FRICTION STIR WELDING OF DISSIMILAR METAL

SUJANURIAH BT SAHIDI

A project report submitted in partial fulfilment of the requirement for the award of the Degree of Master of Manufacturing

Faculty of Mechanical and Manufacturing Engineering Universiti Tun Hussein Onn Malaysia

JUNE 2013

ABSTRACT

Friction Stir Welding is a solid – state thermo – mechanical joining process (a combination of extruding and forging). Joining of steels to aluminium alloys can be used for producing steel/aluminium bimetallic parts in a wide range of industrial areas. The overall aim of this study is to get the optimum parameters for the materials under considerations, to investigate the Heated Affected Zone (HAZ), Thermo – Mechanical Affected Zone (TMAZ) and Weld Nugget (WN) besides to study the defects occurring during welding process by applying different parameters chosen. The welding process was done by using conventional milling machine. Three experiments being used are the Tensile Testing, Optical Microscopy (OM) and Electron Scanning Microscopy (SEM) to get the strength of the joint and the metallographic studies. The findings also found out that suitable parameters being choose give less defect and intermetallic compounds (IMCs). Therefore, at higher speed and lower tool plunge length, the joint strength decreased due to lack of bonding between aluminium and steel.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Joining of steels to aluminium alloys can be used for producing steel/aluminium bimetallic parts in a wide range of industrial areas. (Movahedi, et al.,2013). According to Elrefaey, et al., (2005), the friction stir butt and lap welding of steels to various aluminium alloys have been studied. However, it is difficult to obtain a sound steel to aluminum joint by using the conventional fusion welding processes due to the large difference between the melting points of steel and aluminum alloys and also the formation of thick brittle Al/Fe intermetallic compounds at the joint interface. Based on Taban, et al., (2010), joining of aluminium to steel is generally difficult due to differences between their physical and chemical properties. Both alloys have incomparable melting point, thermal conductivity, coefficient of linear expansion and heat capacity. Compared to the fusion processes, low-heat generation during solid state welding makes it a highly potential approach for aluminum to steel joining.

Friction Stir Welding is a solid-state thermo-mechanical joining process (a combination of extruding and forging), invented by The Welding Institute (TWI) in

1991, that has become a viable manufacturing technology of metallic sheet and plate materials for applications in various industries, including plate materials for applications in various industries, including aerospace, automobile, defense and shipbuilding.

According to Thomas WM, et al. (1991) Friction Stir Welding (FSW) is a relatively new technique developed by The Welding Institute (TWI) for the joining of Aluminium alloys.

Friction Stir Welding (FSW) process is relatively a new joining process that is presently attracting considerable interest. FSW is emerging as an appropriate alternative technology with high efficiency due to high-processing speeds. Since the joint can be obtained below the melting temperature, this method is suitable for joining a number of materials those are extremely difficult to be welded by conventional fusion techniques. (Gene M., 2002). The process is solidstate in nature and relies on the localized forging of the weld zone to produce the joint.

FSW produces welds by using a rotating, non-consumable welding tool to locally soften a workpiece, through heat produced by friction and plastic work, thereby allowing the tool to “stir” the joint surfaces. (Lohwasser and Chen, 2010). In this welding process, a rotating welding tool is driven into the material at the interface of, for example, two adjoining plates, and then translated along the interface. FSW offers ease of handling, precise external process control and high levels of repeatability, thus creating very homogenous welds. No special preparation of the sample is required and little waste or pollution is created during the welding process. Furthermore, its applicability to aluminium alloys, in particular dissimilar alloys or those considered “unweldable” by conventional welding techniques, such as tungsten inert gas (TIG) welding, make it as an attractive method for the transportation sector. The friction stir process involves the translation of a rotating cylindrical tool along the interface between two plates. Friction heats the material which is then essentially extruded around the tool before being forged by the large down pressure. The weld is formed by the deformation of the material at temperatures below the melting temperature. The simultaneous rotational and translational motion of the welding tool during the welding process creates a characteristics asymmetry between the adjoining sides. On one side, where the tool rotation is with the direction of the translation of the welding tool one peaks of the advancing side (AS), whereas on the other hand, the two motions, rotation and translation counteract and one speaks of the retreating side (RS) (M. Steuwer A, M. Withers PJ, 2003).

According to Bhadeshia and Debroy (2009), the level of activity in research on the friction stir welding of steels is dwarfed when compared with that on aluminium alloys. The relative weakness of aluminium makes it ideally suited for the process which requires, at high strain rates, the permanent flow and mixing material without melting. It is apparent that the torment that an FSW tool would have to go through in the case of steel would be much greater than that for aluminium unless temperatures are achieved in excess of some 800 ºC; the steel must be sufficiently plasticized to permit the material flow to enable a sound weld to be fabricated.

In recent years, numerical modeling of FSW has provided significant insight about the heat generation patterns, materials flow fields, temperature profiles, residual stress and distortion, and certain aspects of tool design. The development of new welding tool materials and geometries has made it oossible to join materials such as steel and titanium in the laboratory environment and in a limited number of production applications. In FSW, of steel it has been shown that the lower welding temperature can lead to very low distortion and unique joint properties. FSW of steel is an area of active research, so it is reasonable to expect other production applications to emerge over time. A very attractive application is FSW of steel plate for shipbuilding applications, based primarily on the reduction of welding distortion, but the development of low-cost welding equipment and more robust welding tool materials is required before this application can be exploited.

Buffa and Fratini (2009), have applied the method of applying the role of tool geometry to steels, with validating consisting of a comparison of the far field thermal profiles against published experimental data on the austenitic stainless steel.

1.2 Objectives

For this research, the objectives that are tried to achieve by the researcher are:

1. To get optimum parameters for the materials under considerations i.e. alloy steel and Austenitic Stainless Steel
2. To investigate the Heated Affected Zone (HAZ) and Thermo-Mechanical Affected Zone (TMAZ)
3. Defects occurring during the welding process

1.3 Scope of Study

The focus of the research work will be concentrated in the mechanical performance and the stir zone microstructure by FSW lap and butt welded part having 100mm × 100mm × 3mm thick sheet Aluminium (A6061) and 100mm × 100mm × 3mm thick sheet Austenitic Stainless Steel using different pin diameters. All the testing of welded part will be tested by ASTM standard. Different pin diameters tool will used to conduct experiments.

In this research, Universal Testing Machine (UTM), Optical Microscope (OM) to get the microstructure properties and Scanning Electron Microscope (SEM) will also be used to measure HAZ and TMAZ zone.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Friction stir welding (FSW) is a relatively new solid-state joining process. This joining technique is energy efficient, environment friendly and versatile. In particular, it can be used to join high-strength aerospace aluminum alloys and other metallic alloys that are hard to weld by conventional fusion welding.

FSW is considered to be the most significant development in metal joining in a decade. Recently, friction stir processing (FSP) was developed for microstructural modification of metallic materials.

Due to high corrosion resistance and exceptional mechanical properties and the reference phase diagram of Al-Fe systems, Baker (1993) states that the low solubility of iron in aluminium promotes the formation of brittle intermetallic compounds (IMCs) such as Fe_2Al_5, $FeAl_3$ and FeAl, in the weld zone. Therefore, it seems that obtaining strong joint between aluminium and steel sounds impossible or very difficult by using common fusion welding techniques. Different techniques such as diffusion welding and friction welding have been used to join aluminium to steel. Based on the research done, it is proven that at low melting speeds due to the formation of thick IMCs (which was characterized as Al_6Fe and Al_5Fe_2) in the weld zone the tensile strength of joints was very poor. Even at low welding speeds the tunnel defect was formed. At higher welding speed and lower tool plunge depth, the joint strength decreased due to lack of bonding between aluminium and steel.

According to Mishra and Ma (2005), particular emphasis has been given to (a) mechanisms responsible for the formation of welds and microstructural refinement and (b) effects of FSW/FSP parameters on resultant microstructure and final mechanical properties have been studied. The technology diffusion has significantly outpaced the fundamental understanding of microstructural evolution and microstructure-property relationships between metals and alloys. Moreover, the use of lightweight metals (for example, Al alloy) as the structural components to replace the heavier steel alloy in automotive have been thought to be a promising approach. (Sun,et al., 2013)

2.2 Friction Stir Welding

Friction Stir Welding (FSW) is considered to be the most significant development in metal joining in a decade and is a “green” technology due to its energy efficiency, environment friendliness and versatility (Mishra and Ma, 2005). As compared to the conventional welding methods, FSW consumes considerably less energy. No cover gas or flux is used, thereby making the process environmentally friendly.

The joining, does not involve any use of filler metal and therefore any aluminum alloy can be joined without concern for the compatibility of composition, which is an issue in fusion welding. When desirable, dissimilar aluminum alloys and composites can be joined with equal ease.

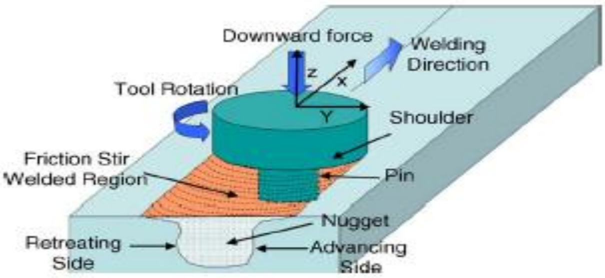


Figure 2.1: Schematic diagram of friction stir welding

In contrast to the traditional friction welding, which is usually performed on small axisymmetric parts that can be rotated and pushed against each other to form a joint, FSW can be applied to various types of joints like butt joints, lap joints, T butt joints and fillet joints. The key benefits of FSW are summarized in Table 2.1.

Table 2.1: Key benefits of friction stir welding (Mishra and Ma, 2005)

<table>
<tr><th>Metallurgical benefits</th><th>Environmental benefits</th><th>Energy benefits</th></tr>
<tr><td>Solid phase process</td><td>No shielding gas required</td><td>Improved materials use (e.g., joining different thickness) allows reduction in weight</td></tr>
<tr><td>Low distortion of workpiece</td><td>No surface cleaning required</td><td>Only 2.5% of the energy needed for a laser weld</td></tr>
<tr><td>Good dimensional stability and repeatability</td><td>Eliminate grinding wastes</td><td rowspan="6">Decrease fuel consumption in light weight aircraft, automotive and ship applications</td></tr>
<tr><td>No loss of alloying elements</td><td>Eliminate solvents required for degreasing</td></tr>
<tr><td>Excellent metallurgical properties in the joint area</td><td rowspan="4">Consumable materials saving such as rugs, wire or any other gases</td></tr>
<tr><td>Fine microstructure</td></tr>
<tr><td>Absence of cracking</td></tr>
<tr><td>Replace multiple parts joined by fasteners</td></tr>
</table>

Before the invention of FSW, there had been some important technological developments of non – fusion welding processes, which have found some limited industrial uses. A significant process of these is friction welding developed at the time just before laser was invented. During friction welding, the pieces to be welded are compressed together and are made to more relative to each other. Thus frictional heat is generated to soften the material in the joining region. The final step is made by applying increased pressure to the softened material to yield a metallurgical joint without melting the joining material. However, the relative movement during the stage of heat generation and material softening can practically only be rotational or linear. Although friction welding operation is simple, the welding geometry is quite restricted and thus its use is also limited.

For solid state welding, the thermomechanical principle of friction welding had actually laid an important base for the later invention of FSW. The Welding Institute (TWI) in the UK had for years engaged in various R&D and industrial activities of friction welding and surfacing. Wayne Thomas and his colleagues in TWI had long worked on and developed friction extrusion, friction hydropillar processing and third-body friction joining processes.

To date it is with aluminium alloys that FSW is most successfully applied. The reason for the predominant use of FSW on aluminium alloys is a combination of process simplicity in principle and the wide use of aluminium alloys in many major industries. It is especially the case where some aluminium alloys are difficult to fusion weld as, for example, is clearly evident in FSW application made by Boeing for making the Delta 2 rocket tanks. FSW allowed them to dramatically reduce their defect rate to nearly zero. Maximum temperature during FSW can reach just below the solidus of the workpiece alloy. For most aluminium alloys, it is significantly less than 660 ºC. Thus, H13 tool steel or high-speed tool steel, which is quite inexpensive, is a satisfactory tool material. Thus, FSW of aluminium alloys is relatively straightforward, although FS engineering, particularly for components and structures of high geometry complexity, can be quite challenging.

According to Ghosh et al.(2011), friction stir welded advanced high strength steel (AHSS) joints are scanty. However, FSW and friction spot stir welding (FSSW) allow the possibility of joining advanced high strength steels and reduce problems associated with resistance spot welding (RSW). In principle, FSW could be applied for welding of all solid metallic materials. During FSW of steels, the local operating temperature generated by both friction and deformation needs to be at 1100 ºC – 1200 ºC so that the workpiece material is sufficiently plasticized for stirring and welding. Such high operating temperatures and the necessary forces acting on the tool during FSW create an extraordinary demand on the mechanical properties of the tool material.

2.3 Friction Stir Welding (FSW) Process Principles

Friction stir welding (FSW) produces welds by using a rotating, non-consumable welding tool to locally soften a workpiece, through heat produced by friction and plastic work, thereby allowing the tool to "stir" the joint surfaces. The dependence on friction and plastic work for the heat source precludes significant melting in the workpiece, avoiding many of the difficulties arising from a change in state, such as changes in gas solubility and volumetric changes, which often plague fusion welding processes. Further, the reduced welding temperature makes possible dramatically lower distortion and residual stresses, enabling improved fatigue performance, new construction techniques, and making possible the welding of very thin and very thick materials.

FSW has also been shown to eliminate or dramatically reduce the formation of hazardous fumes and reduces energy consumption during welding, reducing the environmental impact of the joining process. FSW can be used in any orientation without regard to the influence of gravitational effects on the process. These distinctions from conventional arc welding processes make FSW a valuable new manufacturing process with undeniable, economic, and environmental benefits.

According to Najafabadi et al. (2010), FSW is an innovative solid state bonding technique. In early years, it was introduced for light alloys. Recently, high performance tools materials are employed for FSW of high melting temperature materials such as titanium, nickel and steels.

2.4 Comparison of friction stir welding (FSW) to other welding processes

Comparison of FSW to other welding processes is typically done within the context of justifying the use of the process over other, more conventional techniques. Successful application of FSW depends upon a clear misunderstanding of the characteristics of the process, so favourable technical and economic justification can be developed.

The unique, favourable characteristics of FSW compared to traditional arc welding methods provide several sources for technical justification for use of the process.

The main points for technical justification of FSW compared to arc welding processes are:

- Improved weldability
- Reduced distortion
- Reduced residual stress, improved fatigue, corrosion, and stress corrosion cracking performance
- Improved cosmetic performance
- Elimination of under matched filler metal
- Improved static strength and ductility
- Mechanized process
- High robustness, few process variables

2.4.1 Improved Weldability

According to Mishra and Ma (2005), a solid-state welding process patented by The Welding Institute (TWI), in 1991, is a potential candidate for the joining of dissimilar materials due to the lower processing temperature over conventional fusion welding. (Sato et al.,2004). This is especially the case in certain aluminium alloys.

Some aluminium alloys or material forms, such as castings, are difficult or impossible to weld by traditional arc welding processes due to problems with the formation of brittle phases and cracking. For these alloys, weldability alone may be sufficient to form a justification for the use of FSW over conventional arc welding or other joining techniques, such as mechanical fasteners. Further, FSW makes possible the joining of some dissimilar alloys, which can be of significant benefit in certain applications.

Besides, defect-free welds have now been made by FSW in the joining of different Al alloys (for example Al 2024/Al 7075) (Cavaliere et al., 2008), Al/steel (Lee et al., 2006), and Al/Mg (Kwon et al., 2008).

2.4.2 Reduced Distortion

The reduced peak temperature reached in FSW compared to arc welding processes also generally leads to reduced longitudinal and transverse distortion, although FSW weldments are certainly not free of residual stress. The balance if residual stress in FSW can result in essentially flat weldments in materials of virtually any practically weldable thickness, although this is affected by welding tool design, joint design, welding parameters and fixture design.

2.4.3 Improved fatigue, corrosion, and stress corrosion cracking performance

The reduced maximum temperature and residual stress can also lead to improved performance under cyclic loading conditions. Typically, joints produced by FSW have fatigue strength, but below base metal strength. FSW joints that are machined after welding have been shown to approach base metal fatigue strength. Based from the studied by D.M. Rodrigues et al. (2009), the base material is characterized by a recrystallized microstructure with equiaxed grains, with relatively uniform grain size.

According to P. Cavaliere et al. (2009), the studied friction stir welded joints offer the best fatigue performances only when optimal microstructure configurations are reached. With a revolutionary pitch in the range of 0.07-0.1, the process is in the optimal temperature and strain rates conditions to produce good microstructure quality without defects for butt joints and therefore sound welds are achieved. Based on the studied longitudinal residual stresses, the residual stresses values differences depend on the asymmetry of the FSW process, where higher deformation across the weld line are achieved.

2.4.4 Improved static strength and ductility

Even in cases where adequate filler metals are available, the higher temperature reached and limited material deposition rates in arc welding can degrade the HAZ sufficiently to reduce the joint strength compared to FSW. It is often the case in thin section aluminium alloys that the joint strength in arc welding and FSW are comparable. However, in thick materials, up to 75mm thick, the fact that FSW can be accomplished in a single pass can result in significantly improved joint strength and ductility. In some applications, this may be sufficient to justify the use of FSW over arc welding and mechanical fastening.

2.5 Welding Tools

Many of the advanced made in friction stir welding have been enabled by the development of new welding tools. The welding tool design, including both its geometry and the material from which it is made, is critical to the successful use of the process.

2.5.1 Tool Geometry

Welding tool geometry development led to the first sound welds made in aluminium alloys and this has led to higher weld production speeds, higher workpiece thickness, improved joint properties, new materials and new welding equipment.

According to Mishra and Ma (2005), tool geometry is the most influential aspect of process development. 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 a pin as shown schematically in Fig. 2.2 below. The tool has two primary functions: (a) localized heating, and (b) material flow. In the initial stage of tool plunge, the heating results primarily from the friction between pin and workpiece. Some additional heating are the results from deformation of the material. The tool is plunged till the shoulder touches the workpiece. The friction between the shoulder and workpiece results in the biggest component of heating. From the heating aspect, the relative size of pin and shoulder is important, and the other design features are not critical. The shoulder also provides confinement for the heated volume of material. The second function of the tool is to ‘stir’ and ‘move’ the material. The uniformity of microstructure and properties as well as process loads is governed by the tool design. Generally, a concave shoulder and threaded cylindrical pins are used.

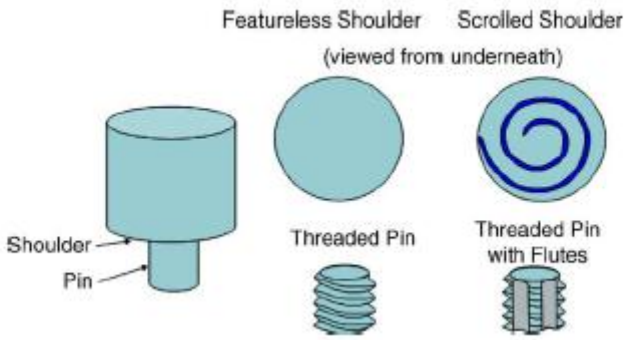


Figure 2.2: Schematic drawing of the FSW tool

With increasing experience and some improvement in understanding of material flow, the tool geometry has evolved significantly. Complex features have been added to alter material flow, mixing and reduce process loads. Thomas et al. (2001) suggested that the major factor determining the superiority of the whorl pins over the conventional cylindrical pins is the ratio of the swept volume during rotation to the volume of the pin itself, i.e., a ratio of the "dynamic volume to the static volume" that is important in providing an adequate flow path. Typically, this ratio for pins with similar root diameters and pin length is 1:1:1 for conventional cylindrical pin.

For lap welding, conventional cylindrical threaded pin resulted in excessive thinning of the top sheet, leading to significantly reduced bend properties. Furthermore, for lap welds, the width of the weld interface and the angle at which the notch meets the edge of the weld is also important for applications where fatigue is of main concern.

2.5.2 Welding Parameters

With the general principles of the effect of process variables on the friction stir welding process have much in common with other welding processes, the details are completely different, as one might expect. The main process variables in friction stir welding are listed in Table 2.2.

Table 2.2: Main FSW process variables

Tool design Variables	Machine Variables	Other Variables
Shoulder and pin materials	Welding speed	Anvil material
Shoulder diameter	Spindle speed	Anvil size
Pin diameter	Plunge force or depth	Workpiece size
Pin length		
Thread pitch	Tool tilt angle	Workpiece properties
Feature geometry		

These variables all act to determine the outcome of the welding process. The welding process affects these joint properties primarily through heat generation and dissipation, so primary attention should be given to the effect of the welding process variables on heat generation and related outcomes.

For FSW, two parameters are very important: tool rotation rate (ω, rpm) in clockwise or counterclockwise direction and tool traverse speed (v, mm/min) along the line of joint. The rotation of tool results in stirring and mixing of material around the rotating pin and the translation of tool moves the stirred material from the front to the back of the pin and finishes welding process. Higher tool rotation rates generate higher temperature because of higher friction heating and result in or intense stirring and mixing of material. However, it should be noted that frictional coupling of tool surface with workpiece is going to govern the heating. So, a monotonic increase in heating with increasing tool rotation rate is not expected as the coefficient of friction at interface will change with increasing tool rotation rate.

In addition to the tool rotation rate and traverse speed, another important process parameter is the angle of spindle or tool tilt with respect to the workpiece surface. A suitable tilt of the spindle towards trailing direction ensures that the shoulder of the tool holds the stirred material by threaded pin and move material efficiently from the front to the back of the pin. Further, the insertion depth of pin into the workpieces (also called target depth) is important for producing sound welds with smooth tool shoulders. The insertion depth of pin is associated with the pin height. When the insertion depth is too shallow, the shoulder of tool does not contact the original workpiece surface. Thus, rotating shoulder cannot move the stirred material efficiently from the front to the back of the pin, resulting in generation of welds with inner channel or surface groove. When the insertion depth is too deep, the shoulder of tool plunges into the workpiece creating excessive flash. It should be noted that the recent development of ‘scrolled’ tool shoulder allows FSW with 0 º tool tilt. Such tools are particularly preferred for curved joints.

Preheating or cooling can also be important for some specific FSW processes. For materials with high melting point such as steel and titanium or high conductivity such as copper, the heat produced by friction and stirring may be not sufficient to soften and plasticize the material around the rotating tool. Thus, it is difficult to produce continuous defect-free weld. In these cases, preheating or additional external heating source can help the material flow and increase the process window. On the other hand, materials with lower melting point such as aluminium and magnesium, cooling can be used to reduce extensive growth of recrystallized grains and dissolution of strengthening precipitates in and around the stirred zone.

2.5.3 Joint design

The most convenient joint configurations for FSW are butt and lap joints. A simple square butt joint is shown in Figure 2.3a. Two plates or sheets with same thickness are placed on a backing plate and clamped firmly to prevent the abutting joint faces from being forced apart. During the initial plunge of the tool, the forces are fairly large and extra care is required to ensure that plates in butt configuration do not separate.

A rotating tool is plunged into the joint line and traversed along this line when the shoulder of the tool is in intimate contact with the surface of the plates, producing a weld along abutting line. On the other hand, for a simple lap joint, two lapped plates or sheets are clamped on a backing plate. A rotating tool is vertically plunged through the upper plate and into the lower plate and traversed along desired direction, joining the two plates (Fig 2.3d). Many other configurations can be produced by combination of butt and lap joints. Apart from butt and lap joint configurations, other types of joint designs, such as fillet joints (Fig. 2.3g), are also possible as needed for some engineering applications.

It is important to note that no special preparation is needed for FSW of butt and lap joints. Two clean metal plates can be easily joined together in the form of butt or lap joints without any major concern about the surface conditions of the plates.

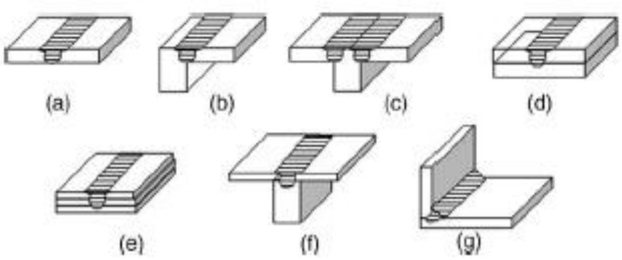


Figure 2.3: Joint configurations for friction stir welding: (a) square butt, (b) edge butt, (c) T butt joint, (d) lap joint, (e) multiple lap joint, (f) T lap joint, and (g) fillet joint

2.6 Joint Geometries

A variety of joint geometries are possible with FSW; however, there are certain limitations and requirements that are unique to the process.

In each of joint designs and fixture arrangements, it is necessary to:

- Provide sufficient area for the welding tool shoulder path
- Provide sufficient containment of softened weld metal
- Provide sufficient force to prevent motion of the workpieces

- Provide adequate heat sink to dissipate the heat of welding

The area required for the welding tool shoulder is a function of material thickness and alloy. For aluminium alloys, the area required for the shoulder is about three to five times the material thickness. Steel and titanium typically would require less shoulder area, since these materials have lower thermal conductivity and therefore require a smaller shoulder diameter.

2.7 FSW of dissimilar materials

According to Coelho et al. (2012), the use of light-weight materials for industrial applications is a driving force for the development of joining techniques. Friction Stir Welding (FSW) inspired joints of dissimilar materials because it does not involve bulk melting of the basic components. In the research by Coelho et al., two different grades of high strength steel (HSS), with different microstructures and strengths, were joined to AA6181-T4 alloy by FSW and the study has proved that the influence of the distinct HSS base material on the joint efficiency.

Dissimilar materials welding are an indispensible technique for many industrial sectors, offering the possibility to optimize the welded component performances with the different material properties for the local loads within a given parts. The melting phase absence allows joining dissimilar materials with the achievement of sound welds (Scialpi et al., 2008). Dissimilar fusion welding between Al alloy and steels is a challenge in welding control because of the large differences in melting temperature and physical and mechanical properties of the alloys involved. The process often results in complex weld poor shapes, inhomogeneous solidification microstructures and segregations in addition, the extremely low solubility of Fe in Al leads to the formation of brittle and excessive Al – rich Fe_xAl_y intermetallic phases which are detrimental for the mechanical properties of the joint.

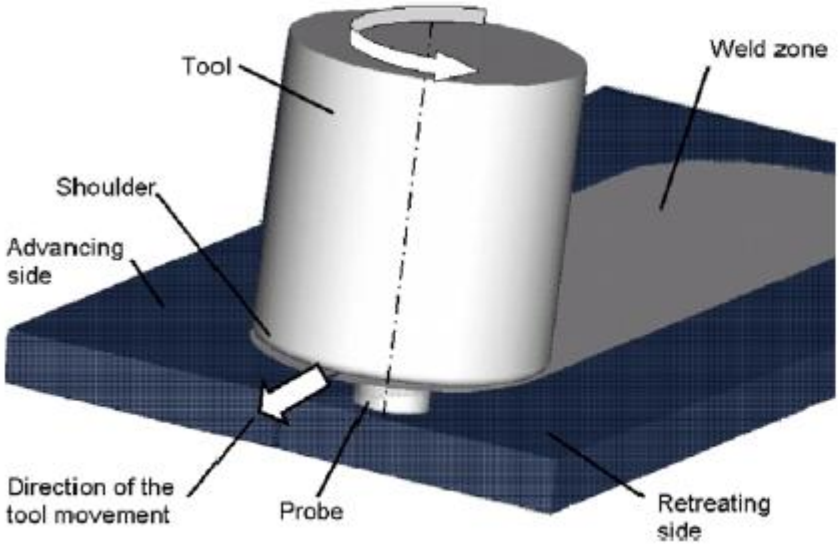


Figure 2.4: A schematic illustration of FSW butt-joint, the two sheets are transparently represented to show the probe

FSW is based on extreme plastic deformation in the solid-state where no associated bulk melting is involved. At early stages of the process development, FSW appears especially attractive for joining Al alloys and other light-weight materials like Mg alloys. This is connected with two main reasons:

1) The process prevents melting and solidification, minimizing residual stresses, cracking, porosity and loss volatile solutes;

2) The plastic deformation (stirring) of such light-weight materials (e.g. Al and Mg alloys) can be realized using relatively simple welding tools (e.g. made of tool steel)

The FSW of steels involved high temperatures; Ohashi et al.(2009), found the base dual phase steel to suffer contamination with Si, N and O when friction stir spot welding using a silicone nitride tool. The contamination with oxygen could be mitigated using an argon shroud, and that from the tool (Si,N) by coating the tool with TiC and TiN. According to Lee et al. (2009), a steel tool is used to make good joints between aluminium alloy sheet of 1mm thickness and underlying steel sheet. The tool does not have to be an exotic material because its penetration during friction stir spot welds did not exceed half the thickness of the aluminium. The underlying steel was never touched by the tool. Nevertheless, a mixed layer just 2 μm in thickness, formed at the aluminium/steel interface, with some intermetallic compound formation, resulting in a metallurgical bond between the dissimilar materials. Furthermore, shear tests demonstrated that with this configuration, it is possible to achieve properties similar to those when the steel is friction stir spot welded to itself.

CHAPTER 3

METHODOLOGY

3.1 Methodology

Proper planning should be taken by every individual in creating successful report writing. Before carrying on the report writing, studies must be performed related to the problem prevailing surrounding issues and create an idea to solve the problem. Besides that, irregular planning will create problem in producing the thesis report writing. Methodology method can be used as guidelines for every step in completing the thesis report writing. The report writing produced based on two main concepts. They are PRIME and 9P concepts.

The PRIME concepts require Problem, Research, Invention, Modification and Evaluation. Meanwhile, for 9P concept, they are Problems, Idea Development, Idea Selection, Material Selection, Prototype Development, Manufacture, Testing, Modification and Recording.

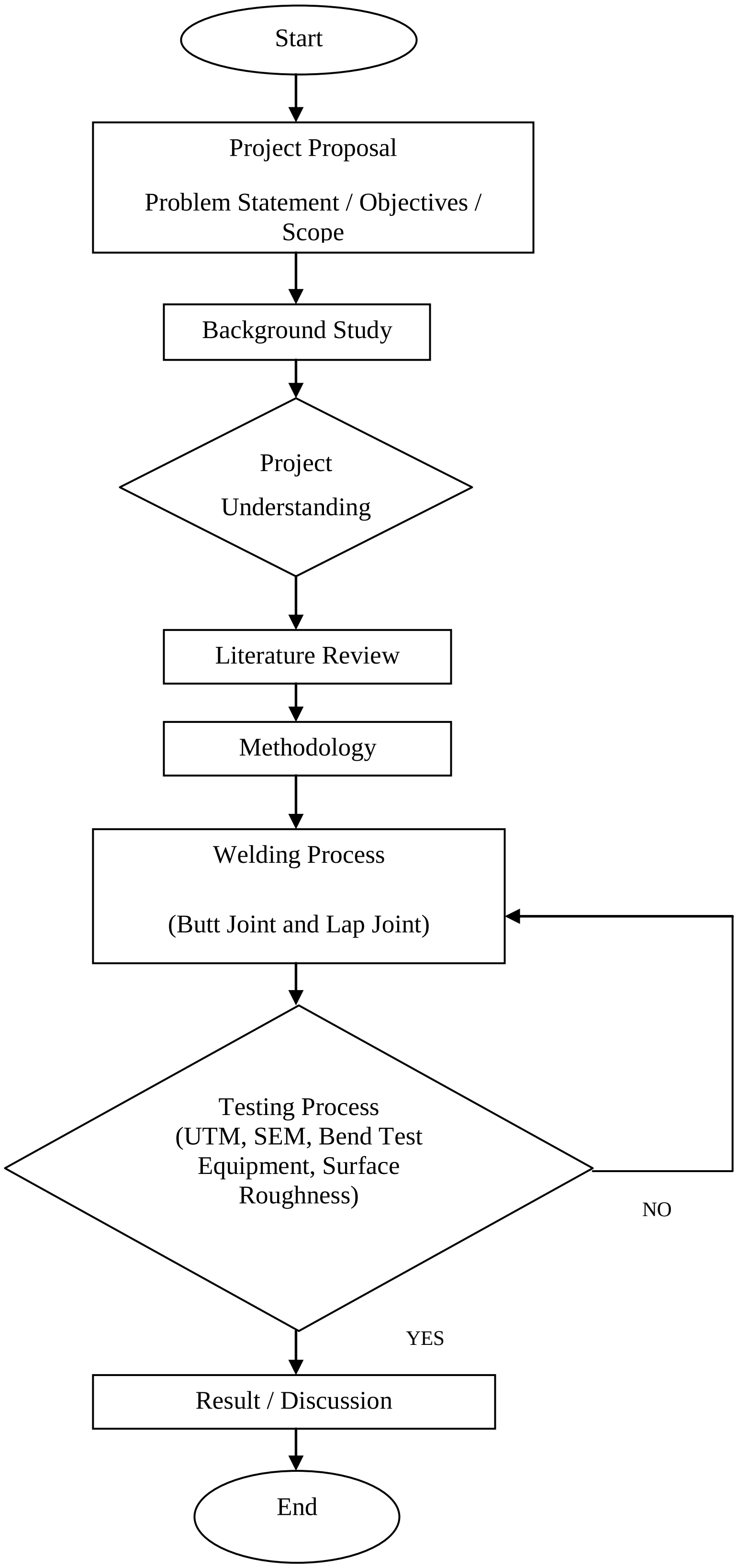
The study of methodology is a method to identify how the project from the early stages up to the final presentation. In this chapter, aspects of the report writing will be described greater depth and detail so that it will be easy to understand.

Identification of the problem is central in the production of report writing. Based on the identified problems, it is necessary to study methods to solve problems.

In the process of preparing the thesis report, researcher has carried out some of the rules and procedures for obtaining a good yield and quality. First of all, when selected the suitable title, the researcher have observed and examined the problems and materials that can used in this project. Once the problems have been identified, the researcher managed to get the problem statement, objectives, scope and categories of projects that will be produced later.

Then after carried out few literature reviews in order to get the basic view for the project, the selection of materials used for the project was identified and the testing equipment used in this research was identified. The selection of materials is not only seen in terms of cost, but also from the quality and durability of material when used on the project to be produced. With the provision of adequate materials and proper, the installation process on a project to produce to be going well soon.

3.2 The Flow Chart



3.3 Workpiece Material

Chosen materials for FSW technique are a commercial 6061 aluminium alloy and austenitic stainless steel 304 was used as starting material for friction stir welding technique. The chemical composition of work materials are listed in Table 3.1, 3.2 and 3.3

Table 3.1: Types of work material used in present study

No	Item	Specifications
1	Sheet metal A6061	100 mm (length) × 100 mm (width) × 3 mm (thick)
2	Sheet metal AISI 304	100 mm (length) × 100 mm (width) × 3 mm (thick)

Table 3.2: Nominal Chemical Composition of the Stainless Steel

Element	C	Cr	Ni	Mn	Si	P	S	Fe
wt (%)	<0.08	17.5 - 20	8-11	<2	<1	0.045	0.03	Balance

Table 3.3: Nominal Chemical Composition of 6061 Aluminium Alloy

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
wt (%)	0.59	0.38	0.26	0.03	0.96	0.25	0.02	0.04	Balance

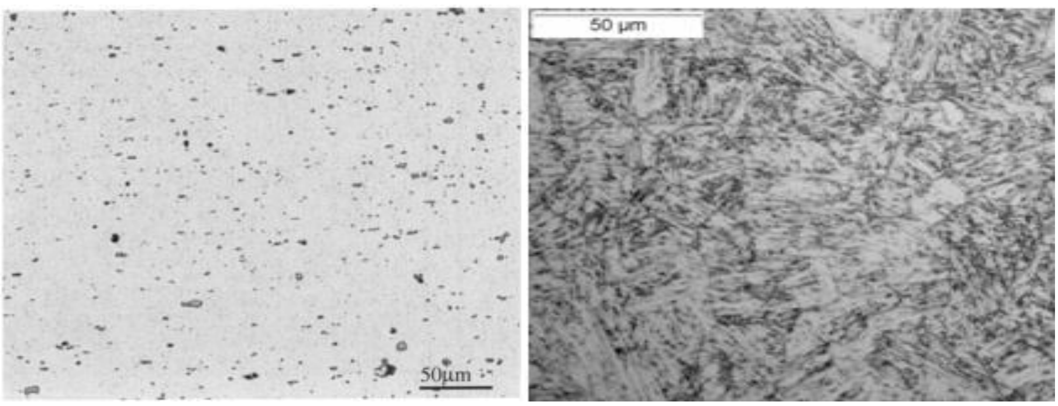


Figure 3.1: Micrographs of the microstructure of the (a) 6061 aluminium alloy and (b) AISI 304 stainless steel

REFERENCES

Movahedi M., et al. Effect of annealing treatment on joint strength of aluminum/steel friction stir lap weld. Material & Design 44 (2013) 487-492

Thomas WM, et al. Friction stir welding, International Patent Appl. No. PCT/ GB92/ 02203 and GB Patent Appl. No. 9125978.8, Dec 1991, U.S. Patent No 5460, 317

Gene M. The Welding of aluminium and its alloys. Cambridge England: Woodhead Publishing Ltd; 2002

Daniela Lohwasser and Zhan Chen. Friction stir welding – From basics to applications. Cambrigde New Delhi: Woodhead Publishing Ltd; 2010

Peel M. Steuwer A, Preuss M. Withers PJ. Microstructures, mechanical properties and residual stresses as a function of welding speed in aluminum AA5083 friction stir welds. Acta Mater 2003;51: 4791-801

R.S Mishra, Z.Y.Ma, Friction stir welding and processing, Materials Science and Engineering R 50 (2005) 1-78

Sato Y S, Park S H C, Michiuchi M, Kokawa H. Constitutional Liquation During Dissimilar Friction Stir Welding of Aluminium and Magnesium Alloys [J]. Scripta Mater, 2004,50: 1233-1236

Cavaliere P, Nobile R, Panella F W, Squillace A. Mechanical and microstructural behavior of 2024-7075 Aluminium alloy sheets joined by friction stir welding [J]. International Journal of Machine Tools & Manufacture, 2006, 46: 588-594

Lee W B, Schmuecker M, Mercardo U A, Biallas G, Jung S B. Interfacial reaction in steel – aluminium joints made by friction stir welding [J]. Scripta Mater, 2006, 55: 355-358

Kwon Y J, Shigematsu I, Saito N. Dissimilar friction stir welding between magnesium and aluminium alloys [J]. Materials Letters, 2008, 62: 3827-3829

P. Cavaliere, M. Cabibbo, F. Panella, A. Squillace. 2198 Al – Li plates joined by Friction Stir Welding: Mechanical and Microstructural behavior. Materials and Design 30 (2009) 3622-3631

W.M Thomas, E.D. Nicholas, S.D. Smith, in: S.K Das, J.G. Kaufman, T.J. Lienett (Eds.), Aluminium 2001 – Proceedings of the TMS 2001 Aluminium Automotive and Joining Sessions, TMS, 2001, p.213

R.S. Coelho, A. Kostka, J.F. dos Santos, A. Kaysser – Pyzalla, Friction - stir dissimilar welding of aluminium alloy to high strength steels: Mechanical properties and their relation to microstructure, Materials Science & Engineering A 556 (2012) 175-183

A. Scialpi, M. De Giorgi, L.A.C. De Filippis, R. Nobile, F.W. Panella, Mechanical analysis of ultra – thin FSW joined sheets with dissimilar and similar materials. Materials and Design 29 (2008) 928-936

R. Ohashi, M. Fujimoto, S. Mironov, Y.S. Sato and H. Kokawa: Science Technology Weld Join., 2009, 14, 221-227