UNIVERSITI TEKNOLOGI PETRONAS

FINAL YEAR PROJECT

Semester : May 2013

FINAL REPORT

Due date : August 2013

Title : Friction Stir Welding (FSW): The effect of tilting angle

---

MUHAMMAD FADHIL ABDUL LATIF

12727 (Mechanical Enginering)

pyol17@gmail.com

FYP SUPERVISOR : Dr Mokhtar B Awang (ACADEMIC/UTP)

mokhtar_awang@petronas.com.my

ABSTRACT

Friction Stir Welding (FSW) is solid-state process of combining two materials using frictional heat generated by rotating tool travel along the weld line. Development of FSW suffers implementation challenges due to expensive actual FSW machine available commercially. As alternative, a typical 3-axis conventional CNC milling machine offers comparable capability to be utilized for this technology as well. However, few modifications on machine parts need to be executed first before it is fully compatible to serve FSW purposes. The first objective of this study is to design and fabricate an adjustable-angle fixture to assist CNC milling machine on accommodating the variety tilting angle during FSW process. Upon completing the concept selection, designing, and fabrication phase, the final fixture prototype will be used to experimentally execute the second objective of this project, which is to determine the effect of varying the tilting angle during the FSW process. The resulted weld joint will be qualitatively analyzed in term of any presence of weld defects. The visual inspection on the weld joint shows that increasing the tilting angle at optimum range of 3.5^0 to 5^o can reduce the possibility of having tunnel defects. This can be justified by the inclined orientation of welding tool's axis of rotation which can randomize the flow of plasticized material during mixing and stirring process. However, further increment of tilting angle more than 5^o is not favourable as it will only encourage severe flash formation and reduce weld maximum joint efficiency.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Background Study

The Friction Stir Welding (FSW) process is solid-state process, which involves joint formation below the base material's melting temperature. The heat generated in the joint area is typically about 80-90% of the melting temperature [1].

In FSW, a cylindrical shouldered tool with a profiled pin is rotated and plunged into the joint area between two pieces of sheet or plate material. The parts have to be securely clamped to prevent the joint faces from being forced apart. Frictional heat between the wear resistant welding tool and the work pieces causes the latter to soften without reaching melting point, allowing the tool to traverse along the weld line. The plasticised material, transferred to the trailing edge of the tool pin, is forged through intimate contact with the tool shoulder and pin profile. On cooling, a solid phase bond is created between the work pieces. FSW can be used to join aluminium sheets and plates without filler wire or shielding gas.

The focus of FSW has traditionally been on non-ferrous alloys, but recent advances have challenged this assumption, enabling FSW to be applied to a broad range of materials. In terms of high-temperature materials, FSW has been proven successful on numerous of alloys and materials, including high-strength steels, stainless steel and titanium. Improvements on the existing methods and materials as well as new technological development, an expansion are expected.

To assure high repeatability and quality when using FSW, the equipment must possess certain features. Most simple welds can be performed with a conventional CNC machine, but as material thickness increases and "arc-time" is extended, purpose-built FSW equipment becomes essential. This inflexibility of regular CNC milling machine has halted the widening of FSW application but a little modification on its fixtures actually can tackle this problem, resulting on more perfect welding quality.

1.2 Problem Statement

One of the major impediments to broader industrial implementation of FSW has been the affordability and suitability of FSW equipment. Current FSW equipment presents implementation challenges due to either high cost or lack of performance to ensure quality of the joint. The regular FSW machine can reach the price of one million US dollar [2]. This is not favourable for the small industries, university laboratory or any individual person of to invest big money for expensive FSW specialised machine.

Fortunately, simple FSW weld can be performed using most typical conventional CNC machine. As FSW process itself requires the needs of rotating tool to frictionally heat and soften the work pieces joint, a regular CNC milling machine can fully suit this application. Dealing with FSW, certain features and parameter should be controlled as it can fully compromise the quality of the welds. They are downward force, tool rotational speed, transverse speed, plunge depth, tool geometry, tilt angle and shoulder diameter. However, those critical parameters cannot be hundred percent met due to limitation and incapability of the conventional CNC milling machine and fixtures. This is the issue faced by existing CNC Bridge milling machine in Universiti Teknologi Petronas (UTP) where the fixed spindle position of the machine is unable to be adjusted to specific tilt angle, which will be the main point of interest of this paper. So, specific advanced modification on current CNC milling machine fixture should be done to overcome its inflexibility in order to produce sound quality of FSW result.

1.3 Objective

1) Design and fabricate an adjustable fixture of CNC milling machine to accommodate the variety tilt angle during FSW process
2) Investigate the effects of varying tilt angle during FWS process on the presence of defects resulted at the weld joint.

1.4 Scope

This paper will focus only on modification and designation of adjustable angle fixture of welding anvil on CNC Bridge Port milling machine. Upon modification, the effects of varying the angle between similar aluminium work pieces, butt joint weld of equal thickness will be tested during actual FSW process, and the result then will be qualitatively analysed.

CHAPTER 2

LITERATURE REVIEW

2.1 Principle of Operation

The basic concept of FSW is remarkably simple. A non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and traversed along the line of joint. The tool serves two primary functions: (a) heating of work-piece, and (b) movement of material to produce the joint. The heating is accomplished by friction between the tool and the work-piece and plastic deformation of work-piece. The localized heating softens the material around the pin and combination of tool rotation and translation leads to movement of material from the front of the pin to the back of the pin. As a result of this process a joint is produced in 'solid state'.

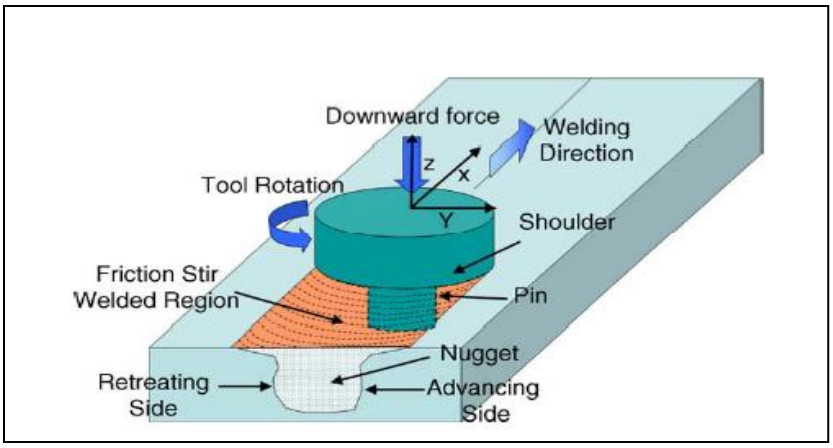


FIGURE 1: Working principle of Friction Stir Welding

Frictional heat is generated, principally due to the high normal pressure and shearing action of the shoulder. FSW can be thought of as a process of constrained extrusion under the action of the tool. The frictional heating causes a softened zone of material to form around the probe. This softened material cannot escape as it is constrained by the tool shoulder. As the tool is traversed along the joint line, material is swept around the tool probe between the retreating side of the tool and the surrounding undeformed material. The extruded material is deposited to form a solid phase joint behind the tool. The process is by definition asymmetrical, as most of the deformed material is extruded past the retreating side of the tool.

2.2. Aluminium Base metal

The predominant focus of FSW has been for welding aluminium alloys, although the process has been well developed for both copper alloys and magnesium alloys. Work is under way to develop the process for materials such as titanium alloys, steels, nickel alloys and even molybdenum. The welding process in these materials takes place at considerably higher temperatures, and although the feasibility of the process has been demonstrated, further work is needed to improve the performance and longevity of tool materials. In addition considerable work has focused on using FSW to join dissimilar aluminium alloys. Furthermore the steady push to lightweight vehicles has largely been responsible for research in joining aluminium alloys to other metals, including aluminium to magnesium, aluminium to metal matrix composites, aluminium to steel and aluminium to copper [4].

Coverage of the present review is confined to the FSW of aluminium alloys. A summary of the AWS designations for wrought Al alloy groups and AWS basic temper designations applicable to heat-treatable Al alloys is contained Appendix 1. Since FSW is a solid state process, it can be used to join all common aluminium alloys, including the 2xxx, 7xxx and 8xxx series which are normally challenging or impractical to weld by fusion processes [13].

TABLE 1 : Chemical composition of base metal

Elements	Cu	Mg	Mn	Fe	Si	Zr	Cr	Ni	Pb	Sn	Zn	Ti	Al
AA1050	0.05	0.05	0.05	0.4	0.25	–	–	–	–	–	0.07	0.05	Bal.
AA6061-T6	0.22	1.1	0.12	0.3	0.58	–	–	–	–	–	–	–	Bal.
AA2024-T3	4.2	1.6	0.6	0.5	0.5	0.2	0.1	0.05	.05	0.05	–	–	Bal.
AA7039-T4	0.1	2.5	0.2	0.2	0.1	0.05	0.15	–	–	–	4.3	–	Bal.
AA7075–T6	1.6	2.5	0.30	0.5	0.40	–	0.23	–	–	–	5.6	–	Bal.

TABLE 2: Mechanical Properties of Base Metal

Material	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Hardness (VHN)
AA1050	105	115	26	70
AA6061	235	283	22	100
AA2024	340	460	18	115
AA7039	400	460	15	130
AA7075	430	520	10	140

2.3. Process Parameter

In FSW process, the 4 main important parameters that would determine the integrity of the welding are tool rotation rate (v, rpm) either in clockwise or counter clockwise direction , tool traverse speed (n, mm/min) along the line of joint, downward force and tool tilting angle.

The tool rotation and traverse speed can be technically defined as how fast the tool rotates and how quick it pass through the interface. These 2 parameters will determine the stirring and mixing pattern 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 [2]. Higher tool rotation rates and low traverse speed will result in hotter weld, which generate higher temperature because of higher friction heating and result in more intense stirring and mixing of material. Excessively high heat input may be detrimental to the final properties of the weld, result in defects due to the liquation of low-melting-point phases .On the other hand, reducing the tool rotation rate and increase the traverse speed can cause material to be not hot enough then voids or other flaws may be present in the stir zone and in extreme cases the tool may break [3].

The plunge depth is defined as the depth of the lowest point of the shoulder below the surface of the welded plate and has been found to be a critical parameter for ensuring weld quality [4]. 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 work piece creating excessive flash. In this case, a significantly concave weld is produced, leading to local thinning of the welded plates [3].

2.3.1 Tilting Angle

Another important process parameter is the tool tilt angle or travel angle, which can be technically defined as angle between the centreline of the tool and a line perpendicular to the surface of the work piece, opposite to the direction of welding [5]. 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..

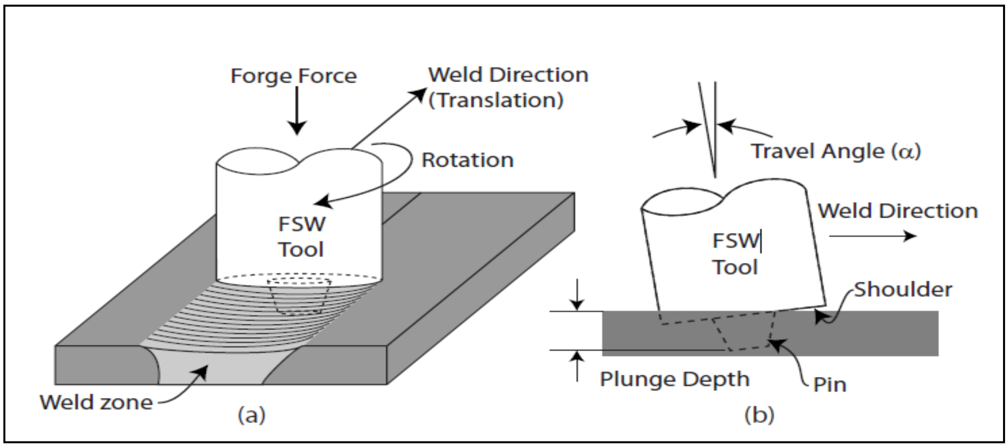


FIGURE 2: Tilt angle of spindle tool

Tilt angle is a significant process parameter because it influences the flow patterns of the stir zone, frictional forces, and the heat generated. Past empirical evidences suggest that travel angle of approximately 2–3 deg is optimal for many aluminium welding applications where variations in part geometry can be expected [5].

Meanwhile, according to Edward F.Shultz and G.Cole on their research, they claimed that 5 deg travel angle maintains a high UTS and joint efficiency [9]. The consistency of the 5 deg travel angle is far greater than those of the 1 and 3 degree. However, their finding probably different from the previous due to procedure of FSW process scoped under their research, where they are experimenting on making a gap in between the work pieces instead of placing them in close contact during welding.

On the other hand, according to Rajiv S.Mishra , generally, above and below certain range of angles, the process becomes more sensitive to flash generation [2]. For similar-thickness optimal travel angles in term of process robustness, tend to be 1.5^0 to 3^0 degree range. Outside this range, the stiffness requirement of the machine may need to be increased to maintain a consistent process.

2.3.2 Downward Force

A downwards force is necessary to maintain the position of the tool at or below the material surface[6]. The magnitude of downward force applied must be sufficiently balanced in order to produce a fine penetration into the work piece, as well as minimizing vibration and weld defects. The downward force is greatly affected by several factors of pre-weld parameters.

The material and alloy can significantly affects the requirement of FSW machine. [2]. FSW of aluminium alloys is the most common application of FSW process. The alloy affects the force requirement of the machine. For example, an FSW, an FSW butt weld in 6mm of aluminium 1100 series can require 2.5 kN (0.28tons) or less welding force, whereas a butt joint in 6 mm 7xxx series can require five times or more force.

In comparison, other materials are also weldable, including lead, titanium, steel and so on [2]. As a broad generalization, the force and stiffness requirement tend to correlate with the melting point and the extrudability of the material that is to be welded. However, specific alloy within a material type can also significantly affect force and stiffness requirement.

Part thickness most significantly affects the force and stiffness requirement of the machine [2]. As thickness increases, force requirement increases. Different joint configurations can also affect the requirement of FSW machine. The partial-penetration butt well requires less force a full-penetration butt well but more than lap weld in the same thickness.

The welding parameters of the FSW process can also affect the technical requirement of the machine. For example, increasing the rotational speed generally reduce the required welding downward force while increasing travel speed will increase the downward force.

Increasing travel angle function may increase required welding force as well [2]. Travel angle of 0^0 can be achieved, which allows for the minimum welding force. However, the consequence is increased process sensitivity that is the range of forces which over which acceptable weld quality is achieved is quite small.. Thus, the machine stiffness and intelligence requirement must be increased if 0^0 travel angle are to be used.

2.4. Effect of tilting angle on mechanical properties

The mechanical properties of a material are those properties that involve a reaction to an applied load. The mechanical properties of metals determine the range of usefulness of a material and establish the service life that can be expected [7]. Among the mechanical properties which are often used as sort of measurement for engineering behaviour of a solid are tensile strength, compressive strength, hardness, ductility, fracture toughness and so on.

According to previous study, tool rotational speed, tilt angle and type of tool pin profile are the significant parameters for tensile strength whereas tilt angle is not significant parameter for hardness [8]. The study suggested that tensile strength increase with increase the tool tilt angle. It is due to surface contact between tool shoulder and work-pieces. At lower tool tilt angle, large surface contact between tool and work-pieces causes excess heat generated. Excessive heat in weld region results, pulling the plasticized material apart from weld line and produce weld joints.

At higher tool tilt angle, the flow of plasticized material is sufficient due to good forging action. Good forging action will lead to less porosity, fine and homogenous grains. So, high tensile strength is achieved.

However, the conclusion of this study contradicts with the fact that tensile strength and hardness are somehow inter-related to each other. The lack of a fundamental definition indicates that hardness is not be a basic property of a material, but rather a composite one with contributions from the yield strength, work hardening, true tensile strength, modulus, and others factor [7]. Hardness is the resistance of a material to localized deformation while tensile strength is stress that a material can withstand while being stretched or pulled before failing or breaking.

The atomic level characteristics that affect strength also play a role in its hardness [7]. Both strength and hardness are measures of a materials resistance to deformation. As the strength of a particular material increases, its hardness also increases. This does not mean that all strong materials are hard nor that all hard materials are strong. But for a particular material to be made stronger (eg,heat treatment) , its correlated hardness value will go up.

2.5 Potential of CNC milling machine for FSW process

Friction stir welding (FSW) has numerous equipment solutions for production and development application. However, each are varied by different capabilities in technical aspects such as force capability, stiffness, intelligence, sensing and flexibility, which will decide the end quality of weld joint produced. In overall, there are 3 basic categories of production equipments for most FSW process which are [2]:

a) Robotic FSW machine
b) Custom-built FSW machine
c) Modified machining center (milling machine)

Several FSW researches which have been done using CNC milling machine has proven that result it’s comparable to the application of actual FSW machine. By considering all the important FSW parameters while executing the process, typical CNC milling machine shows promising potential of producing fine and sounds quality of weld joint. As claimed by Shults and Cole on their research by comparing these 2 machineries, despite having such large differences in compliance, the industrial robot and the mill produce welds of a similar joint efficiency of 90%. [9].

Friction stir welding and processing are similar in nature to machining at high level. Modification of existing machining centres can be an economical means of implementing FSW [2]. However, there are several items that must be considered before deciding whether or not to modify an existing machining center:

a) FWS processing can require relatively more force than machining. The base equipment such as guide, rails, motors and spindle must be investigated to determine its maximum capability [2].
b) In most application, FSW requires at least non zero travel angle. Unless the machining center has five-axis capability, this may pose a challenge. Mechanical fixed solution can be implemented to apply a travel angle to overcome this limitation [2].
c) FSW processing produce heat that can transfer into spindles, which are not designed to handle high temperatures. Thermal flow on material must be considered [2]

2.6 Previous Research on designing adjustable angle fixture of FSW

So far, it is found that there is no similar study which exactly focuses on utilizing the CNC milling machine for FSW by designing and fabricating the adjustable angle fixture. The closest one is only from Kumar Baghel [10] and Badheka [11]. However, the former has fabricated the FSW fixture but more considering the variable dimension aspect on his design instead of the tilting angle, while the latter utilize the conventional milling machine for FSW purpose but his study stresses more on the process parameter rather than physical machine capability.

FIGURE 3: FSW fixture design that can fit to variable dimension of workpiece [10]

There are numerous researches done to develop this FSW technology on every aspect. Some of them are not even experimented with tilting angle adjustment, some by using actual FSW machine which posses the tilting angle capability, but most of FSW research are executed on milling machine by applying very simple approach to provide tilting angle during the process. It is either by using the wedge or angle plate to be placed under the fixture in order to create incline plane before clamped. These are the simplest and cheapest solution but its practicality in term of angle accuracy and clamping strength is still arguable

FIGURE 4: The wedge placed under the fixture to incline the plane [11]

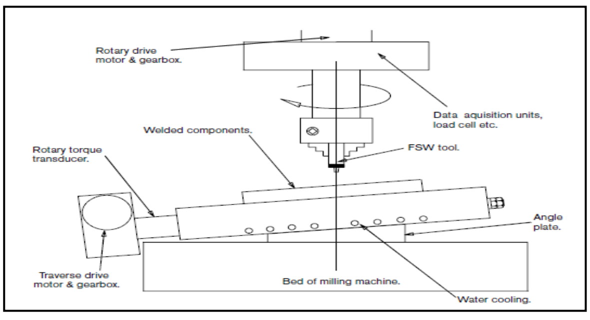


FIGURE 5: Angle plate used to create tilting angle during FSW [12]

2.7 Types of Defect on FSW weld joint

Defects in FSW are related to processing temperatures, metal flow patterns and joint geometry [14]. Both processing temperature and metal flow patterns are a function of processing parameters and pin tool design. Below are list of defects typically occur in FSW.

<u>Hot Processing Defects</u>

a)Tunnel defects

- Tunnel defect can be described as an advancing side tunnel of inadequately consolidated and forged material running in the longitudinal direction [14]. It is caused by insufficient metal flow into the interleaving area on the advancing side above the swirl zone, created due to excessive travel speed for given tool rotational speed.

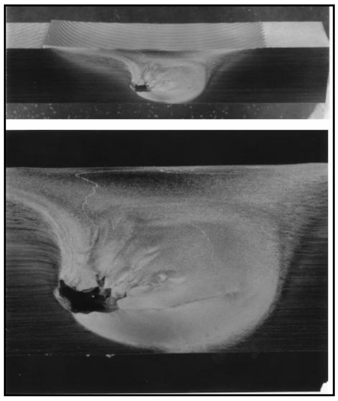


FIGURE 6 : Tunnel Defects cross section [14]

b) Lack of fill

c) Scalloping

<u>Hot Processing Defects</u>

a) Ribbon Flash
   - Flash can be defined as excessive expulsion of material on the top surface leaving a corrugated or ribbon-like effect along the retreating side [14]. It is caused by the excessive forge load or plunge depth. Thickness mismatch between advancing side and retreating side, excessively hot weld or too high weld pitch .

FIGURE 7 : Flash ribbon deposited outside the weld joint [14]

b) Surface LOF

c) -Nugget Collapse

d) -Surface Galling

e) Root Flow Defect

CHAPTER 3

METHODOLOGY

3.1 Project Flow

Literature Review

1) Define objective and Scope
2) Gathering information and facts from book, journal and similar previous researches.
3) Preparing literature review

Project Designation

4) Defining design criteria and limiting considerations
5) Generating several conceptual sketches.
6) Selection of concept
7) Preparing Sketch Design
8) Preparing Computer Aided Design (CAD) design

Procurement and Fabrication

9) Procurement of materials and components
10) Fabrication of each part (self-fabricate or outsourcing)
11) Part Assembly
12) Product testing
13) Feasibility study and modification (if necessary)

Laboratory Testing

14) Identify FSW process parameters
15) Running FSW at different tilting angle on different sample.
16) Preparation of welding joint specimen upon lab test.
17) Measuring Hardness test on weld joint specimen
18) Analyze and compose the result

3.1.1 Design

After some through reviews, the important features and design considerations will be listed before those rough ideas of FSW adjustable angle fixtures designs are generated into several simple conceptual drawings. Every advantages and disadvantages of each design will be taken into account, and the one which potentially demonstrated higher reliability will be chosen. Afterwards, it will be translated into detail engineering drawing using computer-assisted drawing software such as Computer Aided Design (CAD) or Catia.

3.1.2 Procurement and Fabrication

After finalizing the detail drawing and product design features , procurement of the materials and hardware were done before proceeding to next step. However, as most required hardware, equipments and facilities cannot be accommodated by the university, those were bought from the selected outside vendors and services under strict considerations and limited budget. Besides, most fabrication which require the use of milling and welding machine, electric driller, tapper, and other high performance machineries will be outsourced to local expertise who offers better workmanship and capability to fabricate the design with small dimensional tolerance.

3.1.3 Laboratory Testing

The fabricated adjustable fixture of CNC milling machine was tested for its stability and reliability, by operating it at various tilt angle during the real FSW process. Other important parameters such as tool rotational speed and transverse speed are set up at optimum condition, and maintain fixed throughout the experiment.

Material used is aluminium alloy 6061, dimensionally cut to fit the size of the fabricated Adjustable Angle Fixture of FSW. This experiment will use the existing tool from previous research as the main focus of the test is only to determine the capability of the designed fixture and its effect on weld joints. Table 3 has summarized the experiment set up used for this FSW experiment.

TABLE 3: Experiment Set-up for FSW processing

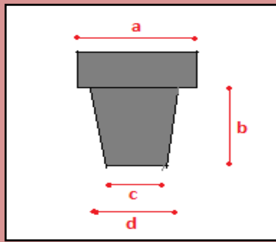
Experiment	Tilting Angle (°)	Experiment Setup
Set 1	0	<u>**Process Parameter**</u> **Tool Rotational Speed :** 1200rpm **Transverse Speed :** 50 **Plunging Feed rate :** 100mm/s **Dwell Time (plunging) :** 20 sec **Dwell Time (withdrawn) :** 4 sec **Welding Length :** 70mm <u>**Material**</u> **Type :** Aluminum alloy 6061 **Dimension :** 100mm x 100mm **Thickness :** 10mm <u>**Tool**</u> **Profile :** Taper **Shoulder Diameter (a):** 18.8 mm **Pin Length (b) :** 8mm **Maximum Pin Diameter (d)** : 8.7mm **Minimum Pin Diameter (c)**: 5.4 mm  Tool Cross Section
Set 2	2.5	
Set 3	3.5	
Set 4	5.0	

Figure 8 shows the adjustable-angle fixture is being tested during FSW process. The resulted work piece which has been successfully welded then will be cut perpendicularly to its weld joint line as shown in Figure 9, by using EDM wire cut machine. These cross section of the weld joint at starting, center and key hole will be observed for any existence of weld defects, before the result of the experiment can be analyzed to conclude the effect of tilting angle on the weld joint.

FIGURE 8 : Adjustable angle Fixture is being tested

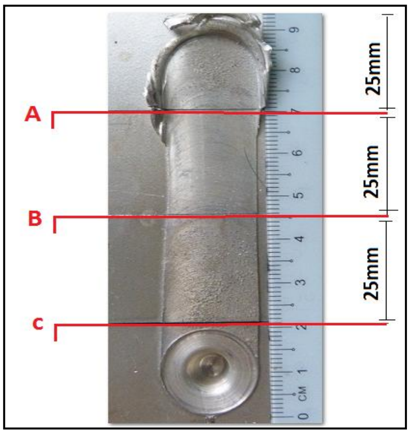


FIGURE 9: Sample is cross sectioned by using EDM Wirecut

3.2 Gantt Chart and Project Milestone

Activities	WEEKS																										Project Milestone
	Final Year Project 1														Final Year Project 2												
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	1	2	3	4	5	6	7	8	9	10	11	12	
Project Scope Validation																											
Project Introduction																											
Literature Review																											25th Feb 2013
Defining design criteria and limiting consideration																											
Generating conceptual sketches																											
Selection of Concept																											
Draw Sketch Design																											
Generate Computer Aided Design (CAD) drawing																											11st April 2013
Procurement of materials and components																											
Fabrication of components part																											
Part Assembly																											25th May 2013
Product Testing																											
Feasibility Study and Modification																											
Running FSW																											
Preparation of weld joint specimen																											
Analyzing result																											July 2013

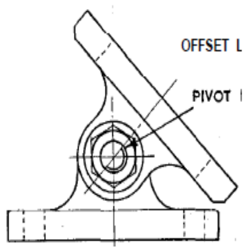
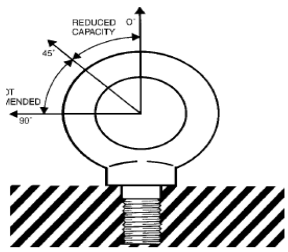
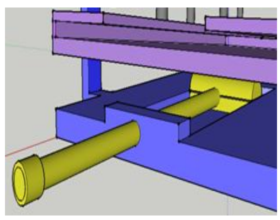
CHAPTER 4
RESULTS

4.1 Product Design

a) Generating ideas and evaluation of concept

A few ideas have been generated and the best design that can suit the objective of creating adjustable angle features was selected based on the highest mark scored during the evaluation, depends on few criteria which will define its suitability for the overall project.

TABLE 4: Evaluation of concept

Criteria	**Concept Evaluation**		
	Concept A	**Concept B**	**Concept C**
Mechanism of adjustable angle	 Rotary table with bolt and nut	 Eye Bolt	 Adjustable wedge
Design Complexity	6	10	8
Functionality	4	8	6
Practicality	6	6	10
Strength	10	4	8
Procurement of material	8	6	10
Workmanship	4	6	8
Total Mark	**38**	**36**	**44**

Evaluation Scale : 0 – bad , 10 – very good , Table 5: Criteria of concept selection

b) Selection criteria

TABLE 5 : Selection Criteria

No	Criteria	Description
01	Design Complexity	Number of different components, mechanism size, number of non-symmetry and complex shape.
02	Functionality	The range of adjustable angle it can provide
03	Practicality	Ease to be operated and used by end user, time taken for preparing the fixture before proceeding to FSW process
04	Strength	Maximum downward force of the machine spindle it can sustain during the FSW. (*specified to min force requires for aluminium welding*)
05	Procurement of material/components	Expected price of the components and its availability in the market to be bought at small package.
06	Workmanship	The capability of the local machine , size, design tolerance , and level of accuracy needed during the fabrication process

These criteria above have been used to measure the suitability of each mechanism concept for the evaluation process in 4.1a section. From the evaluation, Concept C has recorded the highest mark and was selected for this project.

This mechanism has moderately complex design of bolted adjustable wedge to be assembled and moved along its base plane's track. This main mechanism will be the backbone of the overall design to equip the final product with the ability of adjustable tilting angle. The rest are just add-on accessories to properly clamp the work pieces at still to the device against downward and translational force.

On functionality aspect, it can provide the adjustable projectile in between 2.5^o and 5^o working range, which the best is tilting angle used for FSW. Compared to concept A which is specifically designed for angle adjustment in between 1^o and 180^o, this wider range makes the angle selection to be more flexible but not favourable for FSW process. As a consequence, it turns out the angle scale to be less sensitive.

The advantage of mechanism C is its simplicity to be prepared and adjusted at pre-welding process as the wedge mechanism only need to be set and locked to certain degree position at ease. This will reduce preparation time consumed before FSW before. Besides, it's simple design offers great stability, predicted to sustain high downward force which is about 2.5kN at least for aluminium alloy welding.

In terms of workmanship, the rotatable wedge of concept C can be custom-built by using a conventional milling machine. This can avoid price-choking components while buying the ready-made parts at bulk package. Moreover, it has the moderate size design and requires wide degree of tolerance during the assembly process.

c) Conceptual Sketch and component features

**This sketch is not drawn according to actual dimension and scale. It is still subjected to any change prior to proceeding design stage.*

Software used: *Google Sketch up*

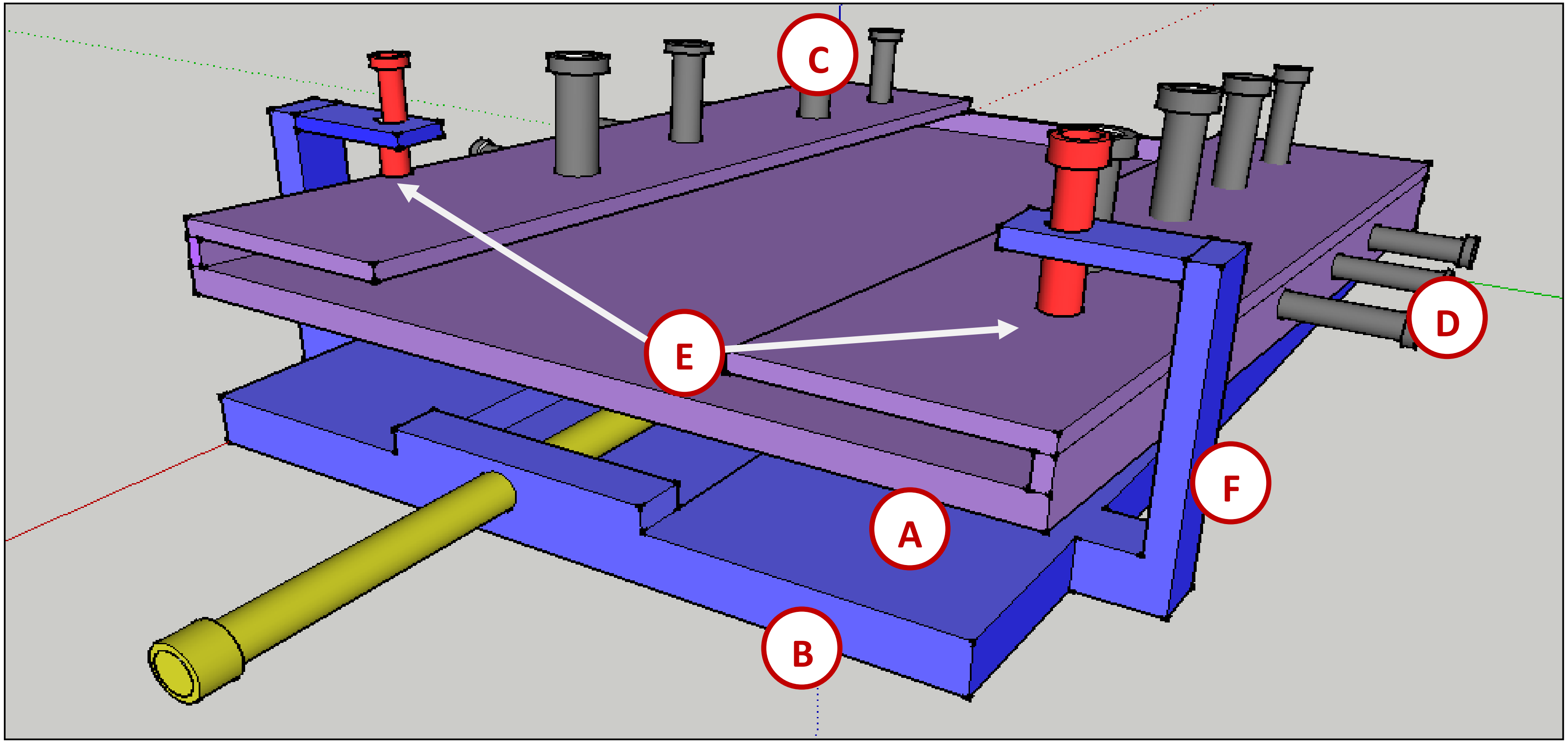


FIGURE 10: Sketch Drawing and Component features

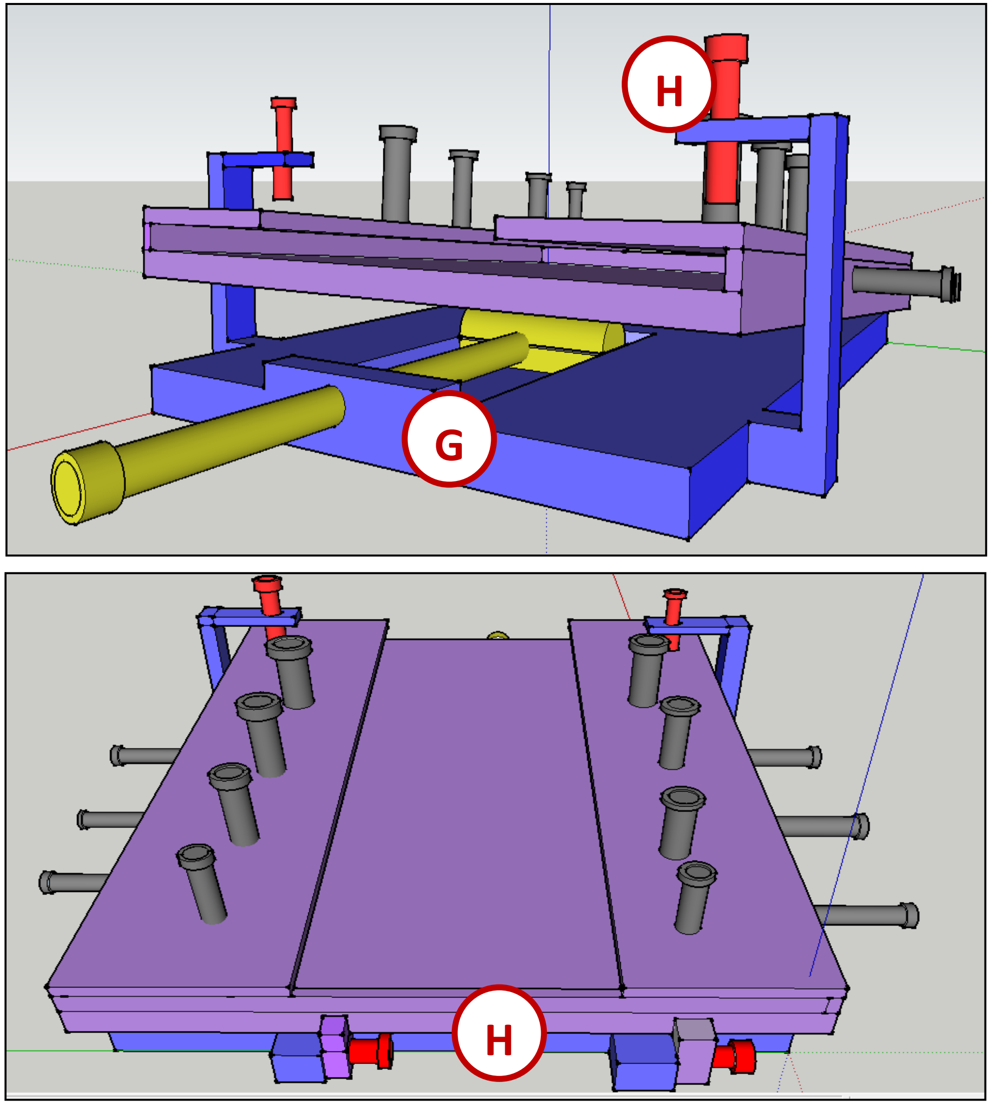


FIGURE 11 : Sketch Drawing and Component features at different view

TABLE 6 : Design features

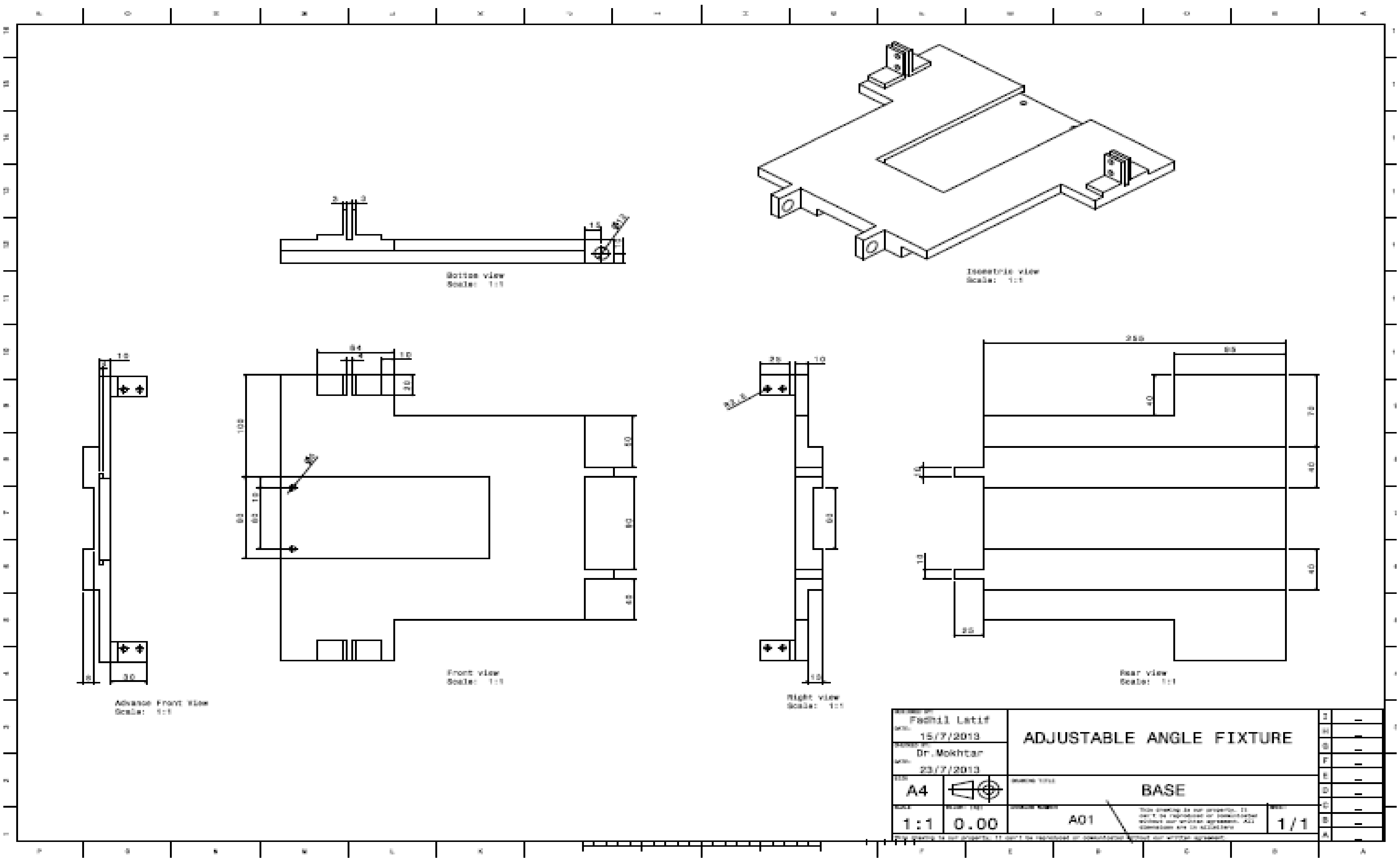
Label	Part Name	Features
A	Top Jig	Interface to hold the work pieces during the FSW process
B	Base	Lower part of the jig that provide the designated slot for adjustable wedge
C	Top Bolt and Nut	Adjust, tighten and restrict the thickness of the work pieces used
D	Side Bolt and Nut	Adjust, tighten and restrict the width of the work pieces used
E	Clamping	Multi-angle bolt to clamp the top bunk at fixed inclination during FSW process
F	Clamping holder	Part of the base that provide the holder for clamping bolt
G	Adjustable wedge (yellow)	Assembly of bolt and wedge that can vary the position of wedge when the bolt is screwed in or out. It turns the rotation force to translational movement.
H	Bolt / shaft (red)	Connecting mechanism between top and bottom parts of the fixture. Allowing top plane to be slightly rotated and inclined at required degree while still attached at to each other

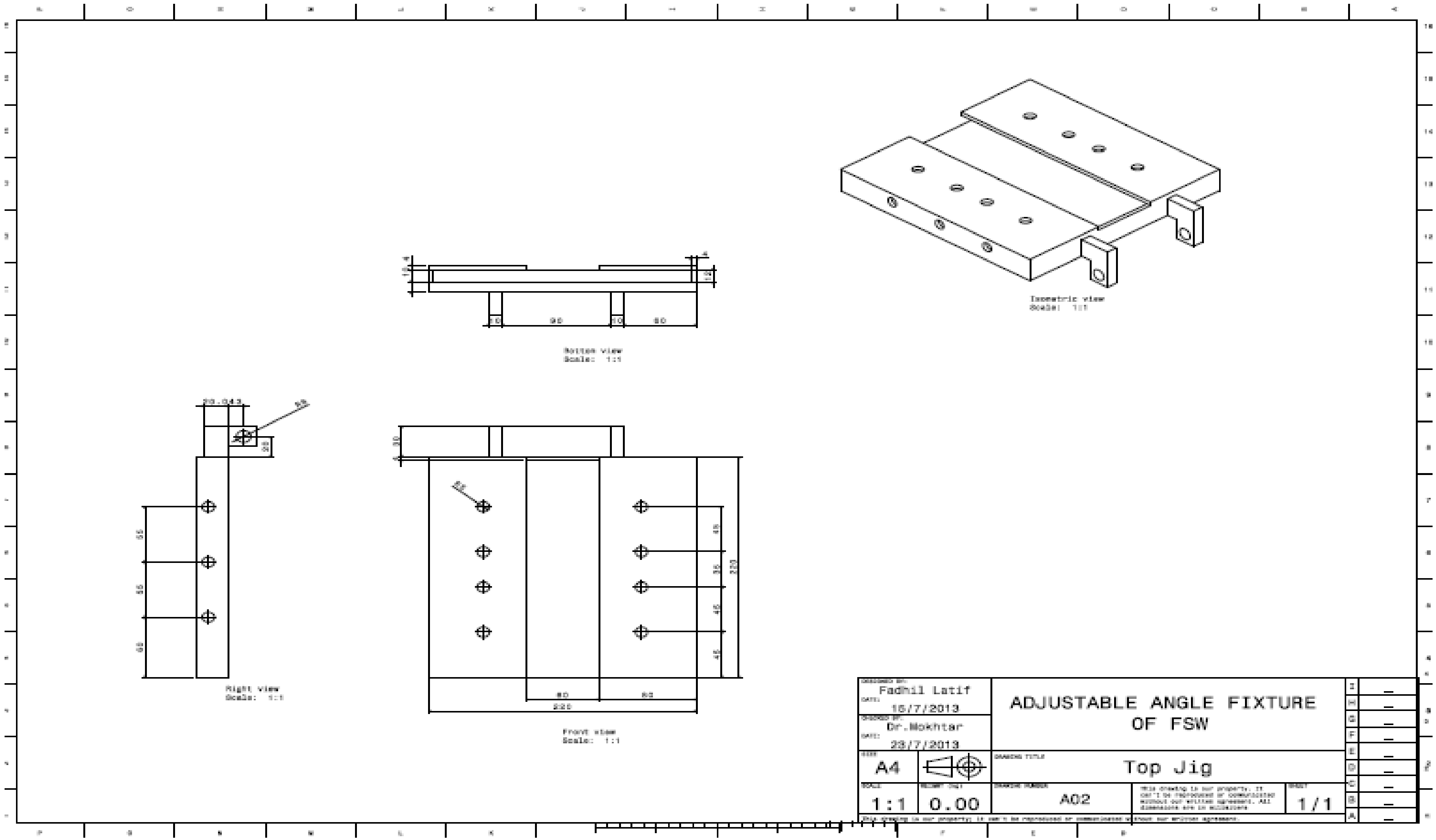
4.2 Engineering Drawing

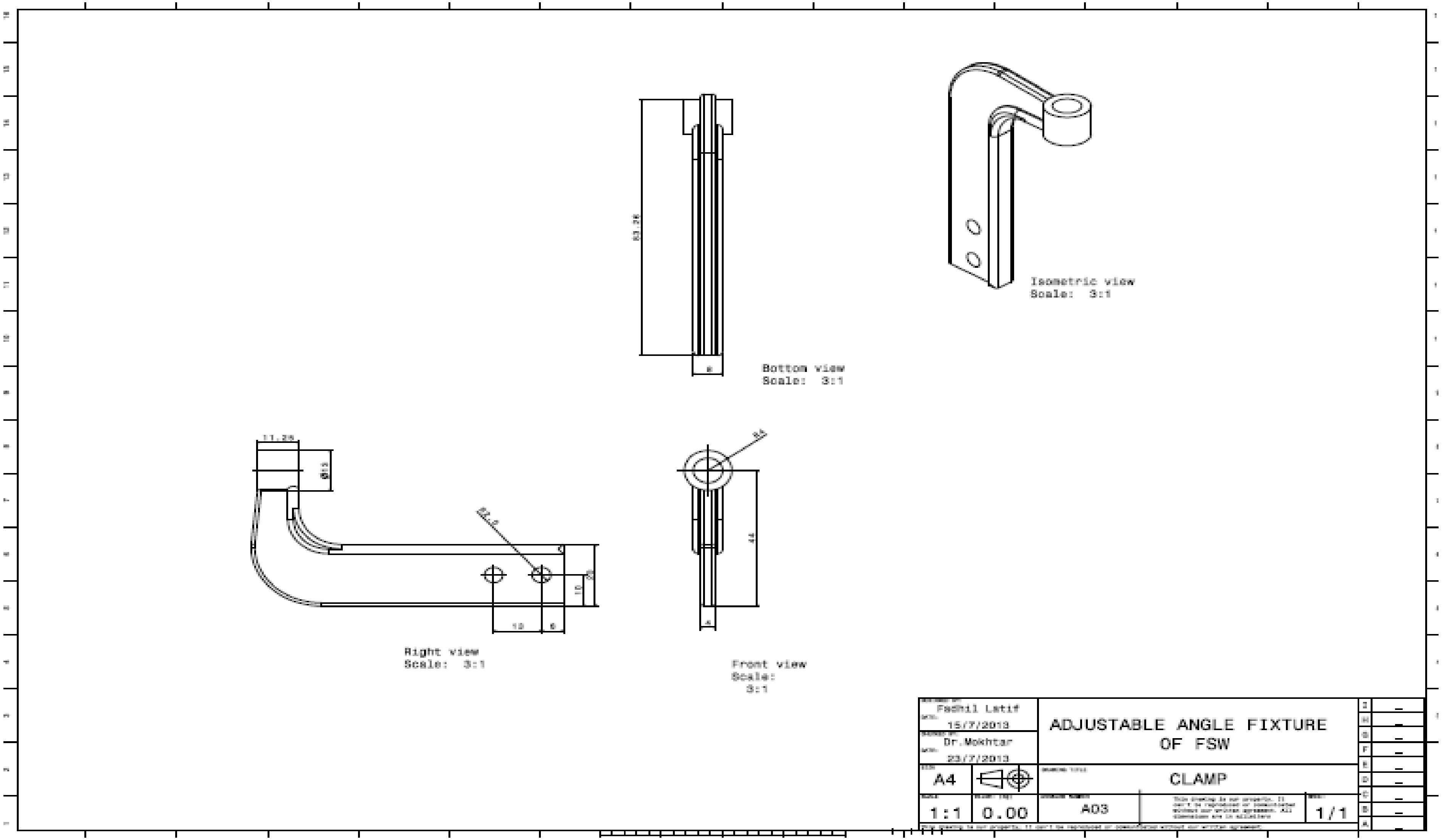
Upon concept selection and drafting, the chosen design is translated into engineering drawing. Plan view for each part is generated at reduced scale and actual dimension. Then, each individual part is assembled together as shown in Assembly Drawing and Isometric Drawing.

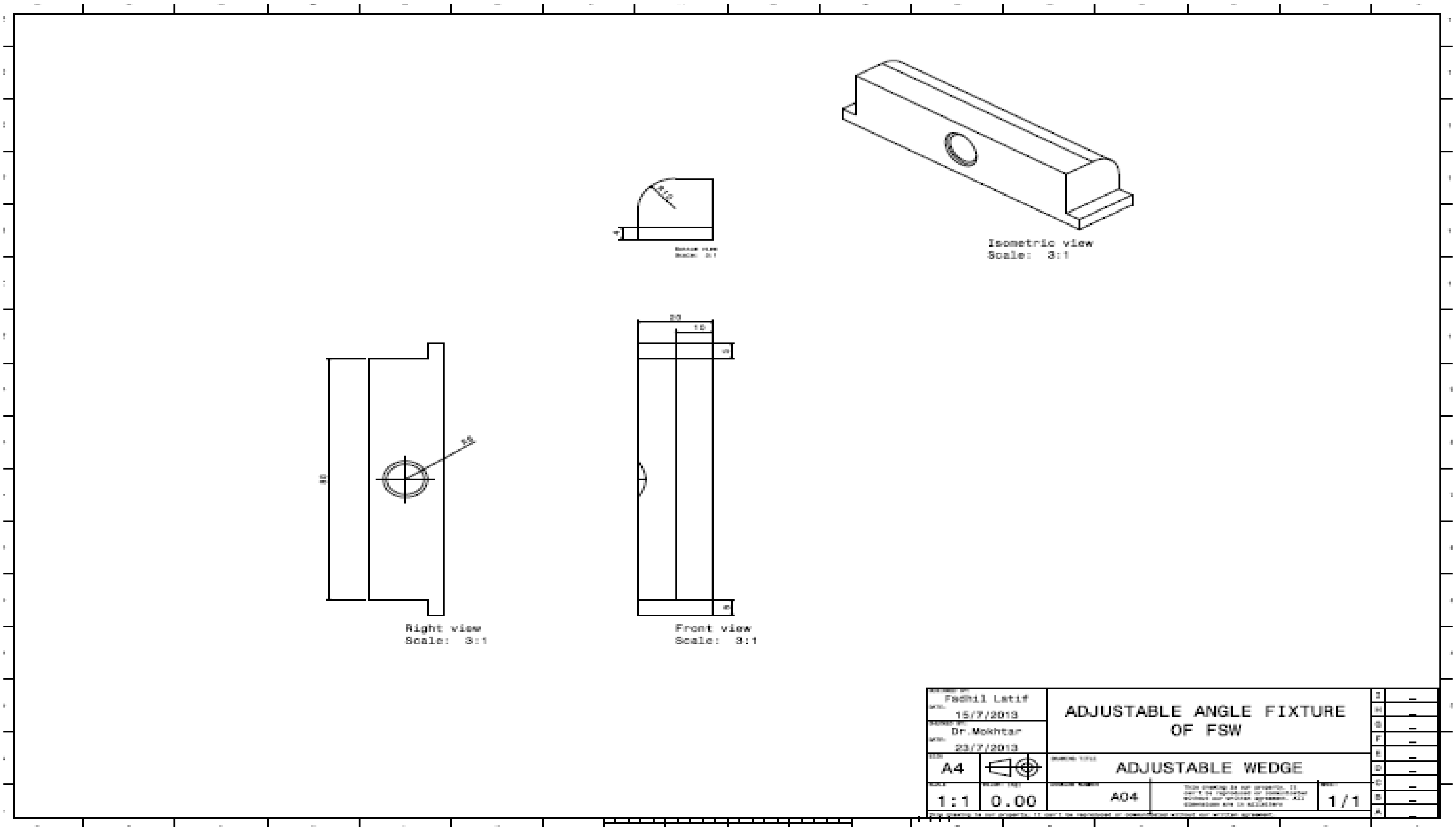
The following pages provide complete engineering drawing for Adjustable Angle Fixture of FSW, which is arranged in order as listed below.

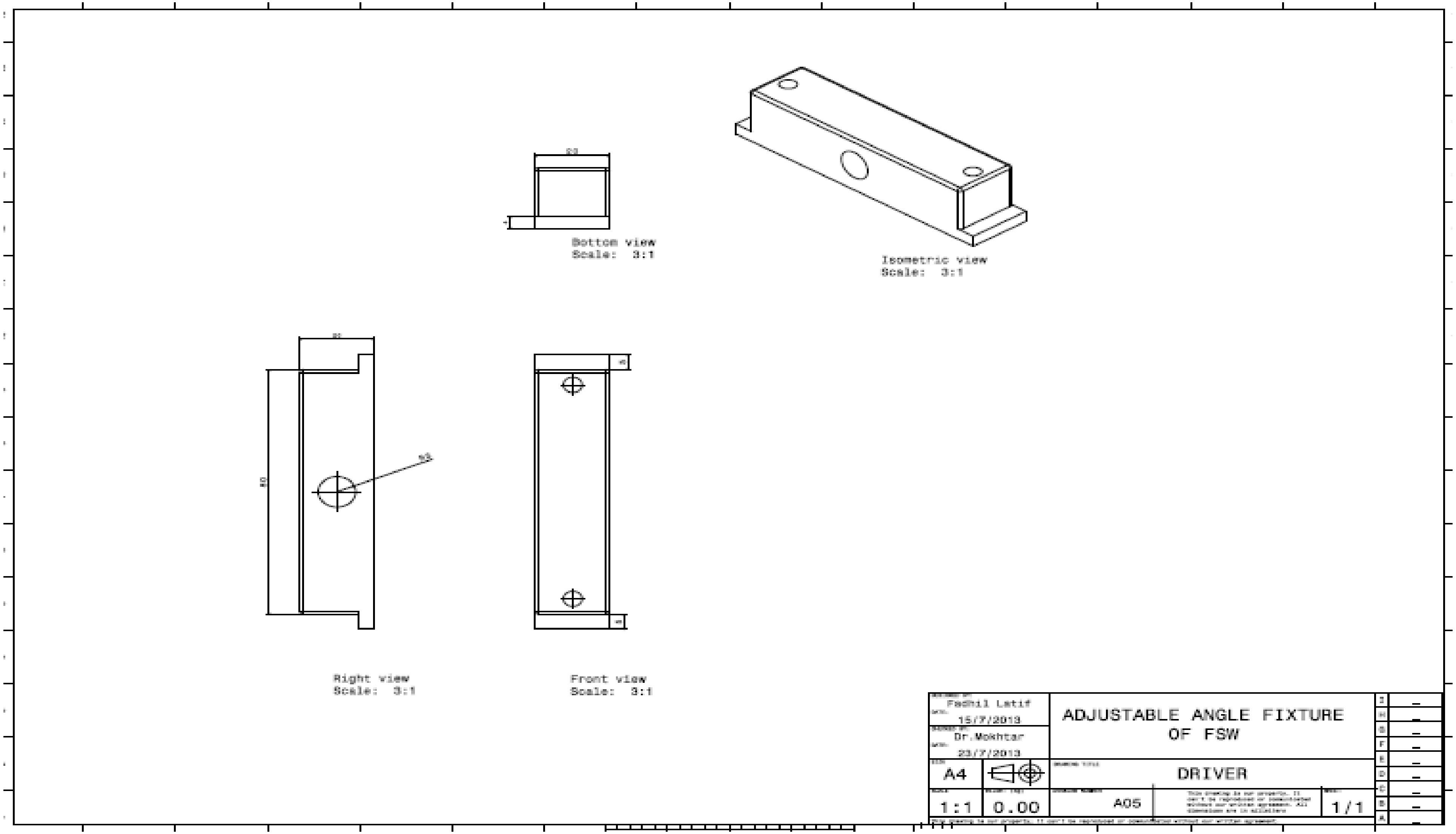
a) A01 : Plan View of Base
b) A02 : Plan View of Top Jig
c) A03 : Plan View of Body Clamp
d) A04 : Plan View of Adjustable Wedge
e) A05 : Plan View of Driver
f) Assembly Drawing and Bill of Material
g) Isometric Drawing
h) Auxiliary Drawing


Bottom view
Scale: 1:1
Isometric view
Scale: 1:1
Advance Front View
Scale: 1:1
Front view
Scale: 1:1
Right view
Scale: 1:1
Rear view
Scale: 1:1
Fadhil Latif
15/7/2013
Dr.Mokhtar
23/7/2013
ADJUSTABLE ANGLE FIXTURE
A4
BASE
1:1
0.00
A01
1/1

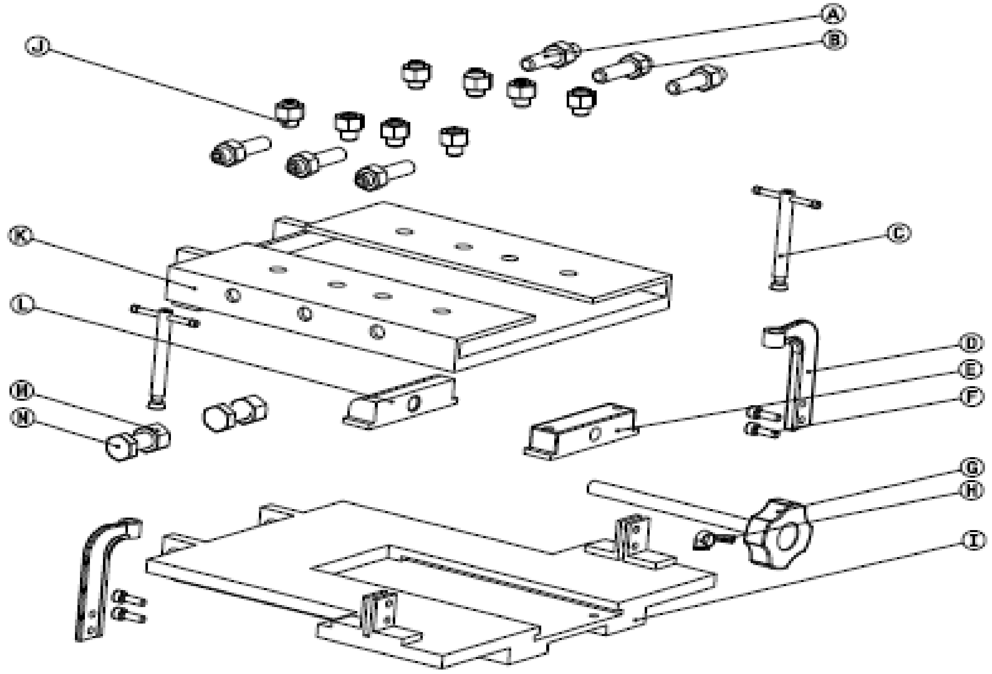

Isometric view
Scale: 1:1
Bottom view
Scale: 1:1
Right view
Scale: 1:1
Front view
Scale: 1:1
Fadhil Latif
15/7/2013
Dr.Mokhtar
23/7/2013
ADJUSTABLE ANGLE FIXTURE
OF FSW
A4
Top Jig
1:1
0.00
A02
1/1


Isometric view
Scale: 3:1
Bottom view
Scale: 3:1
Right view
Scale: 3:1
Front view
Scale:
3:1
Fadhil Latif
15/7/2013
Dr.Mokhtar
23/7/2013
ADJUSTABLE ANGLE FIXTURE
OF FSW
A4
CLAMP
1:1
0.00
A03
1/1


Isometric view
Scale: 3:1
Right view
Scale: 3:1
Front view
Scale: 3:1
Fadhil Latif
15/7/2013
Dr.Mokhtar
23/7/2013
ADJUSTABLE ANGLE FIXTURE OF FSW
A4
ADJUSTABLE WEDGE
1:1
0.00
A04
1/1



Bottom view
Scale: 3:1
Isometric view
Scale: 3:1
Right view
Scale: 3:1
Front view
Scale: 3:1
Fadhil Latif
15/7/2013
Dr.Mokhtar
23/7/2013
ADJUSTABLE ANGLE FIXTURE
OF FSW
A4
DRIVER
1:1
0.00
A05
1/1



Isometric view
Scale: 1:1

Bill of Material: ADJUSTABLE ANGLE FIXTURE

LABEL	PART NAME	TYPE	QUANTITY	STATUS
K	TOP FIXTURE	Part	1	FABRICATED
I	BASE	Part	1	FARBRICATED
E	DRIVER	Part	1	FARBRICATED
L	ADJUSTABLE WEDGE	Part	1	FABRICATED
D	CLAMP BODY	Part	2	FABRICATED
G	ISO 4026 SCREW M10x180 GRADE A STEEL HEXAGON SOCKET HEAD CAP	Part	1	PURCHASED AND MODIFIED
C	CLAMP POWER SCREW M8x80 WITH MULTI-ANGLE-SURFACE BEARING BALL		4	READY-MADE PURCHASE
A	ISO 4028 SCREW M10x20 GRADE A STEEL HEX SOCKET SET WITH FLAT POINT		8	READY-MADE PURCHASE
J	ISO 4026 SCREW M10x50 GRADE A STEEL HEX SOCKET SET WITH FLAT POINT		6	READY-MADE PURCHASE
F	ISO 4762 SCREW M5x16 STEEL HEXAGON SOCKET HEAD CAP		4	READY-MADE PURCHASE
H	EAR NUT M10		1	READY-MADE PURCHASE
B	ISO 4034 NUT M10 STEEL GRADE C HEXAGON HEAD		14	READY-MADE PURCHASE
M	ISO 4034 NUT M12 STEEL GRADE C HEXAGON HEAD		2	READY-MADE PURCHASE
N	ISO 4017 SCREW M12x35 STEEL GRADE A HEXAGON HEAD		2	READY-MADE PURCHASE

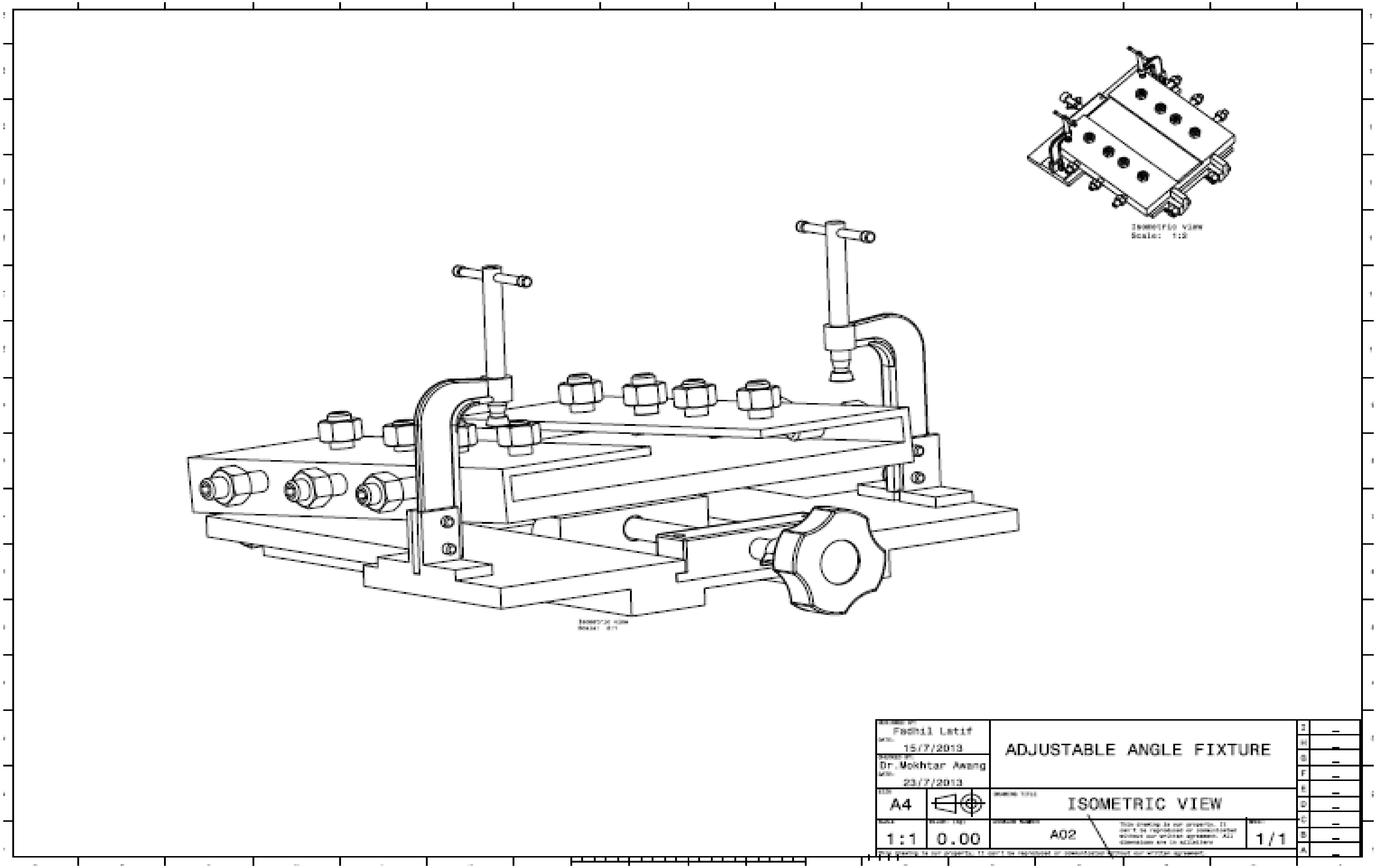
Fadhil Latif
15/7/2013
Dr.Mokhtar Awang
23/7/2013

ADJUSTABLE ANGLE FIXTURE

A4

ASSEMBLY VIEW

1:1 | 0.00 | A02 | 1/1


Fadhil Latif
15/7/2013
Dr.Mokhtar Awang
23/7/2013
ADJUSTABLE ANGLE FIXTURE
A4
ISOMETRIC VIEW
1:1
0.00
A02
1/1

4.3 Product Specification Label

FIGURE 12 : Final Product

TABLE 7 : Product Specification Label

Name	**Adjustable-Angle Fixture of Friction Stir Welding (FSW)**
Application	CNC milling machine Bridgeport
Dimension	360mm x 300mm x 150mm
Weight	14kg
Color	Blue
Material	Mild Steel
Max Tested Downward Force	6.0 kN
Tilting Angle	Minimum : 2.5^{0} Maximum : 5^{0} (also facilitate 0^{0} angle)
Work pieces Dimension *(per piece)*	Maximum width : 110mm Minimum width : 70 mm Maximum Length : 210 mm Minimum Length : 55mm Maximum Thickness : 12mm
Cost	Material cost : RM350 Fabrication Cost : RM250 Total Cost : **RM600**

The final product of Adjustable Angle Fixture has been proven to successfully utilize the typical CNC milling Bridgeport machine for actual FSW application. It possesses the strength to sustain downward load acted by the spindle force against its structure without any breakage, while the working adjustable wedge mechanism is properly functioning as designed.

It can provide steady clamping force to hold the work pieces and the observation on quality of the weld joint shows equally comparable result to actual FSW machine application. But, the advantage of utilizing the existing CNC machine by adopting the application of Adjustable Angle Fixture for FSW process can be justified economically *(830 times cheaper)* , where it is more affordable compared to purchasing new actual FSW machine.

Comparing the Adjustable Angle Fixture to previous one, it demonstrates better advantages in several aspects.

a) Accommodate wider range of tilting angle and dimension
b) Reduce FSW process preparation time

4.4 The effect of tilting angle

The experiment done has shown variation of result at every different tilting angles while maintaining the other variables and parameter at fixed value. The result was observed qualitatively through visual inspection and type of defects that we are going to focus are restricted to tunnel effects, flash formation and collapse only. The rest as described in Figure 5 will not be analyzed. Table 8 below summarize the result of each set of experiment.

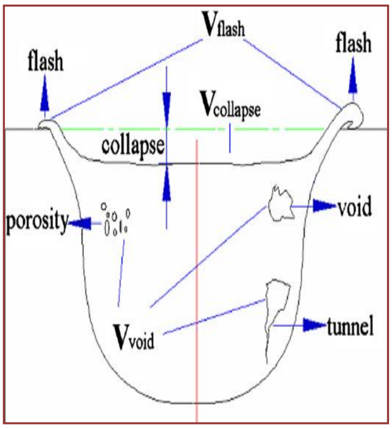
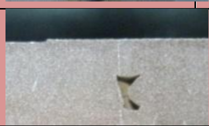
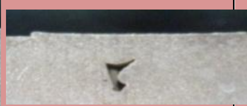
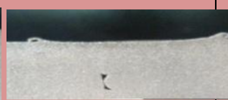
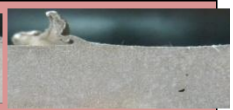
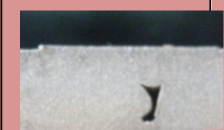
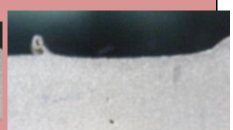
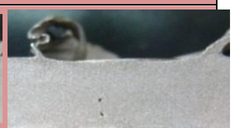


FIGURE 13: Types of Defects [16]

Table 8 : Effect of different tilting angle on weld joint

Tilting Angle		0°	2.5°	3.5°	5.0°
Bead Appearance					
Cross Section	A				
	B				
	C				
Defects		Visual Inspection			
Tunnel		Large	Large	Tiny	Very Tiny
Collapse		No	No	No	Very Litle
Flash Formation *(at section B)*		None	None	Litle	Moderate

4.4.1 Tunnel Defects

Through visual inspection at the weld joint cross section, the results have shown that increasing the value of tilting angle during the process can reduce the formation of tunnel defect. It can be observed that at 0 and 2.5 angles, tunnel defects consume large voids at the weld joint which clearly compromise the integrity of welding. Meanwhile, when the tilting angle is increased to 3.5 degree for the next set, the size of the tunnel defects has been greatly reduced, and almost totally eliminated when tested at 5^{o} tilting angle.

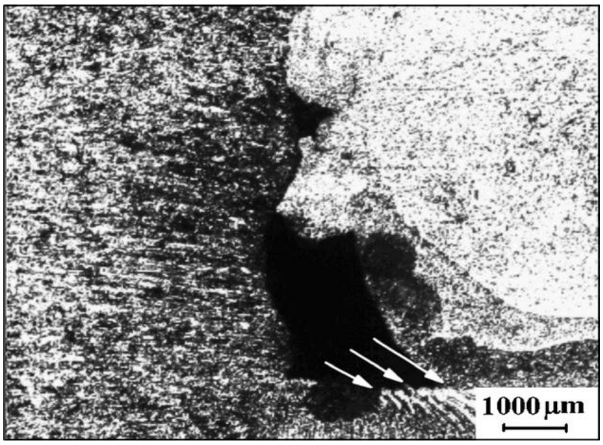


FIGURE 13: Cross section of tunnel defects, indicating 2 unmixed different textures [16]

The microstructure analysis done on previous research of tunnel defects formation has claimed that it was caused by inadequate material stirring and mixing [16]. Figure 8 show that the two sides of tunnel have different texture characters without touch. The material flows on the horizontal plane firstly from the advancing side to the retreating side of FSW welds, and then around the tool rotation.

During the process of tool moving ahead, the plasticized material around tool pin transfers layer by layer and a cavity will remain besides the pin due to unconsumed volume of the plunged pin [16]. The restriction to the material flow from the retreating side to fill the cavity on advancing side depends on the width of plasticized material around the pin and the volume of material transferred per rotation. If the plastic deformed material-flow from the retreating side is not enough to fill the cavity instantaneously before cooling to still-state, the tunnel defect will remain.

Increasing the tilting angle during FSW process can affect the weld result in two ways. First, it will alter the orientation of the rotating tool's shoulder and pin which are travelling below work pieces surface. Tilting angle can shift the tool's axis of rotation from 90^o vertical to non-perpendicular position, which greatly widens the reachable range of tool-workpiece contact and randomize circular pattern of the plasticized material flow during mixing and stirring of FSW process. This slight inclination can assist the flow of material, moving them around the tool from the advancing to the retreating side at better efficiency.

Second, it increases the surface area of the tool which in direct contact with the work pieces. Larger contact surface will induce extra frictional heat to soften the material, where it can help the flow of plasticized around the rotating tool. However, this increase of contact area between tool and work pieces due to tilting angle is very small and its effect is not too significant to affect the overall process. In fact, any attempt to increase the contract area by continually increasing the tilt angle higher than 5^o while operating at inappropriate high tool rotation and slow travel angle will only generate excessive heat and encourage the formation of flash.

4.4.2 Flash Formation

Based on Table 8, visual inspection done at cross section B for each set has shown that flash defect are prone to severely occur at greater tilting angle of 5^o, followed by 3.5^o , and not exist at 2.5^o and 0^o degree .

Flash happens because large mass of plasticized material is ejected outside the weld joint due to softening of the aluminium metal by the excess tool-shoulder frictional heat during the process [15]. Increasing the tilting angle will slightly increase the tool-material contact area which consequently induces extra frictional heat causing flash to form, especially when operated at higher plunger depth. This similar concept of excess frictional heat can be clearly seen at cross section A and C as described in Table 8 where the process is operated at dwelling time of 20 and 4 seconds respectively at respective position. Longer time of the rotating tool operated at fixed position (zero travel speed) will over-heat and soften the metal excessively, then increase the tendency for plasticized material to be splashed outside the joint.

Besides tilting angle, the amount of flash deposited is also the function of plunge depth. At certain combination of these 2 factors, the leading edge of the tool shoulder is possibly dipped below the surface, as described in Figure 15 and 16. This is referred as "plowing" and it is assumed in the model that contacts the tool between the leading edge and workpieces surface is lost as flash and chips [9]. Although plowing may not be ideal, it may be required to achieve maximum joint efficiency.

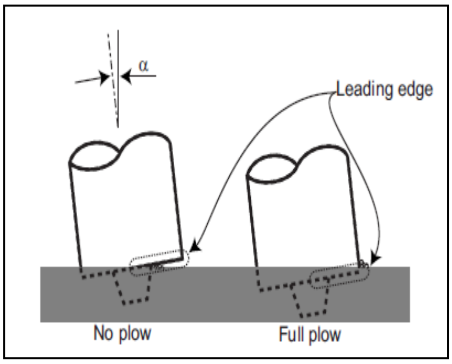


FIGURE 15 : Plowing method [9]

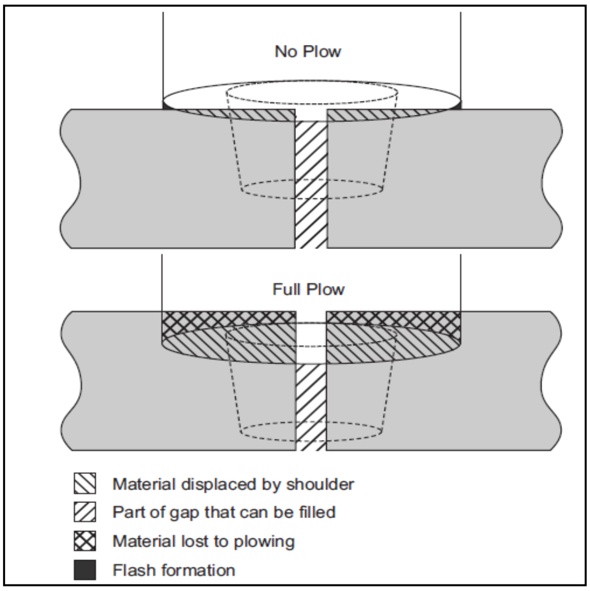


FIGURE 16 : Material deposited due to plowing [9]

At minimum formation, a flash defect is just a matter of appearance but excessive of its occurrence means greater mass loss deposited to the outside, which potentially increase the porosity of the weld joint. However, the flash formation can be reduced by operating the FSW process at optimized tilting angle and appropriate plunge depth, depends on the work piece thickness.

4.4.3 Optimum Tilting Angle

Increasing the tilting angle while operating the FSW has been proven can reduce or possibly eliminate the tunnel defects but at the same time increase the risk of flash formation. Choosing the suitable parameters to avoid the resulted defects often requires give and take consideration. In fact, the existence of tunnel defects and flash formation on the weld joint is not singularly influenced by tilting angle only. Other parameters such as plunge depth, tool profile, shoulder diameter, pin length, tool rotation speed and transverse speed play equally important roles to contribute the result of the free-defect FSW welds, where the matter of choosing the best tilting angle can vary for each different experiment set up. However, assuming all these parameters is fixed at optimum value respectively, the most suitable tilting angle can be theoretically calculated.

The previous research of Shultz and Cole [9] have suggested a powerful model to calculate the maximum joint efficiency as stated in Equation 1, which is the percentage of thinned thickness in the weld zone (t_w) to parent material thickness (t_{wp}) [9].

$$J_{ET} = \frac{t_w}{t_{wp}} \times 100\% \qquad \text{(Eqn 1)}$$

$$t_w = t_{wp} - \left\lceil \frac{d_{plunge} - \sin(\partial) \times (\emptyset_s - \emptyset_p)}{2} \right\rceil - \cos(\partial) \times (l_{pin} - l_D) \qquad \text{(Eqn 2)}$$

The value of thinned thickness in the weld zone can be calculated from Equation 2, where d_{plunge} is the plunge depth, ∂ is titl angle, $\emptyset_s$ and $\emptyset_p$ is shoulder and pin diameters , l_{pin} is pin length and l_D is dish distance [9]. Equation 2 is originated from Equation 1, where when used in reverse can allow the determination of optimum range of tilting angle by specifying the reasonable range of maximum joint efficiency.

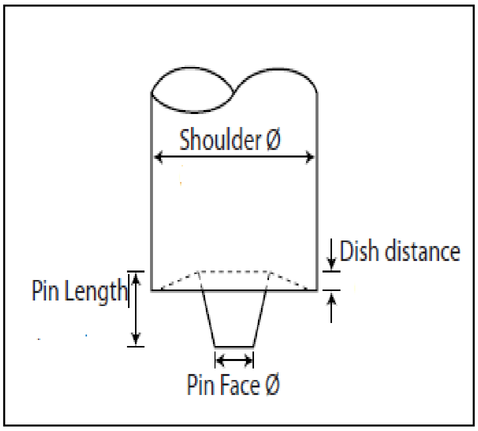


FIGURE 17 : Tool Cross section [9]

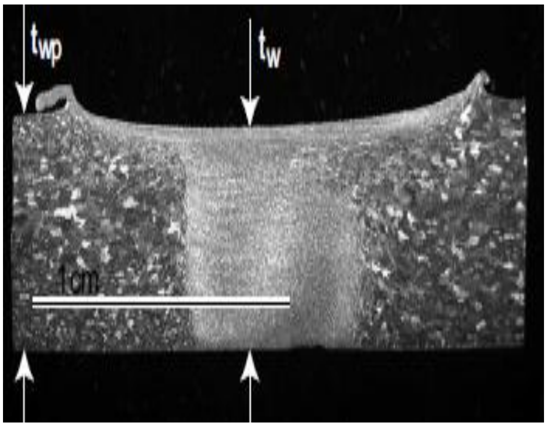


FIGURE 18: Ratio of thinned thickness of the weld zone to parent material thickness [9]

The experimental result proves increasing the tilting angle can reduce the formation of tunnel defects but the angle increment must be maximized at proper extent. If the tilt angle is too large, it will reduce the maximum joint efficiency as calculated in Table 9 below. The calculated joint efficiency is calculated using Equation 2, where other fixed variables is plugged in based on the experimental values from Table 3.

TABLE 9 : Joint Efficiency and presence of defects

Tilting Angle (^{o})	**T_w, Thinned Thickness of Welded Joint (mm)**	**T_{wp}, Parent Material Thickness (mm)**	**Maximum Joint Efficiency (%)**	**Tunnel Defects formation**
0	9.9	10	99	Large
2.5	9.67		96.7	Large
3.5	9.58		95.8	Little
5.0	9.42		94.2	Very Little

The calculated joint efficiency above means the maximum theoretical value, where in real application it will be lower due to mass loss to formed flash and chips deposited outside the weld joint. This model does not cover this factor due to its little significant and its effects can be neglected.

In context of this experiment, it can be seen that the optimum range of tilting angle is in between 3.5^o and 5^o, where it demonstrates acceptable maximum joint efficiency more than 90% while almost eliminating the tunnel defects formation. Further increase of tilting angle is predicted to totally remove the occurrence of tunnel defects as long as it still maintains high allowable joint efficiency required.

As better alternative than increasing the tilting angle more than its optimum range, the tool rotational speed can be increased or transverse speed can be slowed or both to generate more tool-work pieces frictional heat. This extra heat will assist the softening and flow of the plasticized material during mixing and stirring process, without much reducing the joint maximum efficiency.

CHAPTER 5
CONCLUSION

In conclusion, the final product demonstrates great potential to fully utilize the existing CNC milling machine for FSW, resulting comparable quality to actual FSW machine. Increasing the tilting angle while operating the FSW has been proven can reduce or possibly eliminate the tunnel defects but at the same time increase the risk of flash formation. The visual inspection on the weld joint shows that increasing the tilting angle at optimum range of 3.5^0 to 5^o can reduce the possibility of having tunnel defects. This can be explained by the inclined orientation of welding tool which can smoothen the flow of plasticized material during mixing and stirring process. However, further increment of tilting angle more than 5^o is not favourable as it will only encourage severe flash formation and reduce weld maximum joint efficiency. In case the tunnel defects still present while operated at optimum tilting angle, either adjustment on process parameters by increasing the tool rotational speed or reducing the travel speed and plunge depth can serve as better alternative.

REFERENCE

[1] ESAB AB Welding Automation. (2010). *Friction Stir Welding Technical Handbook*.

[2] R.S. Mishra, Z. M. (2005). Reports: A review Journal. *Friction Stir Welding and Processing* , 6.

[3] *Wikipedia*. (n.d.). Retrieved Feb 2013, from http://en.wikipedia.org/wiki/Friction_stir_welding

[4] P L Threadgill, A. J. (2009, March). Friction Stir Welding of Aluminium Alloy.

[5] B. London, M. Mahoney, B. Bingel, M. Calabrese, D.Waldron, in: *Proceedings of the Third International Symposiumon Friction Stir Welding*, Kobe, Japan, 27–28 September, 2001.

[6] *Wikipedia*. (n.d.). Retrieved March 2013, from http://en.wikipedia.org/wiki/downforce

[7] NDT Resource Center. (n.d.). Retrieved March 2013, from http://www.ndt-ed.org/EducationResources

[8] Sanjay Kumar, S. K. (September 2012). Optimization of process parameters for Friction Stir Welding of joining A6061 and A6082 alloys by Tahuchi method. *Journal of Mechanical Engineering Science* .

[9] Edward F.Shultz, E. G. (2010). *Effect of Compliance and Travel Angle on Friction Stir Welding with Gaps.* Madison: Department of Mechanical Engineering , University of Wisconsin.

[10] Baghel, P. K. (2012). *Design and development of Fixture for Friction Stir Welding.* New Delhi:Department of Mechanical Engineering, Delhi Technological University

[11] Badheka, Vishvesh J. (2010). *Utilisation of a conventional milling machine for friction stir welding of commercial aluminium.*

[12] Andrew, R. E. (December 2004). *Friction Stir Welding - An alternative method for sealing nuclear waste storage canister.* Cambridge, United Kingdom: TWI Ltd.

[13] Mokhtar, S. N. (2010). *Fracture Toughness and Fatigue crack growth test of friction stir welded plates.* University Technology Petronas.

[14] Arbegast, W. J. (2003, October 1). Friction Stir Joining : Characteristic Defects. *MET 492-Special Topics : Friction Stir Processing* .

[15] Bo Li, Y. S. (2010). The study on defects in aluminum 2219-T6 thick butt friction stir welds with the application . *Material and Design* .

[16] Y.G. Kima, H. F. (2005). Three defect types in friction stir welding of aluminum die casting alloy. *Material, Science and Engineering* .

APPENDIX 1

Wrought alloy groups		Basic temper designations	
1xxx	Unalloyed 99% Al	F	As fabricated
2xxx	Copper principal alloying element: gives substantial increases in strength, permits precipitation hardening, reduces corrosion resistance, ductility and weldability	O	Annealed: there may be a suffix to indicate the specific heat treatment.
3xxx	Manganese: increases strength through solid solution strengthening and improves work hardening	H	Strain hardened (cold worked): it is always followed by two or more digits to signify the amount of cold work and any heat treatments that have been carried out
4xxx	Silicon: increases strength and ductility, in combination with magnesium produces precipitation hardening	W	Solution heat treated: applied to alloys that precipitation harden at room temperature (natural aging) after a solution heat treatment. The designation is followed by a time indicating the natural aging period, *e.g.* W 1 h
5xxx	Magnesium: increases strength through solid solution strengthening and improves work hardening ability	T	Thermally aged: T1: cooled and naturally aged T2: cooled, cold worked and naturally aged T3: solution heat treated, cold worked and naturally aged T4: solution heat treated and naturally aged T5: cooled and artificially aged T6: solution heat treated and artificially aged T7: solution heat treated and overaged or stabilised T8: solution heat treated, cold worked and artificially aged T9: solution heat treated, artificially aged and cold worked
6xxx	Magnesium-silicon		
7xxx	Zinc-magnesium: substantially increases strength, enables precipitation hardening, can cause stress corrosion		
8xxx	Other elements - Li, for example, substantially increases strength and Young's modulus, provides precipitation hardening, decreases density		