CERTIFICATION OF APPROVAL

Effect of welding tool geometry on microstructure and hardness in Friction Stir Welded Plates

by

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CERTIFICATION OF ORIGINALITY

This is to certifty that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and the original work contained herein have not been undertaken or done by unspecified sources or persons.

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ABSTRACT

Friction Stir Welding is a solid state welding process for joining aluminum and other metallic alloys where the metal is not melted during the process and the original metal characteristic remains unchanged as far as possible. It was invented in 1991 in The Welding Institute (TWI), United Kingdom to substitute conventional welding of aluminum alloy. Friction Stir Welding can be use in shipbuilding marine, aerospace industry and railway industries. The welding parameters and tool pin profile play a major role in defining the weld quality. This report covers the theoretical background of friction stir welding, literature reviews on related research works, implemented methodology, and current results. The objective of the project is to study the effect of welding tool geometry on the microstructure and hardness of welded plates. The project will focus on three types of pin design which are straight cylindrical, threaded cylindrical and tapered. The tools are fabricated using CNC Machine and undergo heat treatment. Two plates of aluminum alloy work piece were set-up in butt joint configuration and clamped rigidly during welding operation. The work pieces are welded using different type of welding tool pin profile and different sets of parameters. Welded work pieces that have been welded by the designed tools were undergo lab testing which are hardness and microstructure test in order to rectify the difference of the weld results. From this project, it can be observed that different geometry of tool will produce different weld results.

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FAIZUL AZIZI BIN AHMAD NORDIN

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CHAPTER 1

INTRODUCTION

1.1 Background Study

Friction Stir Welding (FSW) is a solid-state joining method that was developed in early 1990s by The Welding Institute (TWI). This technique, which uses a rotating, non-consumable tool to weld the work pieces together by “stirring” together the surrounding material, was initially developed for use on aluminum alloys because of the lower temperatures and stresses required to weld those alloys and the ready availability of tool materials to perform the welding [1]. Compared with the usual welding techniques, FSW is energy efficient, environment friendly and versatile [2].

In FSW, a cylindrical-shouldered tool, with a profiled threaded/unthreaded probe (nib or pin) is revolved at a constant speed and fed at a constant traverse rate into the joint line between two pieces of sheet or plate material, which are butted together. The parts have to be clamped rigidly onto a backing bar in a manner that prevents the abutting joint faces from being forced apart. The length of the nib is slightly less than the weld depth required and the tool shoulder should be in intimate contact with the work surface. The nib is afterward moved against the work, or vice versa [3].

Frictional heat is generated between the wear-resistant welding tool shoulder and nib, and the material of the work pieces. This heat, along with the heat generated by the mechanical mixing process and the adiabatic heat within the material, cause the stirred materials to soften without reaching the melting point (hence cited a solid-state process), allowing the traversing of the tool along the weld line in a plasticized tubular shaft of metal. As the pin is moved in the direction of welding, the leading face of the pin, assisted by a special pin profile, forces plasticized material to the back of the pin while applying a substantial forging force to consolidate the weld metal. The welding of the material is facilitated by severe plastic deformation in the solid state, involving dynamic recrystallization of the base material [3].

However, as for any other welding processes, FSW requires a careful choice of process parameter in order for micro structural and mechanical characteristics and defect free welds to be consistently reproducible. Defects in FSW have already been classified as flow or geometric related [4]. The processes are illustrated in *Figure 1*.

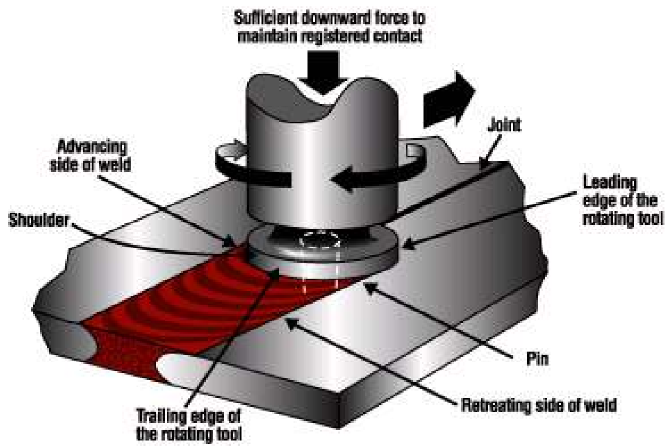
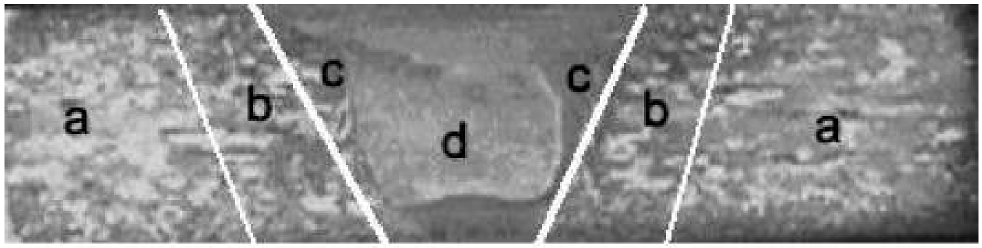


Figure 1 : Process of Friction Stir Welding [5]

FSW joints usually consist of four different regions as shown in Figure 2. They are: (a) unaffected base metal, (b) heat affected zone (HAZ), (c) thermo-mechanically affected zone (TMAZ) and (d) friction stir processed (FSP) zone. The formation of above regions is affected by the material flow behaviour under the action of rotating non-consumable tool [6]. However, the material flow behaviour is predominantly influenced by the FSW tool profiles, FSW tool dimensions and FSW process parameters [7]. The available literature focusing on the effect of tool profiles and tool shoulder diameter on FSP zone formation is very minimal. Hence, in this investigation an attempt has been made to understand the effect of tool profiles and tool shoulder diameter on FSP zone formation. This paper presents the relation between the FSP zone formation and tensile properties of friction stir welded AA2011 aluminum alloy joints.



a = Unaffected Base Metal
b = Heat Affected Zone (HAZ)
c = Thermo-Mechanically Affected Zone (TMAZ)
d = Friction Stir Processed (FSP) Zone

Figure 2: Different regions of FSW joint [8].

A number of potential advantages of FSW over conventional fusion-welding processes have been identified:

i. Good dimensional stability and repeatability
ii. No loss of alloying elements
iii. Solid-phase process
iv. Excellent mechanical properties in the joint area
v. No consumables – friction stir welding steel tools can weld over 1000m of aluminum and no filler or gas shield is required for aluminum
vi. Improved materials use (e.g. joining different thickness) allows reduction in weight
vii. Fine recrystallized microstructure
viii. Low environmental impact
ix. Minimal surface cleaning required
x. Decreased fuel consumption in lightweight aircraft, automotive and ship applications
xi. Easily automated on simple milling machines - lower setup costs and less training.
xii. Can operate in all positions (horizontal, vertical, etc), as there is no weld pool
xiii. No harmful emission

However, some disadvantages of the process have been identified:

- Exit hole left when tool is withdrawn.
- Large down forces required with heavy-duty clamping necessary to hold the plates together.
- Less flexible than manual and arc processes (difficulties with thickness variations and non-linear welds).
- Often slower traverse rate than some fusion welding techniques although this may be offset if fewer welding passes are required.

Friction Stir Welding is a new process, but has been used in production applications since 1995 in Europe. The first applications involved welding of extrusions to form paneling for marine applications. Since then, the process has been commercialized in many other applications, including rail car, automotive, aerospace, heavy truck, medical applications, etc [5]. Nowadays, the process is being moved into fabrication of complex assemblies, yielding significant quality and cost improvements. As the process is maturing, designers are taking advantage of the process, by designing the product specifically for the FSW process.

1.2 Problem Statement

Friction Stir Welding is still considered quite new in Malaysia, compared to other regions around the world especially Europe, America and Japan. According to the literature [1], the main process parameter influencing material flow and weld quality include tool geometry (pin and shoulder design relative dimensions of pin and shoulder), welding parameters (tool rotation rate and direction, traverse speed, plunge depth, tilt angle), base material flow stress behavior and temperature as well as the interaction between the work piece material and the various weld tool features [1]. With consideration to the influence of the tool in the FSW flows field, two different approaches of tool related flows are frequently mentioned in literature: shoulder-driven flow and pin-driven flow. Although several studies concerning the influence of pin geometry in material flow during FSW have been carried out [8, 9], it is still lack of data and research or implementation in Malaysia. Nevertheless, a strong influence of pin geometry on the micro structural and mechanical behavior of the FSW has already been reported [4]. It is important to know the effect of tool geometry on FSW in order to get better welding result.

1.3 Objective

i. To study the effect of welding tool geometry on microstructure and hardness of friction stir welded plates

1.4 Scope of the Study

For this project, the study will focus on three types of pin design which are straight cylindrical, threaded cylindrical and truncated cone pin. The study only focused on steel H13 as the material of the tools. This alloy is one of the Hot Work, Chromium type tool steels [10]. For the work pieces, the author decides to focus on 10mm thickness aluminum alloy 2011. Aluminium alloy 2011 is a high mechanical strength alloy that machines exceptionally well [11]. The tools will be used to join two Aluminum Alloy 2011 plates in butt joint configuration. The samples then were used for conduct hardness and macrostructure examination in order to examine effect on each welded plates.

CHAPTER 2

LITERATURE REVIEW

The design of the tool is a critical factor as a good tool can improve both the quality of the weld and the maximum possible welding speed. It is desirable that the tool material is sufficiently strong, tough and hard wearing, at the welding temperature. Further it should have a good oxidation resistance and a low thermal conductivity to minimize heat loss and thermal damage to the machinery further up the drive train. Hot-worked tool steel such as AISI H13 has proven absolutely acceptable for welding aluminum alloys within thickness ranges of 0.5 - 50 mm but more advanced tool materials are necessary for more demanding applications such as highly abrasive metal matrix composites or higher melting point materials such as steel or titanium [3].

Each of the resistance tool parts (pin and shoulder) has a different function. Therefore, the best tool design may consist of the shoulder and pin constructed with different materials. The work piece and tool materials, joint configuration (butt or lap, plate or extrusion) tool parameters (tool rotation and travel speed), and the user’s own experiences and preferences are factors to consider when selecting the shoulder and pin designs [1].

2.1 Design of tool Shoulders

Tool shoulders are designed to produce heat (through friction and material deformation) to the surface and subsurface regions of the work piece. The tool shoulder produces a majority of deformational and frictional heating in thin sheet, while the pin produces a majority of the heating in thin work pieces. Also the shoulder produces the downward forging action necessary for weld consolidation.

The first shoulder design was concave shoulder [12], commonly referred as the standard-type shoulder, and is presently the most common shoulder design in FSW [13,14]. Concave shoulder produce quality friction stir weld, and the simple design is easily machined. The shoulder concavity is produced by a small angle between the edge of the shoulder and the pin, between 6 and 10^{o}. Appropriate operation of this shoulder design requires tilting the tool 2 to 4^{o} from the normal of the work piece away from the direction of travel [1].

Other shoulder design was scroll shoulder. Scrolls are the most commonly observed shoulder feature [1]. The typical scrolled shoulder tool consists of a flat surface with a spiral channel cut from the edge of the shoulder toward the center. Scrolled shoulder tools are operated with only 0.1 to 0.25 mm of the tool in contact with the work piece; any addition work piece contact will produce significant amount of flash. If the tool is insufficient contact, the shoulder will ride on a cushion of material that will smear across the joint line and make a determination of weld quality difficult [15]. Scrolled shoulder tools can weld two plates of different thickness, but some amount of material from the thicker plate is expelled in the form of flash.

Friction stir tool shoulders can also have a convex design. Early attempts at TWI to use a tool with a convex shoulder were unsuccessful, because the convex shape pushes the material away from the pin. The only reported success with a smooth convex tool was with a 5mm diameter shoulder tool that friction stir welded 0.4mm sheet [16]. The advantage of the convex shoulder is that the outer edge of the tool needs to be engaged with the work piece, so the shoulder can be engaged with the work piece at any location along the convex surface. This shoulder design allow for a larger flexibility in the contact area between the shoulder and the work piece, improves the joint mismatch tolerance, increase the ease of joining different thickness work pieces, and improves the ability to weld complex curvatures[1].

2.2 Pin Designs

Friction stirring pins create deformational and resistance heating to the joint surfaces. The pin is designed to dislocate the faying, or contacting, surfaces of the work piece, shear material in front of the tool, and move material behind the tool. In addition, the depth of deformational and tool travel speed are determined by the pin design [1].

The primary function of the non-consumable rotating tool pin is to stir the plasticized metal and move the same behind it to have good joint. Pin profile plays a crucial role in material flow and in turn regulates the welding speed of the FSW process [17]. The pin normally has cylindrical plain, frustum tapered, threaded and flat surfaces. Pin profiles with flat faces (square and triangular) are associated with eccentricity. This eccentricity allows incompressible material to pass around the pin profile [8]. Eccentricity of the rotating object is related to dynamic orbit due to eccentricity [18]. The relationship between the static volume and dynamic volume decides the path for the flow of plasticized material from the leading edge to the trailing edge of the rotating tool [8].

The pin length is depends by the thickness of the work piece, the tool tilt, and the desired clearance between the end of the pin and the anvil. It is believed that the depth penetration of the pin of welding tool can only be done 80% from the thickness of work piece [19]. In the early TWI work [20], an optimal ratio of shoulder diameter to pin diameter was suggested to assist with tool design. However, the ratio (between 2.5 to 1 and 3 to 1) [20] was dependent on aluminum alloy composition and only applied to 6mm thick plate. As the work pieces thickness increase, the thermal input from the shoulder decrease and the pin must supply more thermal energy. Thus, while the ratio of shoulder diameter to pin determined for 6mm plate may produce a void-free weld, this may not be the optimal ratio for plates thicker than 12mm.

Several researches have examined the effect of tool dimensions on friction stir weld quality. Reynolds and Tang [9] several different variations of cylindrical pins with a concave shoulder to show that defect-free friction stir welds in 8.1mm thick 2195 aluminum alloys could be produced with pin diameter ratios ranging from 2 to 1 to 3.125 to 1. Peel et al. [21] evaluated pin with either a standard metric M5 thread (5mm wide with 0.8mm pitch) or a wider pin (6mm wide) with a coarser thread (1mm pitch). At higher travel speeds (200 mm/min), the broader 6mm tool with the coarser threads was more effective in disrupting the faying interface between the two joined work pieces. This change of pin design produced a 16% increase in joint efficiency (tensile strength of weld divided by tensile strength of base material).

2.2.1 Flat-Bottom Cylindrical Pin

The flat bottom pin design is currently the most commonly used pin design [22]. The surface velocity of a rotating cylinder increase from zero at the center of the cylinder to a maximum value at the edge of the cylinder. The lowest point of the flat-bottom pin tilted to a small angle to the axis is the edge of the pin, where the surface velocity is high. The increased surface velocity at the bottom of the pin would increase the throwing power of the pin, or the ability of the pin to affect metal below the end of the pin.

2.2.2 Threadless pin

Threadless pins are useful in specific FSW applications where threads features would not survive without fracture or severe wear. Tools operating under aggressive environments (high temperature or highly abrasive composite alloys) cannot retain threaded tool features without excessive pin wear [1]. Threadless pins have been used to purposely produce defective welds [22] and to study material flow [23].

2.2.3 Truncated Cone Pins

A simple modification of a cylindrical pin is truncated cone pin [24]. Cylindrical pin were found to be sufficient for aluminum plate up to 12 mm thick, but researchers wanted to friction stir weld thicker plates at faster travel speed. Truncated cone pins have lower transverse load (compared to a cylindrical pin), and the largest moment load on a truncated cone is at the base of the cone, where it is the strongest [1].

2.3 Tool Steel H13

Tool steel refers to a variety of carbon and alloy steels that are mainly well-suited to be made as welding tools. The advantages to using tool steel as friction stir tooling material include easy availability and machinability, low cost, and established material characteristic. It is because of their hardness, resistance to abrasion, their ability to hold a cutting edge, and their resistance to deformation at elevated temperature. With carbon content between 0.7% and 1.4%, tool steels are manufactured under carefully controlled conditions to produce the required quality [19]. An AISI-SAE grade of steel is the most common scale used to classify various grades of tool steel. AISI H13 is a chromium-molybdenum hot-worked air-hardening steel and is known for good elevated-temperature strength, thermal fatigue resistance, and wear resistance [22]. AISI-SAE classification of principal types of tool steel shows in Table 1 below and table 2 shows chemical composition of tool steel H13.

Table 1: AISI-SAE classification of principal types of tool steel [10]

AISI-SAE Number	Description	Typical Uses
W1 or W2	Water Hardening	Cold-heading dies, woodworking tools
S1 or S2	Shock Resistance	Chisels, hammers
O1 or O2	Oil Hardening	Cold forming disc, cutting tools
A2 or A5	Air Hardening	Thread rolling dies
D3 – D4	High Carbon, High Chromium	Uses under 900F, forming dies
H12, H13, H16	Chromium, Hot work	Al/Mg Extrusion dies, mandrels, forging dies
H21 or H23	Tungsten, Hot Work	Brass/Nickel Extrusion dies
T1 or T15	Tungsten High Speed Steel	Original High-Speed Steel
M1, M3, M10, M15	Molybdenum High Speed Steel	98% of all HSS used in US

Table 2: Chemical composition of tool steel H13 [25]

Element	Weight %
C	0.32-0.45
Mn	0.20-0.50
Si	0.80-1.20
Cr	4.75-5.50
Ni	0.30
Mo	1.10-1.75
V	0.80-1.20
Cu	0.25
P	0.03
S	0.03

2.4 Aluminum work piece 2011

Aluminium alloy 2011 is a high mechanical strength alloy that machines exceptionally well. It often called a Free Machining Alloy or 'FMA' it is well suited to use in automatic lathes. Machining at high speeds produces fine chips that are easily removed. The excellent machining characteristics allow the production of complex and detailed parts. In some circumstances Aluminum alloy 2011 can replace free machining brass without the need for alterations to tooling. It has poor corrosion resistance, which means parts made from Aluminum alloy 2011 tend to be anodized to provide additional surface protection. When higher levels of corrosion resistance are required, 6262 T9 may be a suitable replacement [11]. Table 3 shows typical chemical composition for aluminum alloy 2011

Table 3: Typical chemical composition for aluminum alloy 2011 [11]

Element	Weight%
Si	0.4
Fe	0.7
Cu	5.0-6.0
Pb	0.2-0.6
Bi	0.2-0.6
Zn	0.3
Other	0.15
Al	Balance

CHAPTER 3

METHODOLOGY

3.1 Research of FSW

A thorough literature review was done through reference books, internet and journals for further understanding. From the researches, the author decides to use steel H13 as material for welding tools and 10mm thickness aluminum alloy 2011 as work pieces.

3.2 Design of welding tool for FSW

One of the important criteria in Friction Stir Welding is the design of welding tool. Good design of welding tool can improve the quality of the welding. The tool should be strong and hard wearing, at the welding temperature. Further it should have a good oxidation resistance and a low thermal conductivity to minimise heat loss and thermal damage to the machinery further up the drive train.

3.2.1 Design of welding tool using AutoCAD

Welding tools for the FSW will be designed using AutoCAD. The tool needs an extraordinary design with the purpose of run onto work pieces. For this project, the author has design three types of welding tools which are cylindrical pin, tapered pin and threaded pin. All tools are designed with 20mm shoulder diameter and 8mm pin length while the each type of tool have different pin diameter. In addition, all of the welding tools will have 62mm shaft in order to attach the tools onto the Computer Numerically Controlled (CNC) MAZAK Milling Machine. Figure 3 shows the schematic representative of each welding tool and General assembly's drawing of each tool are attached in Appendices. Figure 3 shows schematic representative of welding tools used in the research.

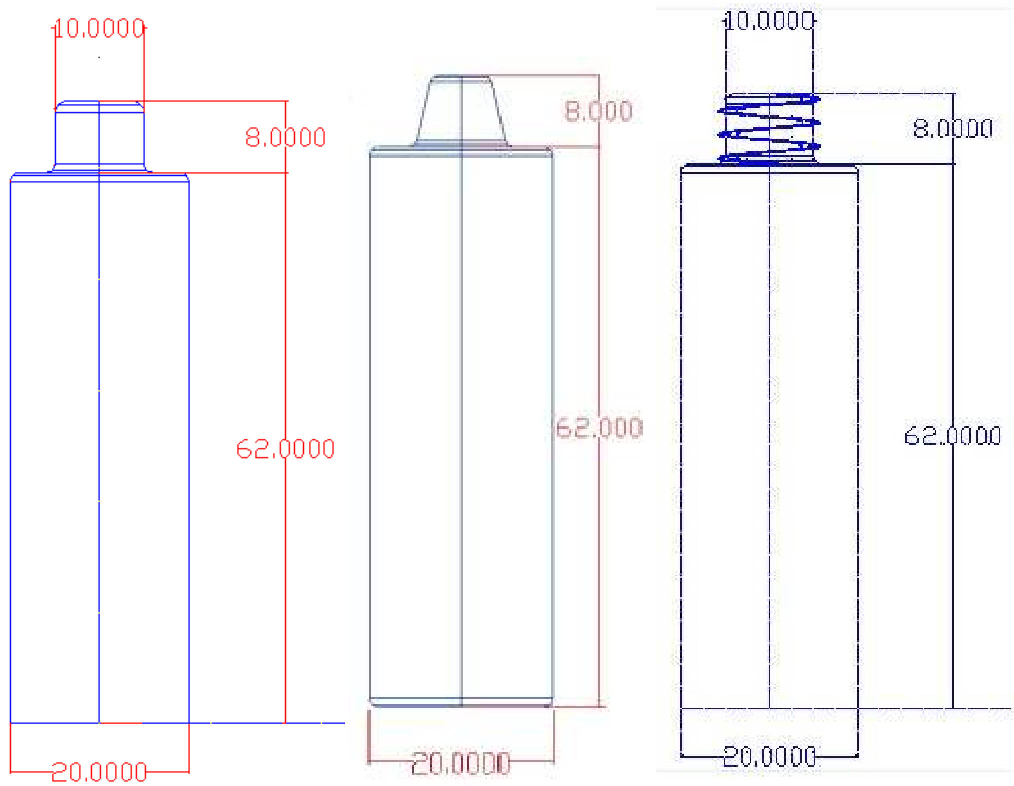


Figure 3: Schematic representative of welding tools used in the research

3.2.2 Tools fabricated using CNC Lathe Machine

Once the design has finished, the tool will set for fabrication using Computer Numerically Control, (CNC) Lathes Machine. The tool will be designed by the Computer-aided manufacturing (CAM) process; the resulting file uploaded to the machine, and once set and trial the machine will continue to turn out parts under the supervision of an operator. CNC Lathe MAZAK Machine is shown in figure 4.

Figure 4: CNC Lathe MAZAK Machine [26]

The machine is controlled electronically via a computer menu style interface; the program may be modified and displayed at the machine, along with a simulated view of the process. The setter/operator needs a high level of skill to execute the process, however the knowledge base is broader compared to the older production machines where intimate knowledge of each machine was considered essential. These machines are often set and operated by the same person, where the operator will supervise a small number of machines. Figure 5 show set up tool steel for fabrication of FSW welding tool and cylindrical pin tool after fabricated using CNC Lathe Turning Machine.

Figure 5: (a) Set up tool steel for fabrication of FSW welding tool. (b) Cylindrical pin tool after fabricated using CNC Lathe Turning Machine

3.2.3 Heat treatment

The tools then undergo the heat treatment before used to run onto work pieces. Heat treatment involves the use of heating or chilling, normally to extreme temperatures, to achieve a desire result such as hardening or softening of a material. Heat treatment techniques consist of annealing, case hardening, precipitation strengthening, tempering and quenching.

Heat Treatment is the controlled heating and cooling of metals to alter their physical and mechanical properties without changing the product shape. Heat treatment is sometimes done inadvertently due to manufacturing processes that either heat or cool the metal such as welding or forming. Figure 6 shows picture of VMK-135-S High Temperature Furnace.

Figure 6: VMK-135-S High Temperature Furnace

Heat Treatment is often associated with increasing the strength of material, but it can also be used to alter certain manufacturability objectives such as improve machining, improve formability, restore ductility after a cold working operation [27]. Thus it is a very enabling manufacturing process that can not only help other manufacturing process, but can also improve product performance by increasing strength or other desirable characteristics.

For this project, the procedures of the heat treatment are as follow:

1. The welding tool is inserted in the Tube Furnace and preheated initially for two hours to raise from -17.78 – 732°C (0 – 1350°F)
2. Next, the welding tool is continued preheated; slowly from 732 – 760°C (1350 – 1400°F) for another two hours
3. Then the temperature will be raised to 1000°C (1800°F) for one hour
4. Finally it will be cooled down to room temperature 24°C (75°F) for two hours

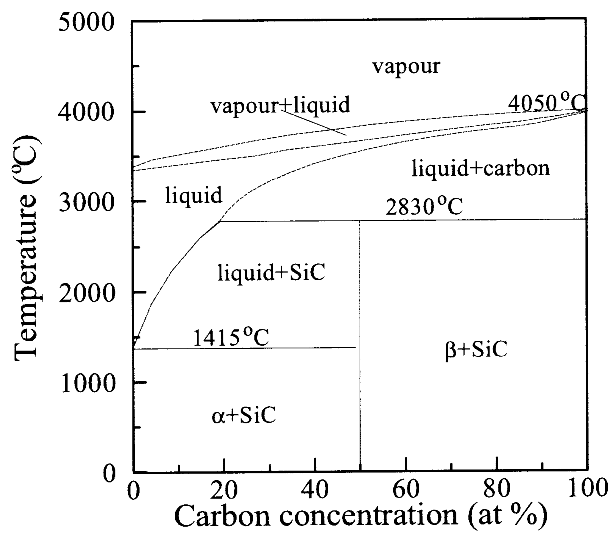


Figure 7: Carbon - silicon phase diagram

Based on carbon – silicon phase diagram shown in figure 7, at 32% carbon composition, the required temperature for phase α + SiC to change to liquidus phase, liquid + SiC is 1415°C. During heat treatment, the applied temperature is 1000°C. Therefore, it can be observed, with reference to the phase diagram above, the phase remains as phase α + SiC. However, a few mechanical properties have changed due to heat treatment. Such heat treating will increase the welding tools strength in terms of yield strength, tensile strength as well as ductility. Figure 8 shows FSW tools after undergo heat treatment process.

Figure 8: FSW tools after undergo heat treatment process

3.3 Welding process

After the heat treatment process, the tools will attach to CNC MAZAK milling machine in order to run onto work pieces. Most CNC milling machines (also called machining centers) are computer controlled vertical mills with the ability to move the spindle vertically along the Z-axis. This extra degree of freedom permits their use in die sinking, engraving applications, and 2.5D surfaces such as relief sculptures. When combined with the use of conical tools or a ball nose cutter, it also significantly improves milling precision without impacting speed, providing a cost-efficient alternative to most flat-surface hand-engraving work.

The welding process had been ease with the addition of the jig which is obtained to support the work piece and gives a better platform during the welding process. A 127mm x 280mm x 25mm aluminum block was obtained and four holes are drilled across the jig in order to hold the work piece in a better firm position and ensure the forces created by the welding tool does not broaden and cause the final product to be sloping out of position. Figure 9 show work piece placed on top of the jig while welding tool attach to spindle.

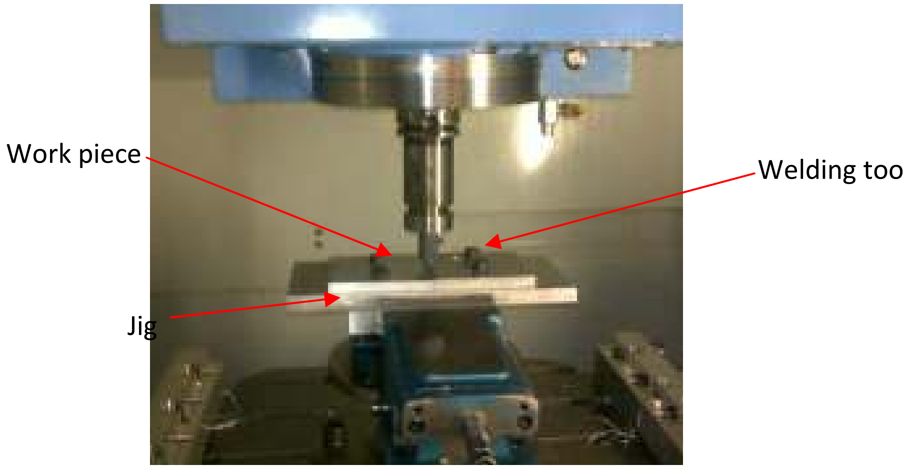


Figure 9: Work piece placed on top of the jig while welding tool attach to spindle

Before conduct the experiment using different tools, four experiments have been done using different parameters in order to select the best parameters to be used in the experiment to identify the effect of different geometry of welding tool on work pieces. Several parameters of FSW are shown in Table 4.

Table 4: Welding parameter for FSW

Run No	Date	Spindle speed (N)/ (rev/min)	Feed Rate (S)/ (mm/min)	Depth of penetration (mm)	Length of weld line (mm)
1	03/03/2010	2500	70	8.0	70
2	01/03/2010	2500	50	8.1	70
3	02/04/2010	2500	30	8.0	70
4	20/04/2010	2500	100	8.0	70

The welded work pieces will be tested to study the effect of the welding tool to the work pieces. It will be done by conducting microstructure examination and hardness test to the welded work pieces. The results of the tests then will be compared and discussed.

3.4 Microstructure examination

Optical microscope was used to identify and analyse the microstructure of Composite 1 and Composite 2. For this project, microstructure test are done in order to compare the effect of using different welding tool geometry on microstructure of the aluminum alloy 2011. The specimens were cut into small pieces and then mounted using hot mounting technique. Then the specimens were ground by wet grinding technique using silicon carbide papers (240, 400, 600, 1000, 1200 grit). Keller's reagent was used as an etchant to reveal the microstructure of the composites.

3.4.1 Sample preparation

In order to conduct microstructure test, a sample preparation is needed by applying Metallorgraphic Technique. Aluminum and aluminum alloys are difficult to prepare because they are soft and contain oxide particles which can become dislodged and scratch the surface. Softer alloys generally are difficult to prepare by mechanical polishing because:

- Deformation caused by cutting and grinding extends greater depth
- The embedding of abrasive particles in the metal during polishing is more likely
- Relief between the matrix and second-phase particles, which are considerably harder than the matrix, develops more readily during polishing.

3.4.2 Sectioning

Sectioning is cutting or separating the work piece from a larger size. Sectioning can be done using non-ferrous abrasive cutter. The intended area to be examined is the welded area region.

3.4.3 Mounting

After the work piece being sectioned into a small specimen, it will undergo mounting process. Small specimens generally require mounting so that the specimen is supported in a stable medium for grinding and polishing. The medium chosen can be either a cold curing resin or a hot mounting compound. During this stage, Auto Mounting Press was used with certain parameters as shown in table 5. Figure 10 shows Auto Mounting Press Machine.

Table 5: Mounting Parameters

Heating time	1 minute 30 seconds
Cooling time	5 minutes
Pressure applied	3500 psi

Figure 10: Auto Mounting Press Machine

3.4.4 Grinding

The aims of grinding are :

- To remove material deformed during cutting
- To remove the superficial layer of the specimen that covers the material destined for examination
- To prepare a flat surface while introducing only some residual or superficial deformation that can be eliminated during polishing (fine grinding)

For the alluminium alloy work piece sample, the useful abrasive of silicon carbide (SiC) is being used for the grinding purpose. Table below shows the procedure taken for grinding of the aluminum alloy sample. MetaServ 2000 Grinder Machine used in is shown in figure 11.

Table 6: Procedure for fine grinding

Step	Abrasive	Gradation	Lubricant	Rotational Speed, rev/min
1	SiC	60	H_2O	200
2	SiC	120	H_2O	200
3	SiC	240	H_2O	200
4	SiC	400	H_2O	200
5	SiC	600	H_2O	200
6	SiC	1200	H_2O	200

Figure 11: MetaServ 2000 Grinder Machine

3.4.5 Polishing

After grinding process, the sample will undergo polishing process. Polishing is the final step in producing a deformation-free surface that is flat, scratch free, and mirror-like in appearance. Such a surface is necessary to observe the true microstructure for subsequent metallographic interpretation, both qualitative and quantitative. The procedures for polishing are shown in Table 7.

Table 7: Procedure for mechanical polishing

Step	Cloth	Gradation	Abrasive	Rotational speed, rev/min	Time, min
1	Napless	3 µm	DP (paste)	150	1
2	Napless	1 µm	DP (paste)	150	1.5

3.4.6 Etching

Metallographic etching encompasses all processes used to reveal particular structure characteristics of a metal that are not evident in the as-polished condition. Examination of a properly polished specimen before etching may reveal structural aspects such as porosity, cracks, and nonmetallic inclusion. Etching is done by immersion or swabbing with a suitable chemical solution. Main objectives of etching are:

- Attack and reveal the grain boundaries and the interface regions between the matrix and phase constituent
- Cover selected phase constituent surface with a thin film of chemical reaction products that improve or reveal contrast between different structure components
- Cover selected phase area with a thin film of chemical reaction products that die/color the phase in a specific manner to allow phase identification

Table 8: Recommended etching reagent for aluminum alloys [29]

Reagent Name	Chemical composition	Conditions	comments
Keller's Etching	190mL Distilled water 5mL Nitric acid 3mL Hydrochloric acid 2mL Hydrofluoric acid	10-30 seconds immersion. Use fresh	For most aluminum and aluminum alloys

3.4.7 Optical Microscopic

Microstructure is always related to grain size and shape. With the optical microscopy, the light microscope is used to study the microstructure; optical and illumination system are its basic elements. Contrasts in the image produced result from differences in reflectivity of the different regions of microstructure. Analysis of this type are often termed metallographic, since metals were first examined using this method. Figure 12 shows optical microscope that has been used for the research.

Figure 12: Optical microscope

3.5 Hardness Test

Principle of any hardness test method is forcing an indenter into the sample surface followed by measuring dimensions of the indentation (depth or actual surface area of the indentation). Hardness is not fundamental property and its value depends on the combination of yield strength, tensile strength and modulus of elasticity. Depending on the loading force value and the indentation dimensions, hardness is defined as a macro- , micro- or nano-hardness. Macro-hardness tests (Rockwell, Brinell, Vickers) are the most widely used methods for rapid routine hardness measurements. The indenting forces in macro-hardness tests are in the range of 50N to 30000N. Micro-hardness tests (micro-Vickers, Knoop) are applicable when hardness of coatings, surface hardness, or hardness of different phases in the multi-phase material is measured. Small diamond pyramid is used as indenter loaded with a small force of 10 to 1000gf. Nano-hardness test uses minor loads of about 1 nano-Newton followed by precise measuring depth of indentation [30].

3.5.1 Brinell Hardness Test

Figure 13 shows schematic of Brinnell Hardness Test. The Brinell Hardness Number (HB) is calculated by the formula:

$HB = 2F/ (3.14D*(D-(D^2 - D_i^2)^{½}))$

Where

F- applied load, kg

D – indenter diameter, mm

D_i – indentation diameter, mm.

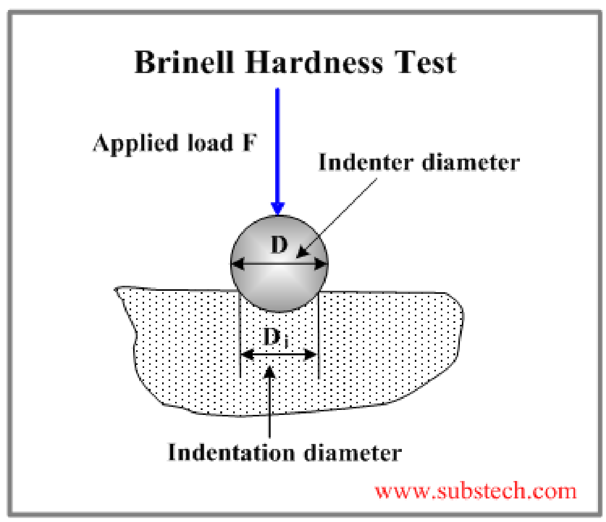


Figure 13: Brinell Hardness Test [31]

3.6 Summary of research methodology

The Summary of research methodology is as below:

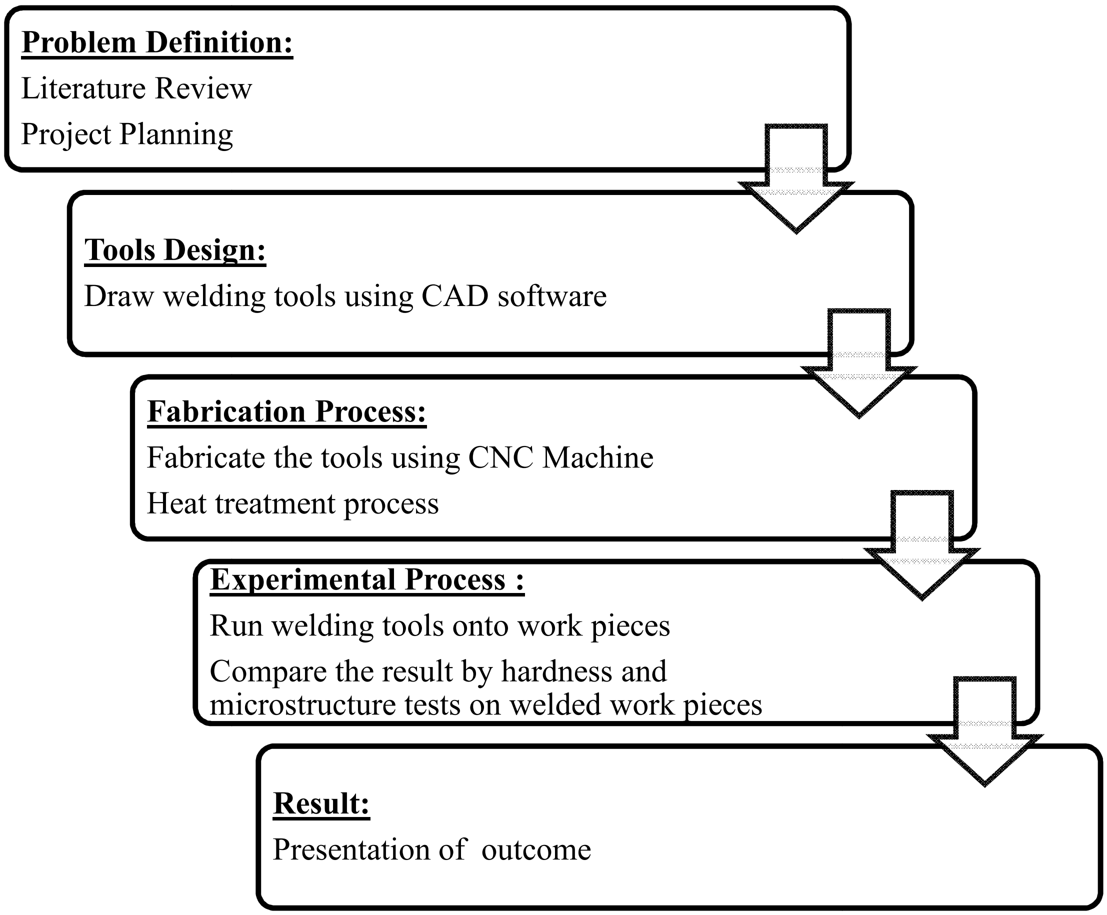


Figure 14: Flow Chart of Methodology

CHAPTER 4

RESULT AND DISCUSSION

4.1 Preliminary run of FSW on work piece

Few experiments have been run to find the best parameters that can be applied on work pieces using FSW. For this section, brief discussions are documented to see the different outcome by applying different sets of parameters in the welding procedure.

4.1.1 Experiment 1 (3rd March 2010)

The first experiment runs on FSW on the work piece. From the figure 15, it can be observed that porosity occur at the bottom surface of the welding zone. . Based on a report [29], porosity is more probably formed mainly due to the inadequate material flow and mixing. For instance, the formation of vortex may cause pores. It was reported that inadequate stirring and mixing can be caused by too fast joining speed, or inadequate combination of welding speed and pin tool rotational rate. At low heat input (i.e. low temperature) material mixing is difficult, leading to the formation of discontinuity and ultimately initiate pores. Table 9 shows welding parameters of experiment 1.

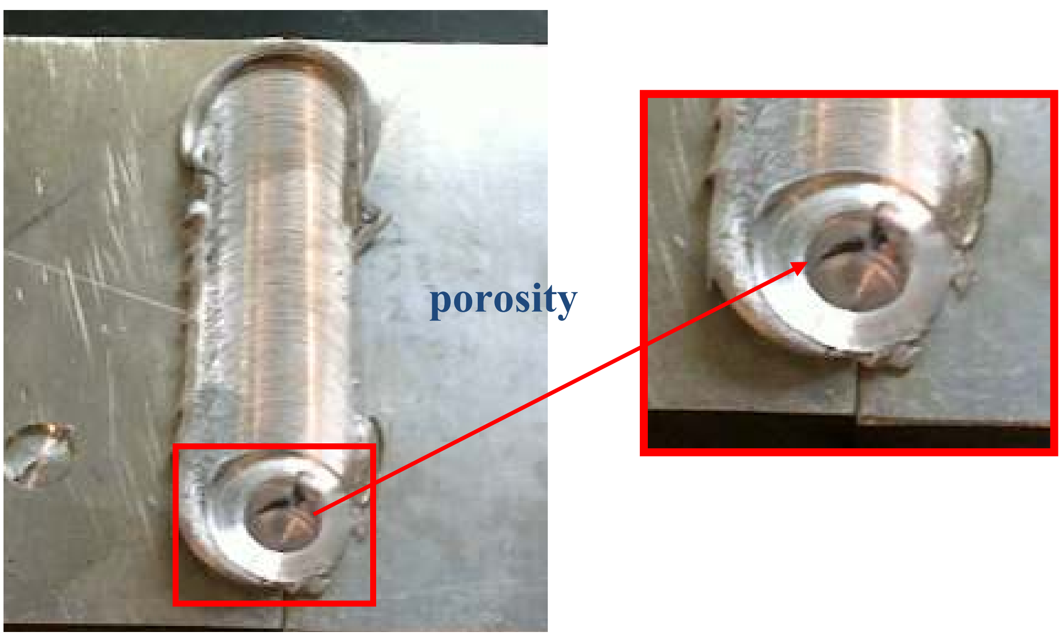


Figure 15: welded result of experiment 1

Table 9: Welding parameters of Experiment 1

Spindle Speed (N) / rpm	2500
Feed Rate (S) / (mm/min)	70
Depth of plunge (mm)	8.0
Length of weld line (mm)	70

4.1.2 Experiment 2 (4th March 2010)

The second experiment is not much different from the first experiment, only decreasing the welding feed rate from 70 mm/min to 50 mm/min and increase the depth of plunge to 8.1mm. Other parameters have been decided to remain unchanged. Same as the first run, the porosity occurred at the bottom of the weld area and also crack occurs along the weld area. Based on literature [35], the exact natural crack initiation in FSW was influenced by the stress level and the severity of surface irregularities. Welding parameters of Experiment 2 are shown in Table 10 and result of experiment 2 is shown in figure 16.

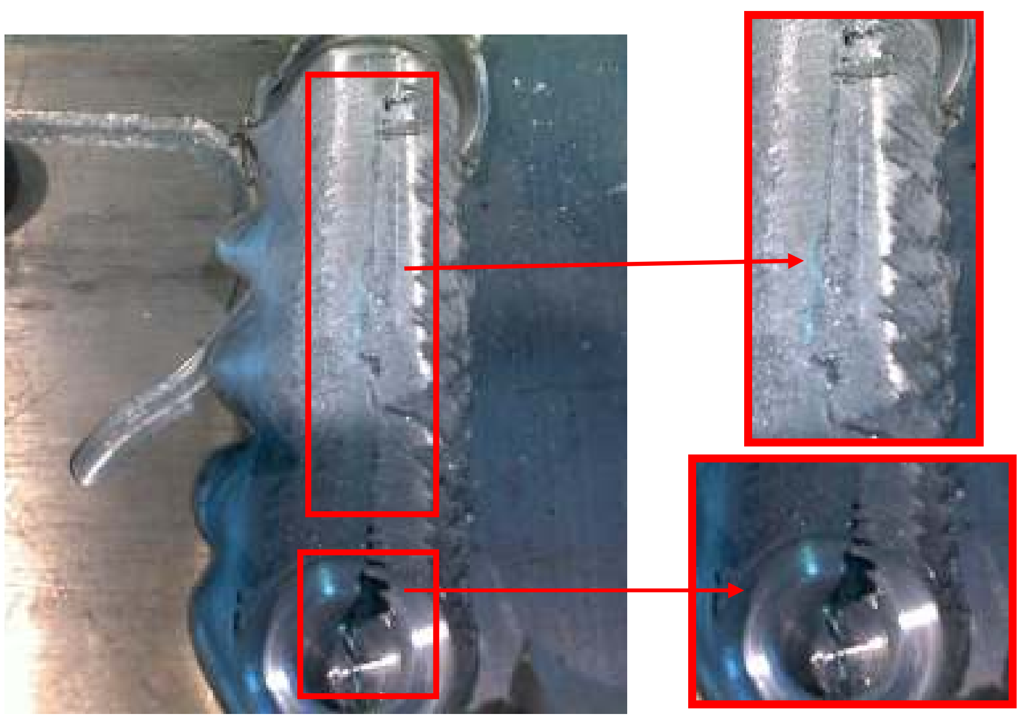


Figure 16: Welded result from experiment 2

Table 10: Welding parameters of Experiment 2

Spindle Speed (N) / rpm	2500
Feed Rate (S) / (mm/min)	50
Depth of plunge (mm)	8.1
Length of weld line (mm)	70

4.1.3 Experiment 3 (2nd April 2010)

Table 11: Welding parameters of Experiment 3

Spindle Speed (N) / rpm	2500
Feed Rate (S) / (mm/min)	30
Depth of plunge (mm)	8.0
Length of weld line (mm)	70

Figure 17: Welded result from experiment 3

From the figure 17, it can be observe that the welding line procedure in experiment 3 is quite similar to the 1st and 2nd Test Run, but the feed rate has been further reduced to 30 mm/min while reducing the depth penetration of the pin by 0.1 mm to 8.0 mm. It is been observed that there are chips spread along the weld area and near the weld area.

4.1.4 Experiment 4 (2nd April 2010)

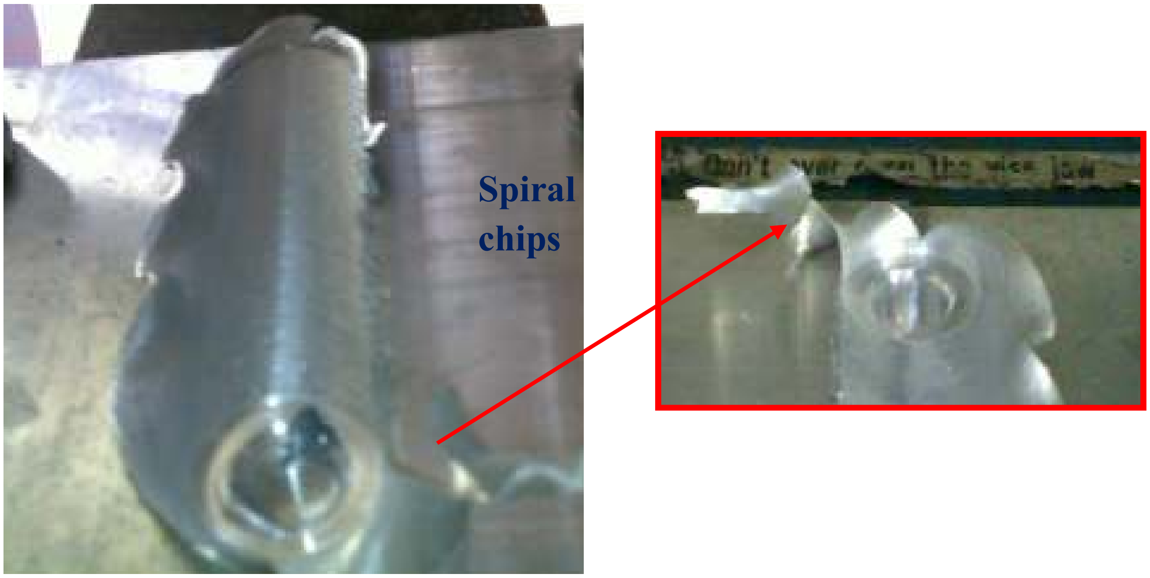


Figure 18: Welded result from experiment 4

Table 12: Welding parameters of Experiment 4

Spindle Speed (N) / rpm	2500
Feed Rate (S) / (mm/min)	100
Depth of plunge (mm)	8.0
Length of weld line (mm)	70

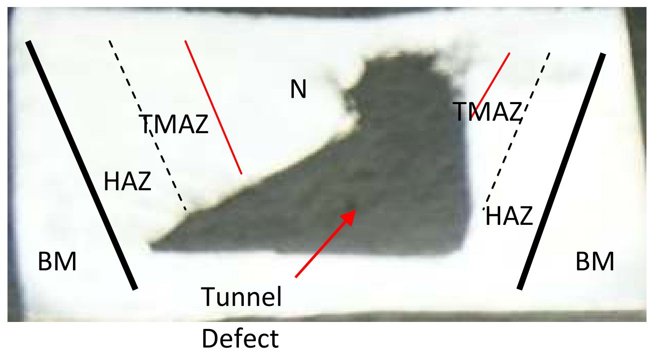
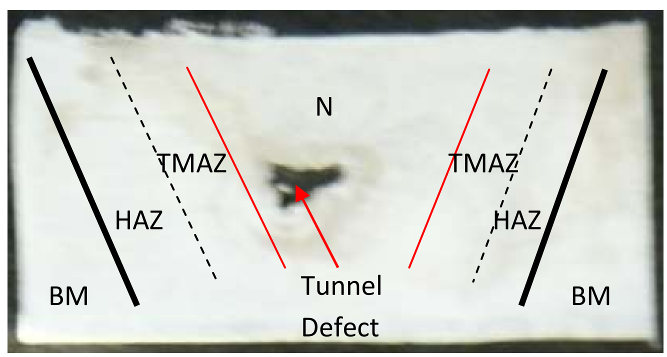
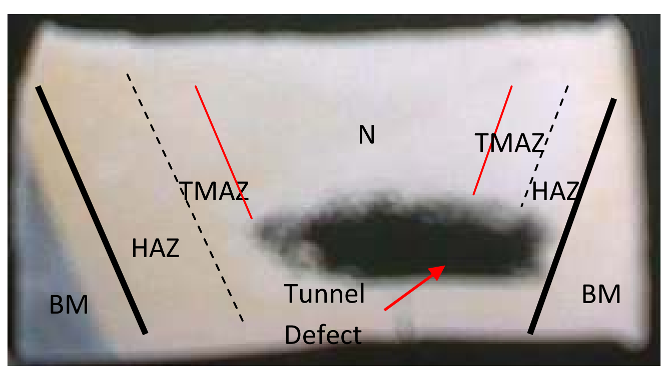
In test run 4, it has been decided to increase the feed rate to 100 mm/min. As usual, the welding line produced are quite satisfactorily, despite some form of defects such as splash occur at the advancing side of the work piece and spiral chips produced at exit hole. Most of the heat generation occurs at the interface between the tool shoulder and the work piece. Significant heterogeneity in heat generation at that interface can lead to defect formation in the form of excess flash due to surface overheating [36].

After 4 experiments which were done in various parameters on the aluminum work piece, the author to use 2500 rpm spindle speed, 70 mm/min feed rate, 70 mm length weld line and depth penetration of the pin 8.0 mm as parameters for next experiment which to study the effect of welding tool geometry. The parameters decided based on results of previous experiment using naked eye.

4.2 Analysis on cross section of Friction Stir Welded plates

After the welding process, the welded plate has been examined to compare the difference in tunnel defect size on each welded plate. The tunnel defect can be seen by naked eye on the cross section area of welded region. The tunnel defect on each welded plate is shown in table 13 below.

Table 13: Cross section of welded plates

Cylindrical Pin Tool	
Tapered Pin Tool	
Threaded Pin Tool	

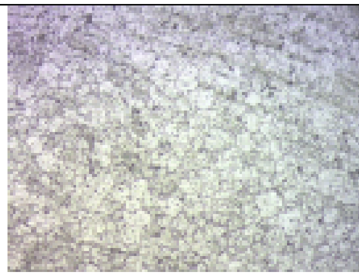
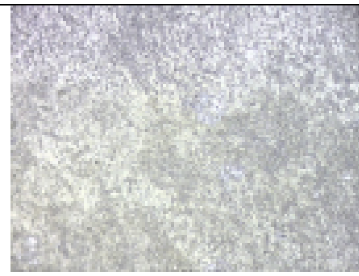
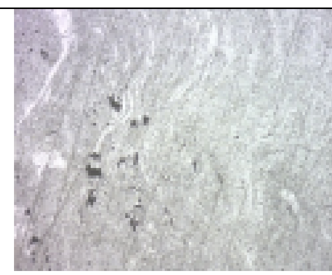
From the above observation, it can be seen that generating of both at the advancing side and retreating side on all of the welded plates generates a non-balancing welding region in terms of generation of different welded zone. This may due of downward forces when the tool shoulder makes contact while it rotates counter-clockwise during welding operation. The contact area width of the tool shoulder becomes larger with the increasing tool plunge down force.

Heat generation during friction stir welding arises from two main sources: friction at the surface of the tool and the deformation of the material around the tool [32]. The heat generation is often assumed to occur predominantly under the shoulder, due to its greater surface area, and to be equal to the power required to overcome the contact forces between the tool and the work piece. Above that, a defect also occurred within the sample, which is referred to as tunnel defect. Based on the observation also, it is shown that sizes of the tunnel defects on the welded plates differ when different geometry of welding tool are used. Cylindrical pin tool produced largest tunnel defect on the welded plates while tapered pin tool produced smallest tunnel defect. It was reported that the formation of porosity is mainly due to two mechanisms (i) volume deficiency and (ii) inadequate material flow and mixing [33]. Excessive metal loss may cause subsurface pores which usually occur at the upper half of the stir zone on the advancing side. However, the porosity observed in this work mainly appeared near the bottom surfaces of the specimens. It is more probably formed mainly due to the inadequate material flow and mixing. For instance, the formation of vortex may cause pores. This means that tapered pin tool produce better material flow and mixing compare to cylindrical and threaded pin tool.

4.3 Microstructure characterization for different welded zone region across the FSW plates.

It is generally known that the union welding of aluminum alloys is go together with the defects like porosity, slag inclusion, solidification cracks, etc., and these defects deteriorate the weld quality and joint properties. However, friction stir welded joints are known to be free from these defects as there is no melting occur during welding and the metals are joined in the solid state itself due to the heat generated by the friction and flow of metal by the stirring action. However, FSW joints are prone to other defects like pin hole, tunnel defect, piping defect, kissing bond, cracks, etc. due to improper plastic flow and insufficient consolidation of metal in the FSP region [8]. Table 14 shows microstructure of different welded zone.

Table 14: Microstructure of different welded zone

Welded Region	Cylindrical pin tool	Tapered Pin Tool	Threaded pin tool
N			
TMAZ			
HAZ			
BM			

All the joints fabricated in this investigation are analyzed at low magnification (10×) using optical microscope to reveal the quality of FSW regions. From optical microscopic test, it can be observe that there could be four different welded zones which are:

- **Friction stir processed zone or nugget (N)**: the fully recrystallized area refers to the zone previously occupied by tool pin. The term stir zone is commonly used in friction stir processing where large volumes of material are processed.
- **Thermo-mechanically affected zone (TMAZ)**: In this region, the FSW tool has plastically deformed the material, and the heat from the process will also exerted some influence on the material. In the case aluminum, it is possible to obtain significant plastic strain without recrystallization in this region, and there is generally a distinct boundary between the recrystallized zone and deformed zones of the TMAZ
- **Heat affected zone (HAZ)**: In this region, which lies closer to the weld-center, the material has experienced a thermal cycle that has modified the microstructure and/or the mechanical properties. However, there is no plastic deformation occur in this area.
- **Unaffected zone or Base metal (BM)**: this is material remote from the weld that has not been deformed and that, although it may have experienced a thermal cycle from the weld, is not affected by the heat in terms of microstructure or mechanical properties.

Based on the observation from table 10, cylindrical pin tool produces largest porosity on welded plate compare to other welded plates that have been welded by tapered or threaded pin tool. On the nugget zone, we can observe that microstructure of welded plates that used tapered pin and threaded pin are fine while welded plate that used cylindrical pin is coarse. On thermo-mechanically affected zone, threaded pin produce the finest grain but it has larger porosity compare to the microstructure that has been produced by tapered pin tool. Cylindrical pin tool resulted with the coarsest grain on the heat affected zone.

4.3 Hardness

Many investigators use hardness data as an initial evaluation of variation in mechanical properties across the weld zone. Hardness is resistance of material to plastic deformation caused by indentation. Sometimes hardness refers to resistance of material to scratching or abrasion. In some cases relatively quick and simple hardness test may substitute tensile test. It is the property of a metal, which gives it the capability to resist being permanently, deformed when a load is applied. Hardness may be measured from a small sample of material without destroying it. Measurement of the macro-hardness of materials is a fast and easy method of obtaining mechanical property data for the bulk material from a small sample. It is also commonly used for the quality control of surface treatments processes. Figure 19 shows schematic diagram of welded plate and figure 20 shows Brinnel Hardness across the welded plate.

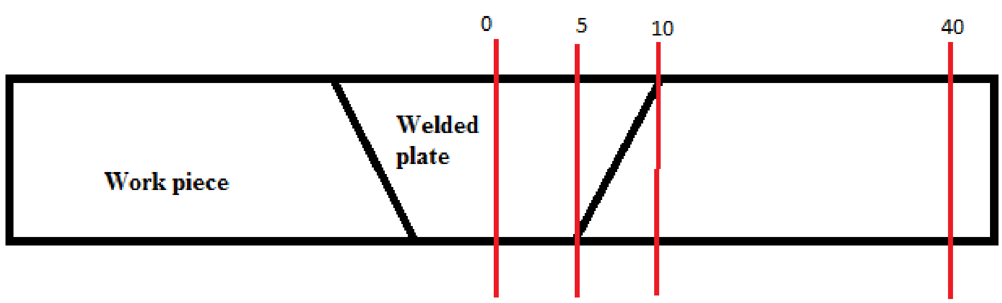


Figure 19: Schematic diagram of welded plate

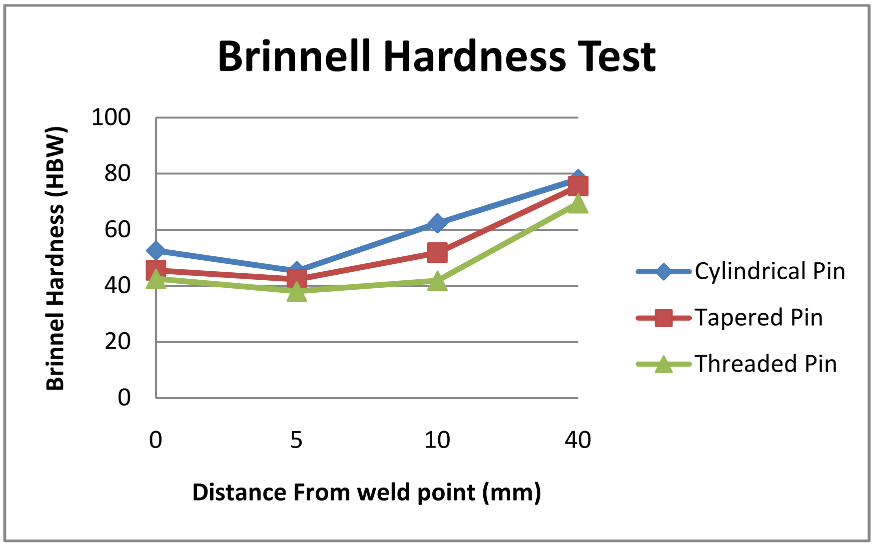


Figure 20: Brinnel Hardness (HBW) across the welded plates

The hardness variation shown in figure 19 is presented as a function of distance from the weld centerline and indicates softened material in the weld zone. All welded plates show the same pattern even being welded by different welding tool pin profile. In this case hardness in the stirred region remains well below that of the parent metal. From the observation, cylindrical pin tool produced highest hardness of welded plate. This might due to the largest diameter of the pin profile. In order to providing sufficient area to prevent failure by through-nugget shear, a wider weld nugget is beneficial because it decreases the amount of bending in a nominally shear loading configuration. Therefore, a tool with a large pin diameter may be favorable for welds loaded in overlap shear [34]. However, based on literature [28], welded work piece age also can affect the mechanical properties where most of the strengthening occurs within a day at room temperature but the mechanical properties are essentially stable after four days. Most of the hardness change occurs in the first week. After this time, the hardness appears to stabilize, and the material reaches an equilibrium condition. In this project, the author done the hardness test for cylindrical and tapered pin tool's welded plate two weeks after welding process but welded plate of threaded pin tool has been done one day after the welding process. So this might affect the hardness of welded plate that used threaded pin tool.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

As for the conclusion, through the proper methodology from design welding tools to run hardness test and microstructure test, the project is understood to achieve its objective in studying the effect of welding tool geometry in Friction Stir Welding. It can be concluded that welding tool geometry in will affect welding result in FSW.

It can be agreed that welding tool geometry will affect the size of tunnel defect on welded plates. Cylindrical pin tool produced largest tunnel defect on the welded plates while tapered pin tool produced smallest tunnel defect.

From the optical microscopic examination images taken shows that welding tool geometry will affect the microstructure of the welded plate. The observation shows that cylindrical pin tool produces largest porosity on welded plate compare to other welded plates that have been welded by tapered or threaded pin tool. Cylindrical pin tool also produced the coarsest grain structure in all region compared to tapered pin tool and threaded pin tool.

The project also can conclude that welding tool pin profile play a major role in determining the hardness of the welded plates. Aluminum alloys which had been welded by cylindrical pin tool have highest hardness due to the pin diameter size.

On overall basis, the project has opened up a new dimension with respect to the technology applicable within this university. It is hope that more researches and projects with regards to the FSW are experimented within this university and perhaps this will catch up the attention of industrial sector to implement this technology.

5.2 Recommendation

Through the project which have been carried out for almost a year, there some recommendations that can be given for future improvement such as:

- To have further study on effect of welding tool geometry especially different profile of shoulder. This can help to have a better finding and further improve the welding results as shoulder profile also play a major role in FSW
- To have a wider proper aluminium alloy as disposal in experimenting the FSW process, such as aluminium alloys 5xxx. This could embark more findings of the FSW process
- This project also could be further enhance by having continuity of research to study the effect on other metal such as metal matrix composites (MMC)

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37. Final Year Project Guidelines for Mechanical Engineering

APPENDICES

Action Plan	Semester July 2009													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Problem Definition														
Project Planning														
Literature Review														
Tool Design														
Selection of Design														
Draw the tool design														
Fabrication Process														
Fabrication of tools														
Welding Process														
Mechanical Testing														
Analytical process														
FYP I														
Submission of Preliminary Report														
Submission of Progress Report														
Seminar														
Submission of Interim Report Final Draft														
Oral Presentation														

Action Plan	Semester Jan 2010													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Problem Definition														
Project Planning														
Literature Review														
Tool Design														
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Analytical process														
FYP II														
Submission of Progress Report I														
Submission of Progress Report II														
Seminar														
Poster Exibition														
Submission of Project Dissertation (soft bound)														
Oral Presentation														
Submission of Project Dissertation (hard bound)														

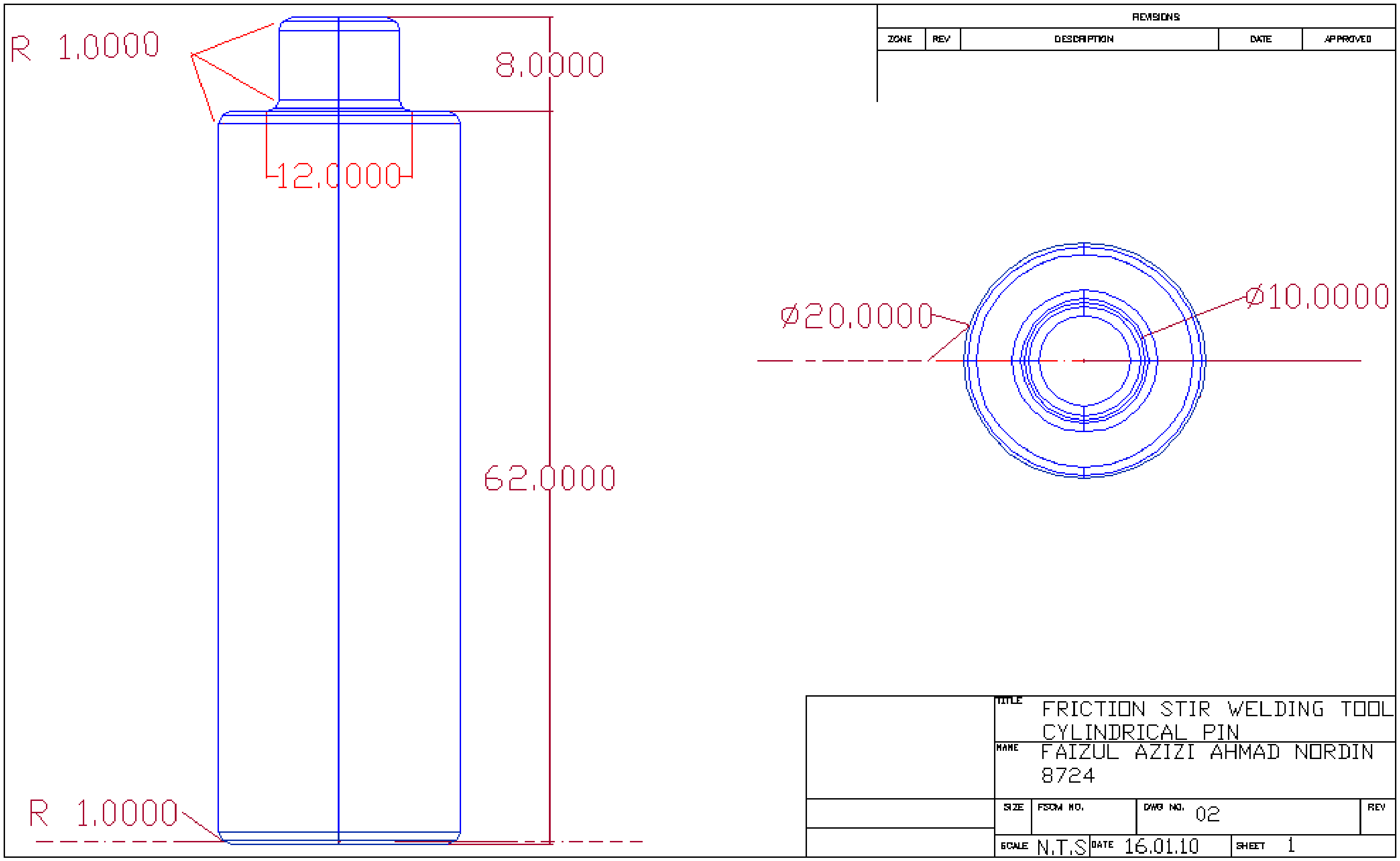

Figure 21:2D view of Cylindrical Pin

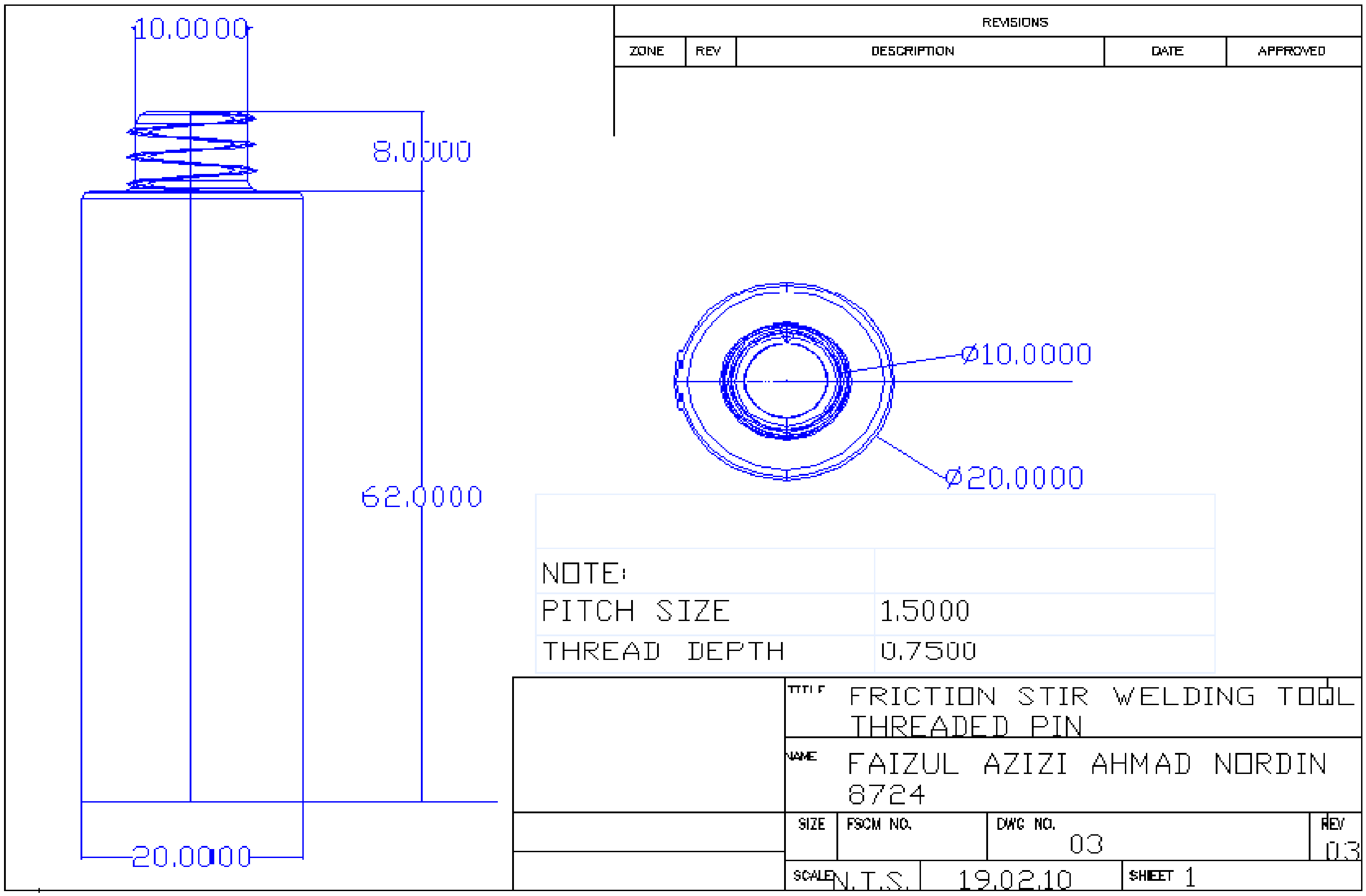

Figure 22: 2D view of threaded pin tool

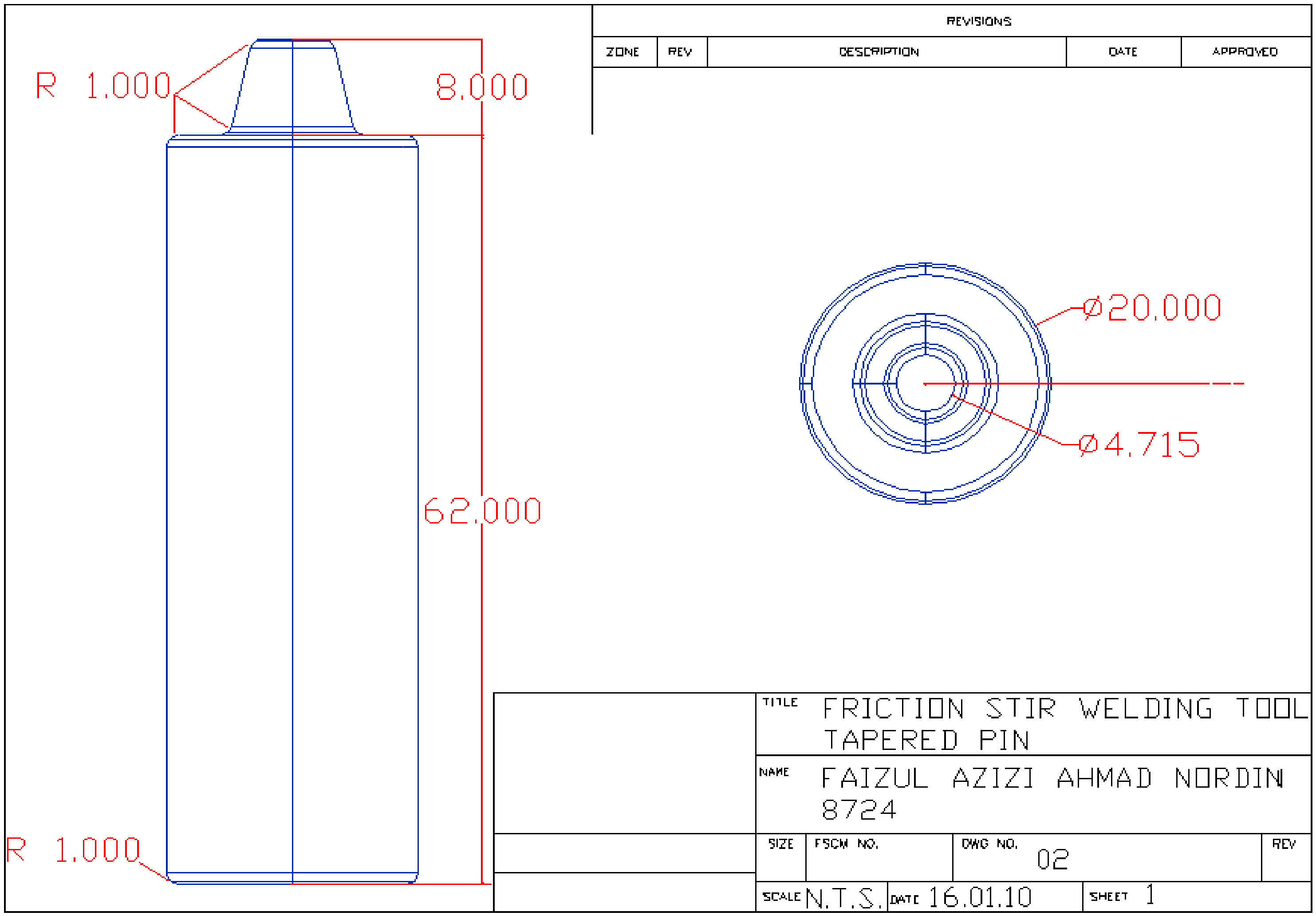

Figure 23: 2D view of Tapered Pin Tool