt joints.
• Its capital cost is high.
• Its application is limited to some classes of material due to tool limitations eg. it is hard to join material like super alloys.

During the welding process, frictional heat associated with the thermal cycle varies in the transverse direction of the weld. The maximum temperature is observed in the FSW zone, which causes an alteration in the precipitate distribution present in the base material and also due to stirring of the plasticized material. These changes in the heat and temperature distribution in the welding process alter the strength and ductility of the joints [9]. Though FSW joints yield better joint efficiency compared to fusion welding processes, the gap between strength values of the base metal and weld metal is considerably large.
1.2 Micro structural zones in FSW

The weld obtained in FSW process is generally fine grained, hot worked with no entrapped oxides or gas porosity. The first attempt on classifying the microstructures of friction stir weld was made by Threadgill [10-11] for aluminum alloys. The complete weld and its surrounding area as obtained by FSW can be classified in four distinct regions (figure 1.3) as:

A. Unaffected or parent material
B. Heat affected zone (HAZ)
C. Thermo-mechanically affected zone (TMAZ)
D. Weld nugget or Stir zone (WN or SZ)

Figure 1.3 Schematic drawing showing micro structural zones in a friction stir weld

A. Unaffected or parent material: This zone is remote from the weld zone, which is not deformed, and which although may have experienced a thermal cycle due to the conductive dissipation of heat from the weld zone, is not affected by heat in terms of microstructure or mechanical properties since the magnitude of temperatures experienced are sufficiently lower.

B. Heat affected zone (HAZ): This zone lies closer to the weld centre. The material in this zone experiences a thermal cycle than can modify the microstructure or mechanical properties. However, no plastic deformation occurs in this area. Metallurgical modifications in this zone are similar to those occurring during traditional fusion welding processes.

C. Thermo-mechanically affected zone (TMAZ): It corresponds to a region where mechanical properties are modified by the friction heat and intense deformations caused by the rotational and
translational motion of the tool. A distinct boundary typically exists between 
the recrystallized (weld zone) and the deformed zones of TMAZ.

D. Weld nugget or stir zone (WN or SZ): The zone directly 
below the tool shoulder and in the closest proximity to the friction stir welding 
tool is subjected to large plastic deformation and also high peak temperature 
resulting in dynamic recrystallization. In this zone the original grain 
boundaries appear to be replaced with fine, equiaxed recrystallized grains. This 
zone is referred as SZ.

1.3 FSW variables

FSW involves complex material movement and plastic deformation. Tool 
geometry and weld parameters exert significant effect on the material flow pattern and 
temperature distribution, thereby influencing the micro structural evolution of material.

1.3.1 Tool geometry

The tool geometry plays a critical role in material flow and in turn governs the 
traverse rate at which FSW can be conducted. An FSW tool consists of a shoulder and 
pin as shown in figure 1.4.

Figure 1.4. Schematic drawing of the FSW tool
(i) **Tool shoulder:** The function of the tool shoulder is to provide heat by application of a large compressive force and tool rotation over the surface of the material being welded and to contain the softened, plasticized metal beneath it [10]. The compressive stress also minimizes the formation of voids or pores in the consolidated metal. In the case of welding thin sheets, almost all of the frictional heat is provided by the friction between the tool shoulder and the work piece.

(ii) **Tool pin or tool probe:** The function of the tool probe is to move the highly plasticized material from the front of the probe to the rear and also to move the material in a vertical direction. The latter movement of the plasticized material is achieved by the presence of threads or similar features on the tool probe. The probe also promotes dispersion of oxides or impurities present in the joint line [10]. As the thickness of the plate increases, the ratio of heat input from the shoulder to heat input from the probe decreases.

### 1.3.2 Recent developments in tool design

A variety of tool designs have been developed in order to improve the material flow and to reduce the required axial welding forces, which would ultimately lead to improved weld quality, reduced energy costs and increased utilization of the FSW process. Following are a few examples.

1. **The Skew-Stir FSW tool** [11] was developed at TWI in which the shoulder face is oblique to the axis of the tool probe but normal to the axis of the machine spindle. The probe is cut from one side to make it asymmetrical, which improves material flow. Use of this technique increases the proportion of the dynamic volume relative to the static volume of the weld. This ratio is significant in reducing void formation in the weld. Also, because a larger volume is stirred, this tool is better suited for FS processing. Figure 1.5 shows the principle of operation of a Skew-Stir™ tool.
2. The Whorl™ tool was developed at TWI [12, 13] and consists of a scoop-shaped shoulder with a tapered, frustum-shaped probe which has a helical ridge with side flats which auger plasticized material downwards. For enhancing material flow, it is preferred that the distance between each ridge is greater than the thickness of the ridge itself. Some variants of this tool have a progressively decreasing pitch. This tool enables welding of thick sectioned alloys (25 to 75mm) in a single pass, since it provides better frictional heating and material flow due to the design of the probe. Figure 1.6 shows variants of the Whorl™ tool.
3. The Triflute™ tool was recently developed at TWI. Like the Skew-Stir tool, the dynamic to static volume ratio is higher than that for a conventional tool (2.6:1 as opposed to 1:1). Investigations at TWI have shown that use of the Triflute tool gave a 100% increase in traverse rate and a 20% reduction in the axial force. Furthermore, the upper plate thinning (due to tool plunging required to achieve defect-free welds) was reduced by factor of 4 [14]. Figure 1.7 shows a design of this tool.

Figure 1.7 Design of a Triflute™ tool

1.4 Tool rotation and traverse speeds

There are two tool speeds to be considered in friction-stir welding; how fast the tool rotates and how quickly it traverses the interface. These two parameters have considerable importance and must be chosen with care to ensure a successful and efficient welding cycle. The relationship between the welding speeds and the heat input during welding is complex but, in general, it can be said that increasing the rotation speed or decreasing the traverse speed will result in a hotter weld. In order to produce a successful weld it is necessary that the material surrounding the tool is hot enough to enable the extensive plastic flow required and minimize the forces acting on the tool. If the material is too cool then voids or other flaws may be present in the stir zone and in extreme cases the tool may break.
At the other end of the scale excessively high heat input may be detrimental to the final properties of the weld. Theoretically, this could even result in defects due to the liquation of low-melting-point phases (similar to liquation cracking in fusion welds). These competing demands lead onto the concept of a 'processing window': the range of processing parameters that will produce a good quality weld. Within this window the resulting weld will have a sufficiently high heat input to ensure adequate material plasticity but not so high that the weld properties are excessively reduced.

1.5 Welding forces

During welding a number of forces will act on the tool. A downwards force is necessary to maintain the position of the tool at or below the material surface. In a milling machine the vertical position of the tool is preset and so the load will vary during welding. The traverse force acts parallel to the tool motion and is positive in the traverse direction. Since this force arises as a result of the resistance of the material to the motion of the tool it might be expected that this force will decrease as the temperature of the material around the tool is increased.

Torque is required to rotate the tool. It depends upon the downward force and the friction coefficient. The forces acting on the tool should be as low as possible so as to minimize wear and tear of the tool. If the forces acting on the tool are too low, it requires high heat input and low traverse speed. This is undesirable for productivity. Hence optimum force should be selected which yields good strength and productivity.

1.6 Onion rings in FSW

One of the first things that strike anyone looking at the cross-section of a friction stir weld is probably the onion rings. A picture of the onion rings in the cross-section of a FSW is shown in Fig. 1.8 [15].

The appearance of onion rings has been attributed to a geometrical effect in that a section through a stack of semi-cylinders would appear like onion rings with ring spacing being wider at the center and narrower towards the edge. The formation of the onion rings is due to the rotation of the tool and the forward movement of the tool that extrudes the metal around to the retreating side of the tool. The spacing of the rings is equal to the forward movement of the tool in one direction [15].
1.7 Welding of aluminum and aluminum alloys

In general welding of aluminum is difficult as compared to welding of steel. Aluminum has several chemical and physical properties that need to be understood. The specific properties that affect welding are its oxide characteristics, solubility of hydrogen in molten aluminum, its thermal and electrical characteristics, its lack of colour change when heated, and wide range of mechanical properties and melting temperature that result from alloying with other materials [16].

Aluminum is the most abundant metal in nature. Many rocks and minerals contain a significant amount of aluminum. Unfortunately, aluminum does not occur in nature in the metallic form. The ore from which most aluminum is presently extracted, bauxite, is a hydrated aluminum oxide. Aluminum oxide should be cleaned from the surface prior to welding. Aluminum is the most difficult metal to weld. It comes in heat treatable and non heat treatable alloys. Heat treatable aluminum alloys get their strength from a process called ageing.
1.7.1 Characteristics of aluminum

The physical and chemical characteristics of aluminum, contrasted with those of steel, e.g. melting point. The oxides of iron all melt close or below the melting point of the metal; Aluminum oxide melts at 2060°C, some 1400°C above the melting point of aluminum). Other characteristics of aluminum are durability, (the oxide film on aluminum is durable, highly tenacious and self-healing. This gives the aluminum alloys excellent corrosion resistance, thermal expansion (the coefficient of thermal expansion of aluminum is approximately twice that of steel), thermal conductivity (the coefficient of thermal conductivity of aluminum is six times that of steel). The specific heat of aluminum is twice that of steel, electrical conductivity of aluminum is high, only three-quarters that of copper but six times that of steel.

Some of these properties are discussed in brief in the subsequent sections:

1.7.1.1 Aluminum oxide

Aluminum oxidizes immediately when exposed to air. Moisture in ambient atmosphere increases thickness of oxide. In case of arc welding, aluminum oxide can act as an insulator and can prevent arc initiation if it is thick enough. In case of arc welding, the ground is usually provided to the work piece and not on the worktable, as oxide present on the surface may act as an insulator and cause arcing. Also in case of GMAW, the oxide present on the filler wire may act as an insulator and cause arcing at the electrode and GMAW contact. The oxide melts at 2050°C, which is much higher, that melting point of aluminum, so it cannot be removed by melting [16]. So if the oxide layer is not removed it leads to incomplete fusion.

1.7.1.2 Hydrogen solubility

Hydrogen dissolves very rapidly in molten aluminum, and is almost insoluble in solid aluminum. Hence, the initially dissolved hydrogen, that exceeds the effective solubility limit on cooling, forms gas porosity, if it does not escape from solidifying weld [16]. Sources of hydrogen are lubricant on base metal, moisture etc.
1.7.1.3 Thermal characteristics

Even though the melting point of aluminum is lower than that of steel, it requires higher heat input as aluminum has a higher value of specific heat [16]. Thermal conductivity of aluminum is six times higher than that of steel [16]. High thermal conductivity makes aluminum very sensitive to fluctuation in heat input by welding process and causes variations in penetration and fusion. Thermal expansion of aluminum is about twice that of steel, and aluminum welds shrink by about 6% by volume during solidification [16]. Hence they are prone to solidification cracking.

1.8 Aluminum alloy designation – wrought alloys

Pure aluminum is readily alloyed with many other metals to produce a wide range of mechanical properties. This means by alloying elements aluminum alloys are classified into two categories: non heat treatable and heat treatable.

1. First digit – principal alloying constituent(s)
2. Second digit – variations of initial alloy
3. Third and fourth digits – individual alloy variations

- 1xxx – Pure Al (99.00% or greater), 2xxx – Al-Cu alloys, 3xxx – Al-Mn alloys,
- 4xxx – Al-Si alloys, 5xxx – Al-Mg alloys, 6xxx – Al-Mg-Si alloys, 7xxx – Al-Zn alloys,
- 8xxx – Al + other elements, 9xxx – Unused series.

1xxx series alloys: This series is referred as pure aluminum series because it is required to have minimum 99% aluminum. They are non heat treatable and weldable. When considered for fabrication, these alloys are selected mainly for superior corrosion resistance such as in specialized chemical tanks and piping or for their excellent electric conductivity as in bus bar applications. These alloys have relatively poor mechanical properties and are seldom used for structural applications. These alloys are welded with matching filler material. Examples are 1050, 1100, 1200, 1350 etc.

2xxx series alloys: These are heat treatable and major alloying element is copper (with copper additions ranging from 0.7 to 6.8%). They are high strength, high performance alloys and are often used for aircraft applications. These alloys have susceptibility to hot cracking. The base materials are welded with 2xxx series filler
material alloys, but sometimes can be welded with 4xxx series fillers containing silicon or silicon and copper. Examples are 2024, 2219, 2618 etc.

3xxx series alloys: These are non heat treatable alloys containing manganese as the major alloying element (manganese additions ranging from 0.05 to 1.8 %) and are of moderate strength having good corrosion resistance. They are in heat exchangers in vehicles and power plants. These base alloys are welded with 1xxx, 4xxx and 5xxx filler alloys. Examples are 3003, 3104, 3105 etc.

4xxx series alloys: These are the only series which contain both heat treatable and non-heat treatable with silicon as the major alloying element (silicon additions ranging from 0.6 to 21.5 %). Silicon when added to aluminum reduces its melting point and improves its fluidity when molten. This characteristits is desirable for filler materials. Hence this alloys is used as filler material. Examples are 4045, 4032 etc.

5xxx series alloys: These are non heat treatable alloys with magnesium as the major alloying element ( magnesium additions ranging from 0.2 to 6.2 %) and have highest strength among non heat treatable alloys. Alloy of this series is readily weldable and hence used for wide range of applications like ship building, transportation, pressure vessels, bridges and buildings. The base alloys with less than 2.5 % magnesium are welded with 5xxx or 4xxx series filler alloys and which contain higher amounts of magnesium are only welded with 5xxx series fillers. Examples are 5005, 5454, 5083, 5182 etc.

6xxx series alloys: These are heat treatable alloys with magnesium and silicon as the major alloying element (magnesium and silicon additions of around 1 %). The addition of magnesium and silicon to aluminum produces a compound of magnesium silicide, which provides the material its ability to become solution heat treated for improved strength. They are used in structural applications. They have moderate tensile strength and are less strong than 2xxx and 7xxx alloys. The addition of adequate amount of filler material during the arc welding process is required in order to provide dilution of the base material, thereby preventing hot cracking problem. They are welded with 4xxx and 5xxx filler materials. Examples are 6061, 6063, 6151 etc.
**7xxx series alloys**: These are heat treatable alloys containing zinc as the major alloying element (zinc additions ranging from 0.8 to 12%). It is the highest strength aluminum alloy. They are used in high performance applications such as aircraft and competitive sporting equipments. They are weldable with 5xxx series alloys. Examples are 7075, 7475 etc.

**8xxx series alloys**: These are non heat treatable alloys containing lithium and other elements. They are used in building wire and service cables as ACM alloy. ACM stands for aluminum conductor material.

### 1.9 Problems encountered during welding of heat-treatable aluminum alloys

The problems encountered during welding of heat-treatable aluminum alloys in general and Al-6061 in particular are discussed below in brief.

#### 1.9.1 Crack-sensitivity during welding

Heat treatable alloys are prone to cracking during welding to such an extent that the weldability of these alloys is defined as their resistance to weld cracking. The two types of cracking occurring during welding are 'solidification cracking' and 'liquation cracking' as explained below:

**a. Solidification cracking**

Solidification cracking occurs when high levels of thermal stress and solidification shrinkage are present while the weld pool is undergoing solidification. High heat input contributes to solidification cracking. The percentage of alloying constituents present in the alloy dictates the solidification crack sensitivity [16]. Al-6061 has relatively high solidification crack sensitivity [16].

**b. Liquation cracking**

An important element of the heat affected zone for precipitation-hardenable alloys is the thin boundary layer adjacent to the fusion zone that is referred to as the partially melted region. This region is produced when eutectic phases or constituents that have low melting points (melting points below the melting point of bulk material) liquate of melt, at grain boundaries during welding. It occurs in precipitation hardenable alloys.
because of relatively large amount alloying additions available to form eutectic phases. During welding these phases liquate and tears may accompany if sufficient stress is present. Under extreme conditions, continuous cracks may be formed along the fusion zone interface [16]. As expected, higher heat input widens the partially melted region and makes it prone to cracking.

1.9.2 HAZ degradation

The other problem associated with the welding of heat treatable alloys in the degradation of the HAZ. There is sudden decrease in hardness in the HAZ region as compared with the fusion zone and the unaffected base metal zone during welding of Al-6061-T6 alloy [16]. This happens due to transformation of the strengthening precipitates to the non-strengthening precipitates [16]. This transformation is nothing but over aging of the HAZ and proceeds at a greater rate when temperatures are between 290°C and 425°C [16]. The same temperature range is experienced by the HAZ during welding. At higher temperatures, close to the fusion zone, the particles are dissolved into the solid solution and upon cooling precipitate as strengthening precipitates. Hence the fusion zone has higher hardness value as compared to the HAZ [16]. Post weld heat treatment to convert the non-strengthening precipitates to the strengthening precipitates in the HAZ, increases the hardness value in the HAZ. But during this the base metal and the fusion zone undergoes over aging and the hardness value in these regions drop as compared to the as-welded condition [16].

As seen above the main problems in welding of aluminum alloys in general is melting of the metal, high heat input to the metal during welding, and the stubborn nature of aluminum oxide. All these problems are eliminated to some extent during friction stir welding of aluminum alloys. This is due to absence of melting of metal, lesser heat input during welding, easy removal of oxide by mechanical means. Hence FSW can be considered as a promising welding process to weld aluminum and aluminum alloys.

1.10 Applications of the process

FSW has been used for the manufacture of butt welds, overlap welds, T-sections, fillet and corner welds. Since gravity has no influence on the solid phase welding process,
it can be used in horizontal, vertical, overhead and orbital configurations. Applications of FSW are summarized as follows [17]:

**Shipbuilding and marine industries:**

The process is suitable for joining panels for decks and floors, aluminum extrusions, hulls and superstructures, helicopter platforms, offshore accommodation, marine and transport structures, masts and booms for sailing boats etc.

**Aerospace industry**

Most of the aircraft parts are welded by friction stir welding. It results in reduced manufacturing costs and weight savings and is superior compared to riveting. Aluminum alloy fuel tanks are usually friction stir welded. The size of commercially available sheets can be increased by FSW before forming, therefore this process can be used for welding wings, fuselages, cryogenic tank for space vehicles, aviation fuel tanks, for military rockets etc.

**Railway industry**

Applications of FSW in railway industries include welding of container bodies, goods wagons, underground carriages and trams.

**Land transportation**

FSW is currently used by many automotive companies for various applications that include welding of engine chassis, wheel rims, truck bodies, tail lifts for trucks, mobile cranes, body frames, fuel tankers etc.

**Construction industry**

Portable FSW equipments can be used for welding aluminum bridges, window frames, aluminum pipelines, aluminum reactors for power plants, heat exchangers, air conditioners and pipe fabrication.

**Electrical industry**

FSW is used for welding of electric motor housing, bus bars, electric connectors etc.
Other industry sectors

FSW can also be used for refrigeration panels, cooking equipments, white goods, gas tanks and gas cylinders, connecting of aluminum or copper coils in rolling mills and various furniture.

1.11 Motivation and dissertation objectives

Light weight components are of crucial interest for all industries producing moving masses especially aerospace, automobile and ship building industries. The aim of reducing weight is closely followed by high production efficiency and component manufacture. FSW is a relatively new and promising welding process that can produce low cost and high quality joints. It has opened up the horizon to seamless joints in metals that are impossible or difficult to join by conventional welding methods. The motivation behind choosing 6061 T6 AA is that, it is of moderate strength and possesses excellent welding characteristics over high strength aluminum alloys. Hence alloys of this class are extensively employed in marine frames, pipe lines, storage tanks and aircraft applications [18]. It has good resistance to corrosion and better stiffness to weight ratio (ratio of elastic modulus to density) and strength to weight ratio than most other structural metals.

Ever since its invention, FSW has been most extensively studied and applied for welding of aluminum alloys as well as other lightweight metals. However, modeling efforts of the process have been limited, mostly because of many unknown factors involved with the process modeling of FSW. Such modeling of heat transfer can aid in the proper selection of different process parameters for optimum weldments. Modeling of the process can play a key role in accelerating process development and reducing experimental costs. There are many applications in which dissimilar metal joining between aluminum and its alloys, aluminum with copper are used, which is difficult to join by fusion welding methods. Optimum selection of weld parameters increases the tensile strength of the joint and makes the process commercially viable. These considerations provide motivation towards the current study.
The specific objectives of the present work are:

(i) To understand the mechanism of heat transfer in friction welding through experimental study and numerical heat transfer analysis.

(ii) To study the feasibility of joining aluminum to copper, pure aluminum 1100 to 6061 AA and pure Cu to pure Cu by studying the mechanical properties.

(iii) Measure and analyze the forces during FSW process.

(iv) To compare FSW process with conventional tungsten inert gas (TIG) welding process.

(v) To obtain optimum process parameters for FSW of 6061 T6 AA using Taguchi L9 orthogonal design method.

1.12 Methodology

To understand the fundamental mechanism of friction stir welding process through experimental and numerical heat transfer analysis, a series of FSW experiments were conducted for 6061 AA with on-line monitoring of temperatures at number of points close to the weld interfaces. A three dimensional heat transfer model using finite element software ANSYS is developed and experimentally validated to quantify the thermal history. The force exerted by tool on work piece in x, y and z direction was measured by digital milling tool dynamometer. Feasibility of joining Cu with 6061 AA was studied by shifting the tool centre line towards copper side. Mechanical properties for joining of Cu-Cu, Cu-6061 AA, 6061 AA- 6061 AA and 6061 AA-pure aluminum 1100 were studied by finding out the micro hardness and tensile strength. A comparative study of FSW with conventional TIG welding process was also studied using optical microscopy and finding mechanical properties. Finally optimum condition which yields maximum tensile strength was carried out experimentally using Taguchi L9 orthogonal design.

1.13 Layout of thesis

The present thesis is organized into six chapters. The first chapter gives a brief introduction of friction stir welding process, motivation and objectives of the work. Second chapter presents a detailed literature survey towards experimental and theoretical
studies reported so far on friction stir welding process leading to the basis of the present research. Third chapter presents the experimental work carried out for temperature measurements, comparative study of FSW and TIG welding, FSW of similar and dissimilar welds of 6061 AA-6061 AA, 6061 AA- pure 1100 Al and 6061 AA- pure Cu, forces measured during FSW and optimum selection of weld parameters using Taguchi L9 orthogonal design. Fourth chapter presents a numerical study of three dimensional heat transfer model. In the fifth chapter results and discussion is presented. Finally in sixth chapter the work presented in previous chapters is concluded and scope for further work is suggested to make the study complete.