Effect of Tool Pin Profiles on the Weldment of AA6061-T6 Friction Stir Welded Plate

by

Choong Weng Hong
16777

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical)

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CERTIFICATION OF APPROVAL

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Approved by,

____

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May 2015

CERTIFICATION OF ORIGINALITY

This is to certify 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 that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Choong Weng Hong

ABSTRACT

Friction stir welding (FSW) is a solid state welding in which a rotating non-consumable tool with pin and shoulder is plunged into the joint between workpiece and traverse along the joint, and generates heats from the friction to weld the workpiece. FSW is capable to weld hard-to-weld metal such as aluminium alloy which commonly used in lightweight construction. Since lightweight construction is in high demands nowadays, it is necessary to carry out research on FSW of aluminium alloy. In addition, tool geometry play vital role in formation of FSW joint. The potential variation in tool geometry is virtually infinite, considering pin and shoulder related to dimension. Thus, the main focus of this study is to investigate the effect of tool pin profile on the microstructure and hardness of friction stir welded AA6061-T6 plate. Five different types of tool pin profile including straight cylindrical, threaded cylindrical, tapered cylindrical, square and triangle are selected for this study. Heat treatment is performed on the tools fabricated to improve the hardness, resistance to thermal fatigue and wear. Microstructural analysis and Rockwell hardness, B scale test are performed for the purpose to investigate the microstructure and hardness on the stirred zone of AA6061-T6 FSW joint. The result shows that square pin profiled tool produces finer grain on the stirred zone and in turn yields higher hardness. Tool with flat faces has higher stirring action during FSW and result in producing joint with fine grain and high hardness.

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Choong Weng Hong

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CHAPTER 1

INTRODUCTION

1.1 Background

Friction stir welding (FSW) was invented by The Welding Institute (TWI) in 1991. FSW is viewed as the most important joining technique that has been developed in term of its energy efficiency, environmental friendly and versatility. By comparing to conventional welding methods, the energy consumption of FSW is considerably lesser. No gas or flux is used in FSW, thereby making the process environmental friendly. Furthermore, compatibility of composition, which is an issue in fusion welding, is solved using FSW because the process does not use any filler metal. Another advantage of FSW is it can be applied to various types of joints such as butt joints, fillet joints T-butt joints and lap joints. FSW is mostly used in lightweight construction because it is capable to weld hard-to-weld metals such as aluminum alloy, titanium and so on [1].

A schematic diagram of FSW technique is shown in Figure 1. A rotating non-consumable tool with specially designed shoulder and pin is plunged into abutting edges of plates to be joined and traverse along the line of joint. As the tool traverse, heat is produced from the friction between tool and workpiece and the plastic deformation of the material of workpiece in the stir zone. The localized heating softens the material of workpiece around the pin and combination of rotating and traversing tool leads to movement of material from the front of the pin to the back of the pin. As a result of this process, joint is produced in solid state [1].

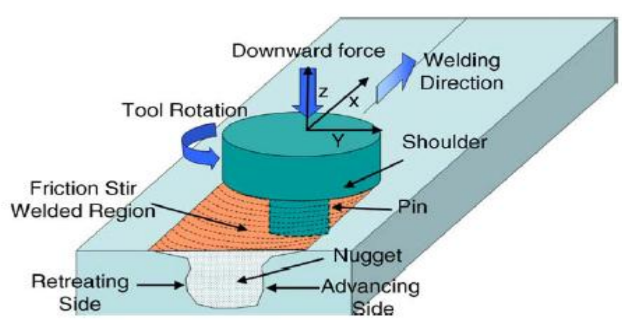


Figure 1: Schematic Diagram of FSW Process [1]

FSW joint consists of four different regions and they are unaffected base metal, heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ) and stirred zone. Figure 2 is showing the four regions of the FSW joint. Heat produced does not affect the region of unaffected base metal, thus there is no changes in microstructure and properties in the region. In HAZ region, the heat produced influences the microstructure but plastic deformation does not take place. As for TMAZ, the region experiences plastic deformation from the heat produced, however it is insufficient to induce recrystallization in the material. Stirred zone is the region where the material of workpiece is affected the most due to heat produced and stirring process of the tool. In this region, the material has major changes in microstructure and mechanical properties because it experiences plastic deformation and recrystallization [2].

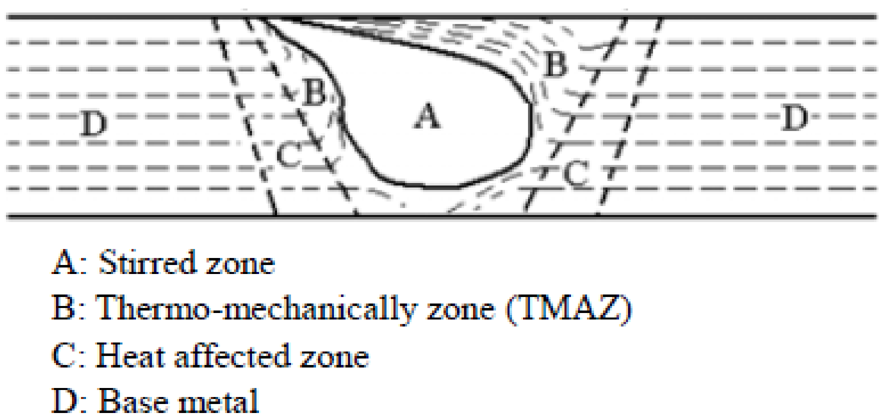


Figure 2: Regions of FSW Joint [2]

1.2 Problem Statement

FSW is a joining technique that able to weld metal which is considered hard-to-weld metal such as aluminum alloy. This advantage causes FSW is widely used in aircraft and automotives industries. Furthermore, lightweight construction is in high demands nowadays, thus study on FSW need to be done in order to improve the quality of the welds and apply in industry. FSW involves complex material flow behavior and plastic deformation. During FSW process, the welding parameters combined with tool geometry exert a significant effect on the material flow pattern and temperature distribution, thereby influencing the microstructural evolution of material, the formation and mechanical properties of the joint. To broaden the application of FSW, it is necessary to clarify the effect of weld parameters and tool geometry on the properties of the joint. Although numerous of studies on the effect of welding parameters and tool geometry on microstructure and mechanical properties of FSW joint have been done, the tool geometry studies is still limited. This is due to the potential variation in tool geometry (pin and shoulder design relative to tool dimensions) is essentially infinite [1]. Hence, the study on the effect of tool pin profile on FSW joints has to be done for the purpose to optimize the FSW welds.

1.3 Objectives

The objectives of this research are as follows:-

i. To investigate the effect of tool pin profile on the microstructure of the friction stir welded AA6061-T6 plate.
ii. To investigate the hardness of friction stir welded AA6061-T6 plate fabricated using different tool pin profiles.

1.4 Scope of Study

The main focus of this project is to investigate the effect of tool pin profile on the friction stir welded aluminium alloy plates. Five different types of pin profiles including straight cylindrical, threaded cylindrical, tapered cylindrical, square and triangle are used in this project. In addition, AA6061-T6 is chosen as the material of the workpiece. Each of the five tools is used to weld a butt joint of AA6061-T6. Since the main focus of this project is to investigate the influence of tool pin profile on the friction stir welded AA6061-T6 plate, the process parameters including traverse speed, rotational speed and applied force used to fabricate the joints are constant for every each pin profile tooled. The fabricated butt joints are performed microstructural analysis and Rockwell hardness test. The preparation of specimens for these experiments is carried out as per American Society for Testing of Materials (ASTM). The result collected are then analyzed and compared in order to investigate the effect of the different pin profiles on the FSW weldment of AA6061-T6.

CHAPTER 2

LITERATURE REVIEW

2.1 Tool Material

The material of FSW tool ought to be strong, tough and hard wearing enough under the frictional heat along with good oxidation resistance and low thermal conductivity. Several materials have been used to fabricate FSW tool and these materials include tool steels, high speed steel (HSS), Ni- alloys, metal carbides and ceramics. Out of these materials, tool steels are the most common tool material used in FSW of aluminium alloys and aluminium matrix composites (AMCs) and it can used to weld thickness of up to 50mm of these materials of workpiece. Tool steels have a good resistance to damage from abrasion and deformation in the process of FSW of aluminium alloys. Furthermore, tool steel can be used to weld both similar and dissimilar welds as lapped joints or as butt joints [3].

Various types of tool steel are used in FSW process of aluminum alloys and AMCs such as stainless steel (SS), high carbon high chromium steel (HCHCr), high speed steel (HSS), H13 and C40. For instance, H13 and HSS are used in the research of FSW of AA6061 and AA6351 respectively [3]. Tool meterials used for FSW of several aluminium alloys are listed in Table 1.

Table 1: Types of Tool Steel for FSW of Aluminium Alloys [3]

Materials Welded	Tool Steels
AA5083	HCHCr
Commercial grade Al-alloy	SS310
AA2011 and AA6063	HSS
AA6082 and AA2024	C40
AA5754 and C11000 copper	H13
AA6061-T6 and AISI 1018 mild steel	H13

2.2 Tool Geometry

Tool design is one of the most important factors to be considered while designing FSW process because its geometry plays a vital role in the material flow behavior of the metal taken for joining [4]. A typical FSW tool is shown in Figure 3 and it shows that the tool consists of shoulder and pin.

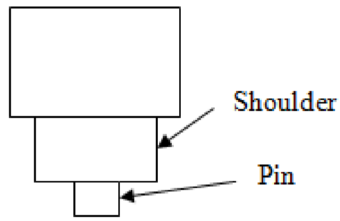


Figure 3: Typical FSW Tool Geometry

2.2.1 Tool Shoulder

Tool shoulders are designed to generate heat to the surface and subsurface regions of the workpiece. The tool shoulder creates a majority of the deformational and frictional heating in thin sheet. Thus, diameter of the shoulder is one of the most vital parameter of FSW tool since it has significant effect to the amount of frictional heat. The choice of shoulder diameter requires consideration during the designing of FSW tool. Shoulder is categorized in two types and they are concave and convex shoulder [4].

Concave shoulder was the first shoulder design, which also known as standard-type shoulder. Concave shoulder produces quality friction stir welds, and the design is simple which makes it easily machined. The concavity of the shoulder is produced by a small angle between the edge of the shoulder and the pin within a range of 6 to 10 º. While the plunge of tool, material displaced by the pin is fed into the cavity of the shoulder. The material serves as the start of a reservoir for the forging action of the shoulder. Forward movement of the tool forces new material into the cavity, pushing the existing material into the flow of the pin. Tool with this type of shoulder is tilted 2 to 4 º from the normal of the workpiece away from the direction of travel for proper operation [4].

Convex shoulder is the tool with the addition of shoulder feature, scroll to prevent the convex shape pushed the material from the pin. The scrolls on the convex shoulder moves material from the outside of the shoulder in toward the pin. This type of shoulder allows greater flexibility in the contact area between the shoulder and workpiece, improves the joint mismatch tolerance, increases the ease of joining different thickness workpieces, and improve the ability to weld complex curvatures [4].

To increase the amount of material deformation produced by the shoulder, some FSW tool is designed with addition feature on shoulder. This feature assists in increasing the workpiece mixing and higher quality friction stir welds. These features can consist of scroll, ridges or knurling, grooves and concentric circles as shown in Figure 4 [4].

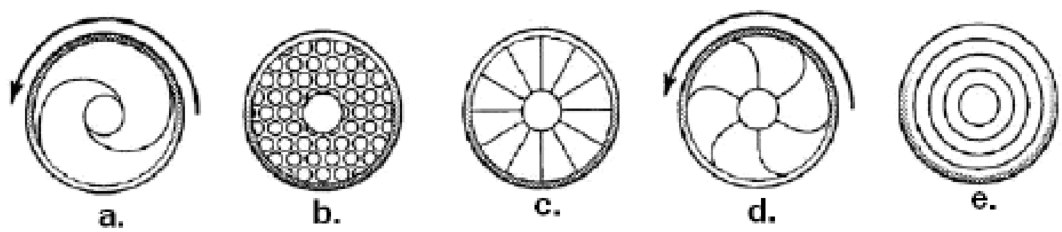


Figure 4: Different Shoulder Features [4]

2.2.2 Tool Pin

The pin or probe of tool has the ability to produce deformational and frictional heating to the joint surfaces. The pin is designed to disrupt the faying or contacting surfaces of the workpiece, shear material in front of the tool, and move material behind the tool. Besides that, the depth of deformation and tool traverse speed are controlled by the pin design [4].

One of the commonly used pin profile is round-bottom cylindrical pin. It is a round end to the pin tool which can reduces the tool wear upon plunging and improves the quality of the weld root directly underneath the bottom of the pin. Besides that, flat-bottom cylindrical pin is also one of the commonly used pin profile. With flat-bottom cylindrical pin, the friction velocity of a rotating cylinder increases from zero at the center of the cylinder to a maximum value at the edge of the cylinder. The local velocity coupled with the friction coefficient between the pin and the metal dictates the deformation during friction stirring. Truncated cone pin is also a type of tool pin profile. This pin usually used to friction stir weld thicker plates at faster traverse speed. Moreover, this pin also has lower traverse loads and the largest moment load on a it is at the base cone, where it is the strongest. There are many types of pin have been developed for FSW tool and some examples are shown in Figure 5 [4].

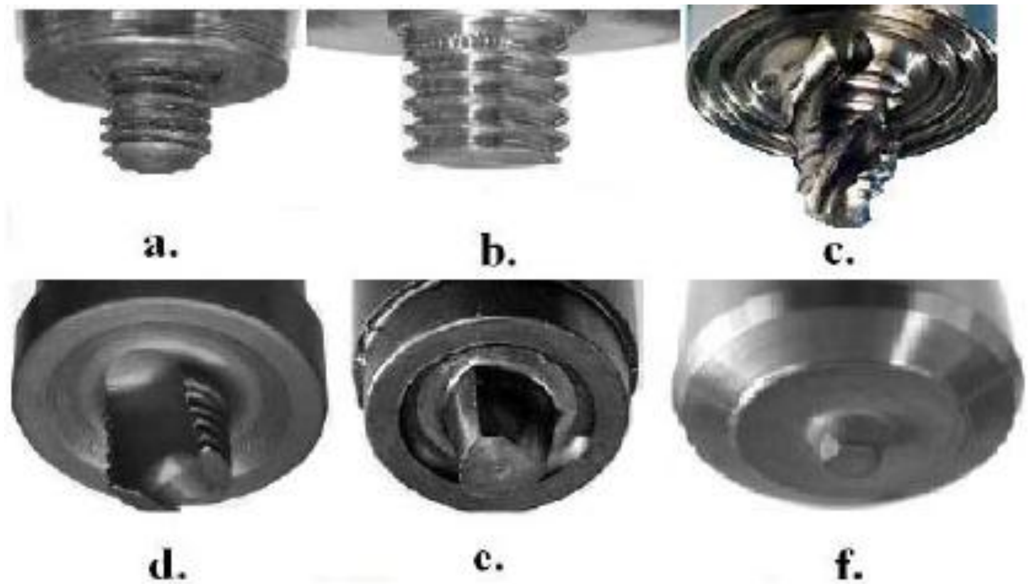


Figure 5: Different Tool Pin Profiles [4]

2.3 Influence of Tool Geometry

FSW is a complex process, in which the weld quality is affected by FSW process parameters. These FSW process parameters are predominantly influence the material flow behavior and mechanical properties. Tool controlled parameters are one of the two categories of FSW process parameters. The tool parameters which are controlled during tool design include tool pin profile, shoulder diameter, pin diameter, pin length and tool tilt angle [2].

A high shoulder diameter produces inferior tensile strength because of larger contact area between the shoulder and workpiece which leads to wider TMAZ and HAZ. The smaller diameter of the shoulder resulted in lower heat generation due to smaller contact are. Pin profile has high influence on the microstructure evolution of material of workpiece because the stirring of material of workpiece is controlled by the rotating pin of the tool. For the pin length, it is usually slightly shorter than the thickness of workpiece to prevent the tool from penetrate through the bottom surface of workpiece [2].

In order to optimize FSW process, numerous experiments had been done. For instance, a research on the effect of tool pin profile on the microstructure and mechanical properties of friction stir welded AA6351 concluded that square tool pin profile and ratio of shoulder diameter to pin diameter of 3 produced finer microstructure, greater micro-hardness and superior tensile strength [5]. The several studies on the effect of tool pin profile on the microstructure and mechanical properties of aluminium alloys FSW joint that had been conducted are summarized and tabulated in Table 2 and Table 3 in the Appendices.

2.4 Influence of Welding Parameters

Welding parameters of FSW process include spindle or tool rotational speed, tool traverse speed and axial or plunge force. Increasing rotation speed or decreasing the traverse speed will result in hotter weld also for good weld quality as shown in Figure 6 [6]. Higher tool rotational rates generate higher temperature because of higher friction heating and result in more intense stirring and mixing of material and leads to formation of coarse grains [1]. At lower traverse speed, the amount of heat supplied to the deforming material in weld area is greater and therefore wider is the softened area around the stirring tool leading to more improved metal flow and more effective bonding in the weld [7]. Table 2 and 3 are showing the experiments that have been done to study the FSW parameters. However, the increasing of rotational speed or decreasing of traverse speed is not virtue in fabricating good FSW weld when it exceeds optimum value or critical value [2].

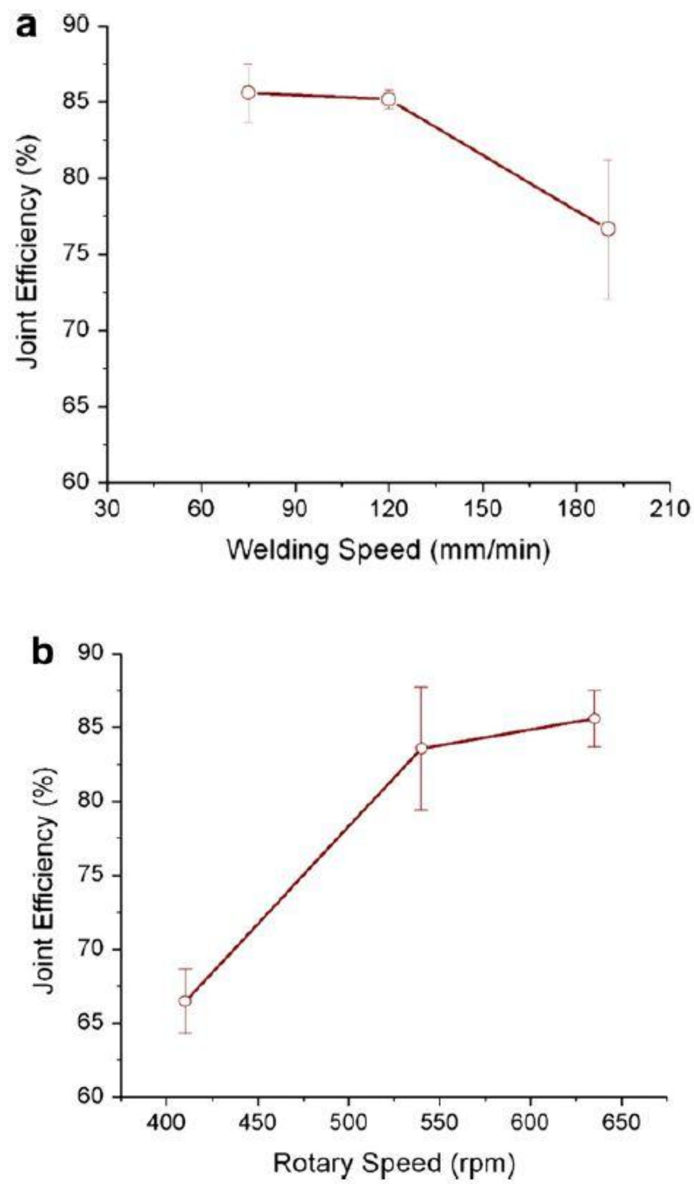


Figure 6: Welding Speed and Rotary Speed versus Joint Efficiency [7]

As for axial force, sufficient axial force is required to form the sound weld because the temperature developed during the process will control the amount of plasticized material and temperature is heavily depend on the axial force. As far as axial for force concern, for low axial force tunnel like defects were formed, insufficient stirring was possible. With the high axial force the weld produced was sound with full penetration [2].

CHAPTER 3

METHODOLOGY

3.1 Project Planning

Process flow, Key Milestone and Gantt Chart have been developed for this project and are used as a guide to monitor the progress of this project and ensure that this project can be finish within time frame. The process flow, Key Milestone and Gantt Chart are as shown in Figure 7 and 8 and Table 6 respectively.

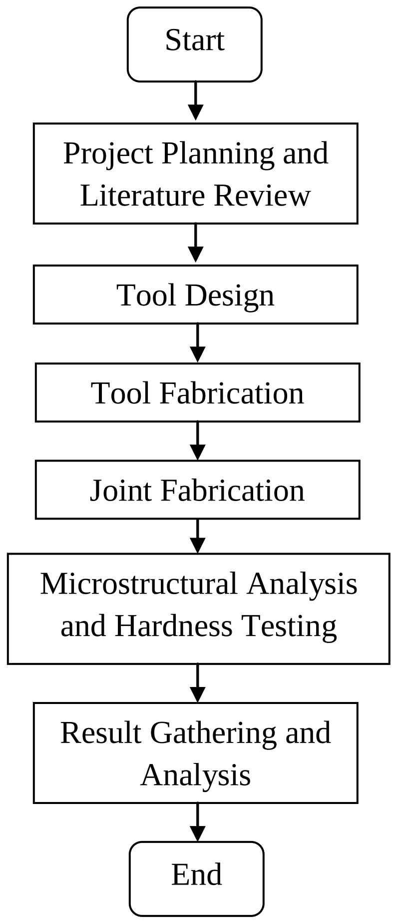


Figure 7: Process Flow of Project

Figure 8: Key Milestone for Project

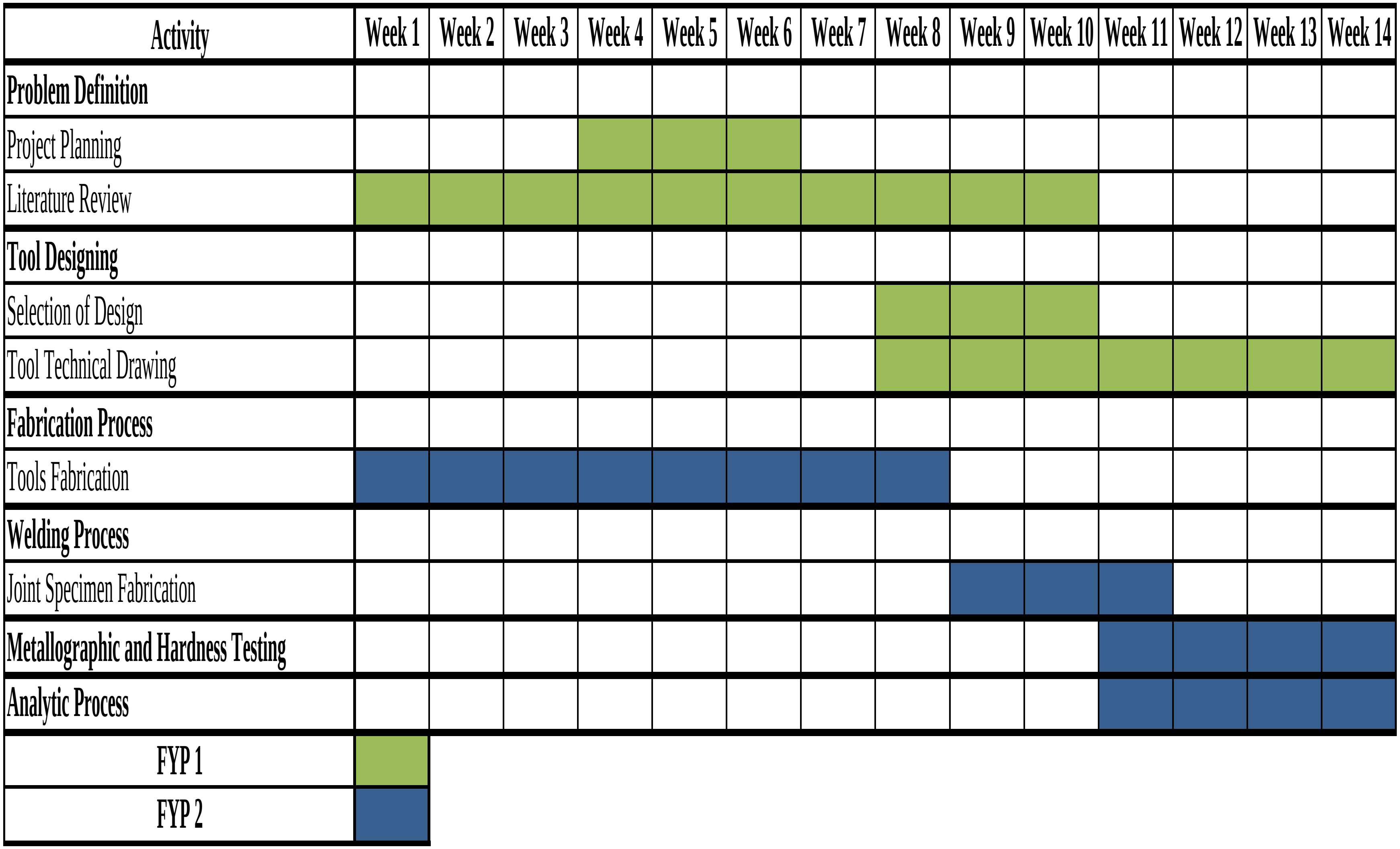


Figure 9: Gantt Chart for FYP 1 and 2

3.2 Tool Designs

Five tool pin profiles had been selected and studied in this project, they includes straight cylindrical, threaded cylindrical, tapered cylindrical, square and triangle. During tool designing stage, dimension of the tool such as diameter of pin and shoulder, pin length, shoulder length are determined. These dimensions are determined based on the found out identified from the journals or experiments that had been carried out to optimize FSW tool and process. For the holder of the tool, the diameter is referring the tool sample of the FSW machine. Technical drawing of all the five tools are drawn using a computer aided design (CAD) software called Catia, after the pin profiles and dimension of are designed and determined respectively. The drawings are shown in Figure 10 to Figure 14. The dimensions are in metric and with a tolerance of ±0.05mm.

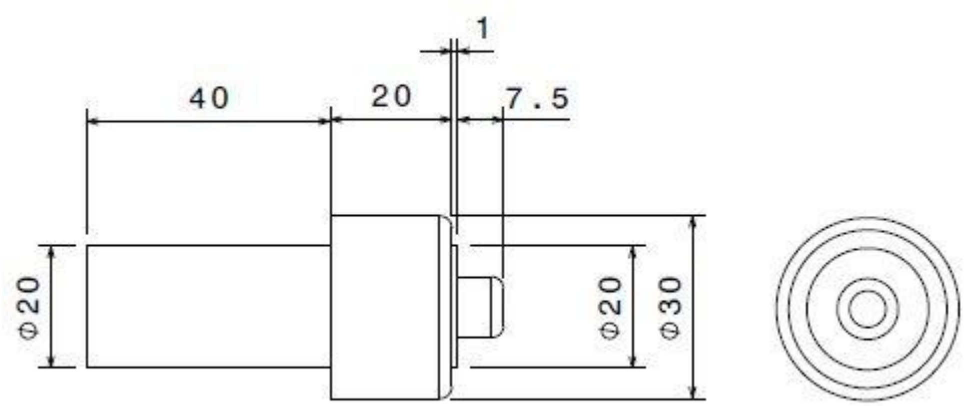


Figure 10: Straight Cylindrical Pin Profile

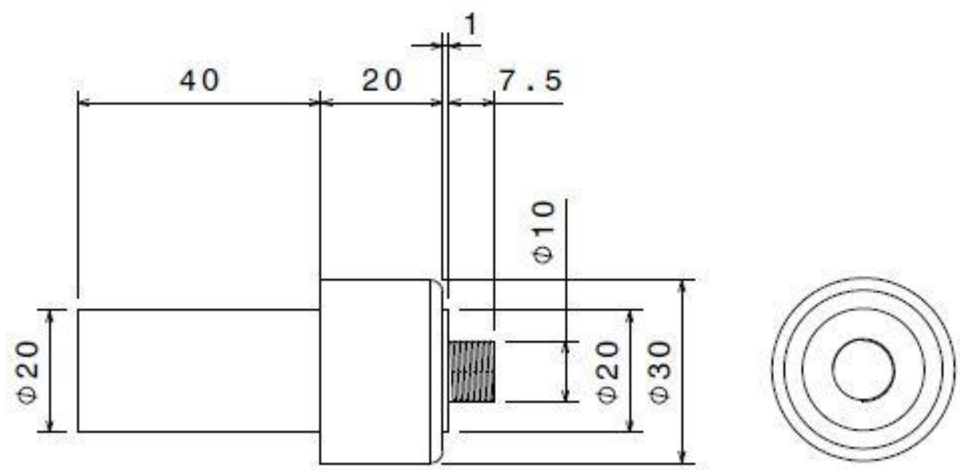


Figure 11: Threaded Cylindrical Pin Profile

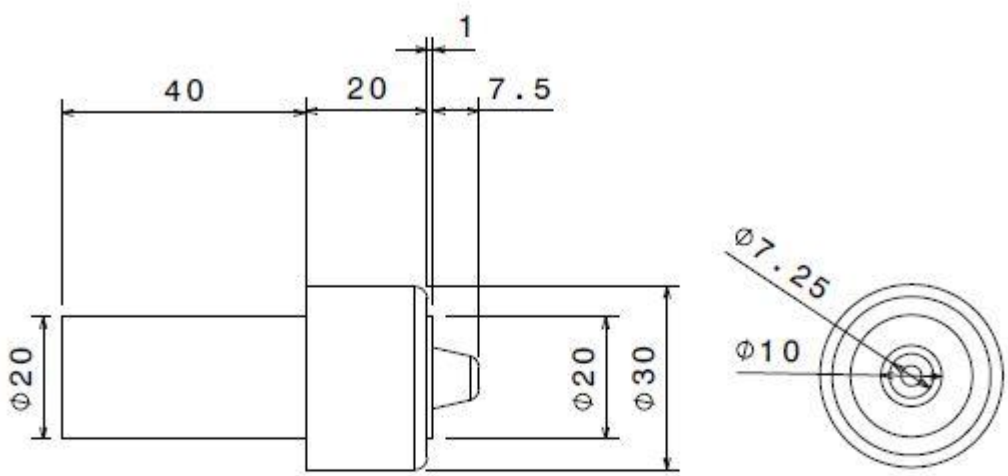


Figure 12: Tapered Cylindrical Pin Profile

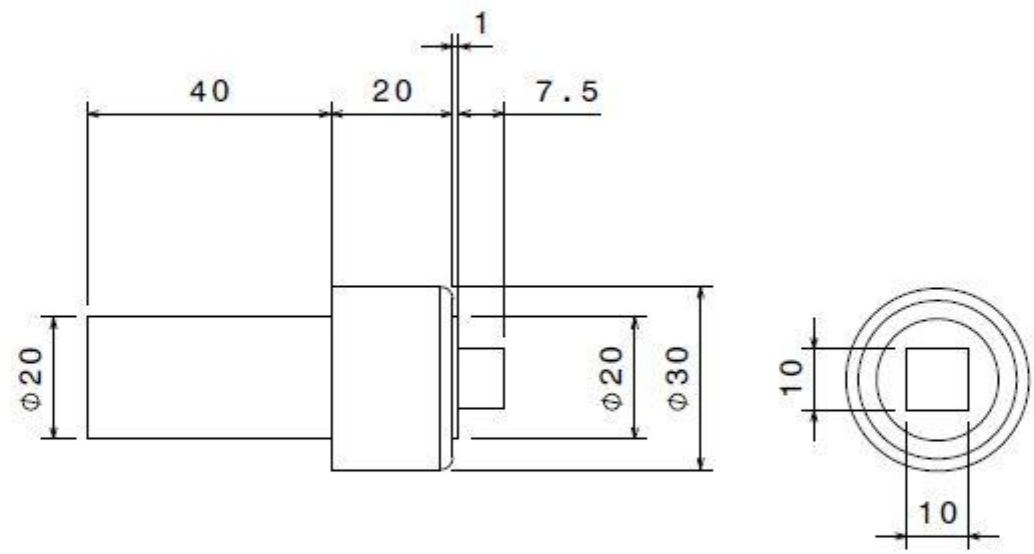


Figure 13: Square Pin Profile

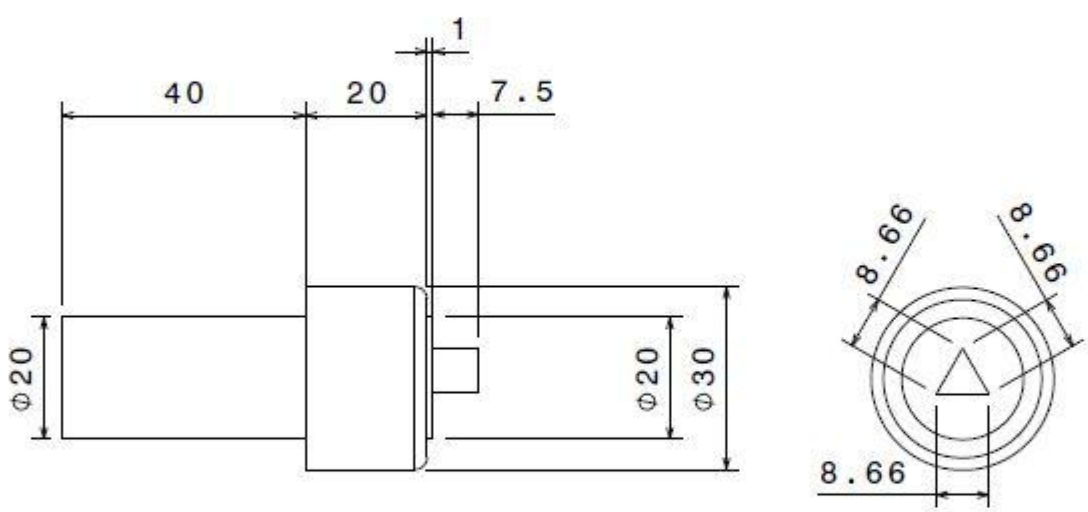


Figure 14: Triangle Pin Profile

3.3 Tool Fabrication

Tool steel H13 which is a type of hot working tool steel is selected and used to fabricate the five FSW tools with different tool pin profile. The chemical composition of tool steel H13 is shown in Table 4. Tool steel H13 rod with 30mm diameter and 70mm length is used to fabricate the five tools for FSW. The five tools as shown in Figure 15 are fabricated using CNC lathe machine and milling machine. Straight cylindrical and tapered cylindrical pin tool are fabricated using CNC lathe machine. While for threaded cylindrical, it is first fabricated as straight cylindrical without fillet on the pin’s tip, the threaded profile is then produced manually after that. As for the fabrication square and triangle pin tool, CNC lathe and milling machine are used. Milling machine is used to produce the flat surface of square and triangle profile.

Table 4: Chemical Composition of Tool Steel H13

Tool Steel H13	
Element	Content (%)
Chromium, Cr	4.75-5.50
Molybdenum, Mo	1.10-1.75
Silicon, Si	0.80-1.20
Vanadium, V	0.80-1.20
Carbon, C	0.32-0.45
Nickel, Ni	0.30
Copper, Cu	0.25
Manganese, Mn	0.20-0.50
Phosphorus, P	0.03
Sulphur, S	0.03

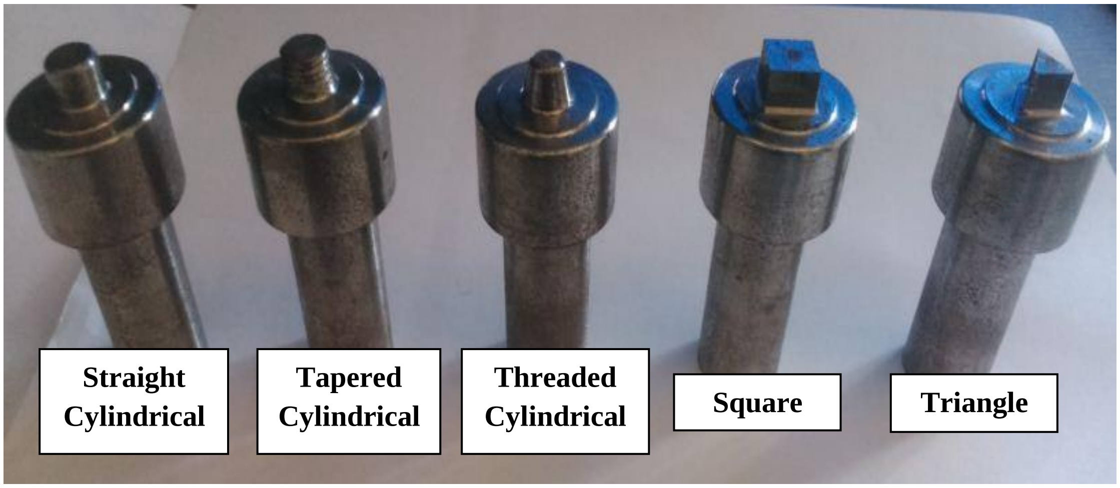


Figure 15: Five Different Tools Pin Profile

By referring to the tool sample for the FSW machine, there is a flat surface on the holder. The purpose of the flat surface is to prevent the tool from loosen when it is revolving by tightening with screw. The diameter of the screw is measured to be 10mm. For the screw to hold the tool, the flat surface has to be at least 10mm width. To produce the flat surface, conventional milling machine and cutting tool with 10mm diameter is used. Figure 16 is showing the tools with flat surface on the holder.

Figure 16: Tools with Flat Surface on Holder

The five FSW tools fabricated are then performed heat treatment in order to improve the properties of tool such as hardness, resistance to thermal fatigue and wear. Heat treatment in this project involves pre-heating, austenitizing, air quenching and double tempering. The control of heating and cooling during heat treatment alters the physical and mechanical properties without major transformation in shape. Thus, this technique is used to improve the performance of the tool by enhancing the properties. Carbolite heat treat furnace shown in Figure 17 is used to perform heat treatment on the tools. Tools after heat treatment process are shown in Figure 18. The procedure of heat treatment for the FSW tools in this project is as follows:-

1. The tools are pre-heated to 788 ℃ (1450 ℉).
2. From the pre-heat, the tool is heated to 1010 ℃ (1850 ℉) and hold for 30 to 45 minutes for austenitizing.
3. Air is used as medium for quenching. The tools is cooled down to 50 ℃ (122 ℉) to 60 ℃ (140 ℉).
4. The tools are then heated up to 552 ℃ (1025 ℉) and hold for 2 hours and cooled in still air to ambient temperature for tempering. This tempering is repeated for second cycle.

Figure 17: Carbolite Heat Treat Furnace

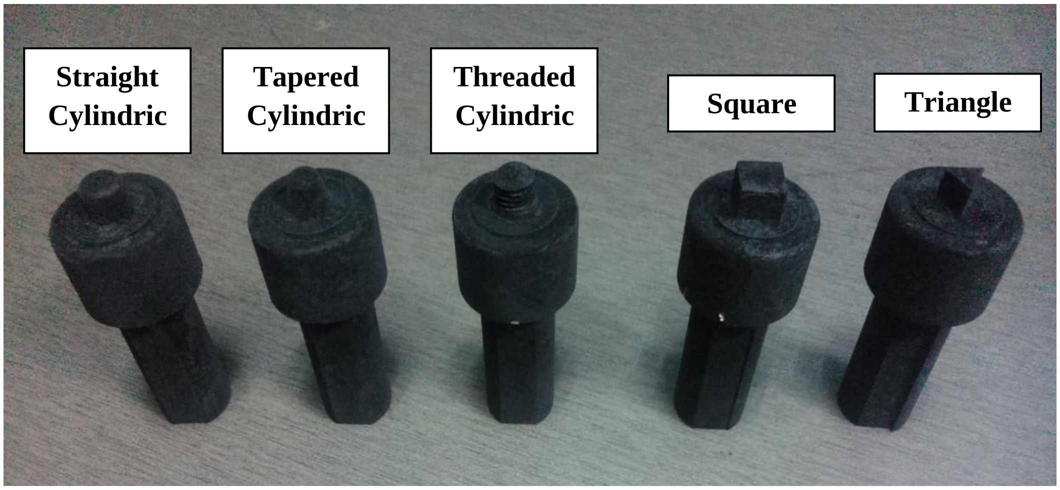


Figure 18: FSW Tools After Heat Treatment

3.4 Joint Specimen Fabrication

AA6061-T6 plates with 200mm long, 150mm wide and 10mm thick are used to fabricate the joint specimens. The chemical composition of this aluminium alloy is shown in Table 5. The edges of two pieces of the plate are abutted and performed butt welding using FSW in this experimental study. Each fabricated tools are used to produce one FSW joint using machine shown in Figure 19. Welding parameters used for joint fabrication are shown in Table 6. During FSW process, the tool is tilted 3^{o} from the normal of the work piece away from the direction of welding. All the butt joints are produced using a FSW machine at a constant rotational speed of 1100rpm and welding speed of 40mm/min.

Table 5: Chemical Composition of Al6061-T6

AA6061-T6	
Element	Content%
Magnesium, Mg	0.80-1.20
Manganese, Mn	0.00-0.15
Iron, Fe	0.00-0.70
Silicon, Si	0.40-0.80
Copper, Cu	0.15-0.40

Table 5: Chemical Composition of Al6061-T6 (Cont.)

AA6061-T6	
Element	Content%
Zinc, Zn	0.00-0.25
Titanium, Ti	0.00-0.15
Chromium, Cr	0.04-0.35
Other (Each)	0.00-0.05
Others (Total)	0.00-0.15
Aluminium, Al	Balance

Figure 19: FSW Machine

Table 6: Welding Parameters

Welding Parameters	Values
Tool Rotational Speed	1100 rpm
Tool Traverse Speed	40 mm/min
Tool Tilted Angle	3 °

3.5 Microstructural Analysis

Preparation for microstructure analysis on FSW joints is performed as per ASTM in order to determine which tool pin profile produces the best quality of joint in term of microstructural view. First step of the preparation for the analysis is sectioning, the joint specimens are sectioned using wire cut machine to the required size (20×20 mm) from the joints where the cross section is comprises with stir zone. Three specimens are sectioned from the each five FSW joint in which along the rear, middle and front of the joint as Figure 20 shows. Thus, there will be 15 specimens in total.

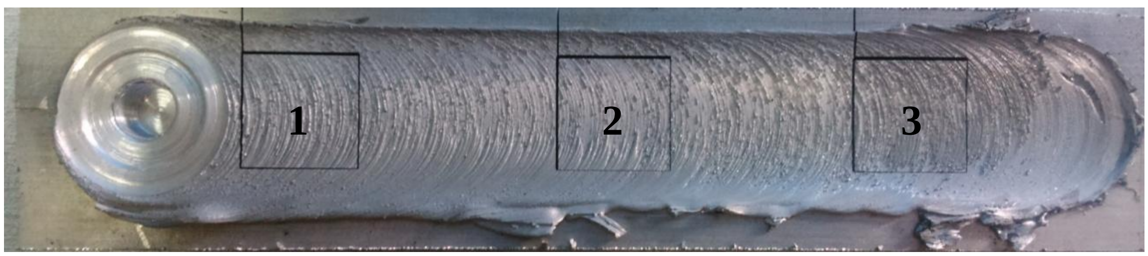


Figure 20: Microstrutural Analysis Specimen from FSW Joint

Mounting is then carried out using mounting machine shown in Figure 21 on the specimens so that it can be supported in stable medium for grinding and polishing. The specimens are then performed grinding to remove material deformed produced from sectioning. Grinding process is followed by polishing process, polishing is to remove the scratch from the surface of specimens for analysis. Diamond polishing is carried out after standard polishing. During diamond polishing, 3 micron diamond polishing compound is used. These three processes are using grinding or polishing machine shown in Figure 22. Lastly, the specimens are immersed into Keller's reagent for 1 to 2 minutes. The chemical composition of Keller's reagent used as listed in Table 7 [8 and 9]. The etched specimens are then examined under Scanning Electron Microscopy (SEM) shown in Figure 23 and the microstructure of the cross section of the joints is analyzed.

Figure 21: Mounting Machine

Figure 22: Grinding or Polishing Machine

Table 7: Chemical Composition of Keller's Reagent [9]

Keller's Reagent	Composition	HF	HCl	HNO_3	Water
	Volume (ml)	2	3	5	190

Figure 23: Scanning Electron Microscopy (SEM)

3.6 Hardness Test

Rockwell hardness test is an indentation hardness test using a verified machine to force a diamond spheroconical indenter or tungsten carbide (or steel) ball indenter, under specified conditions, into the surface of the material under test, and to measure the difference in depth of the specified preliminary test force as the force on the indenter is increased from a specified preliminary test force to a specified total test force and then returned to the preliminary test force. The preliminary test force for Rockwell hardness test is 10 kgf [10]. Table 9 shows various scales of Rockwell hardness which defines the combination of indenter and test forces that used. The value of Rockwell hardness is calculated using equation below.

$$\text{Rockwell Hardness} = 100 - \frac{\text{h}}{0.002} \tag{3.1}$$

In which,

h = difference in the two indentation depth measurements

Table 8: Rockwell Hardness Scales [10]

Scale Symbol	Indenter	Total Test Force, kgf	Dial Figures	Typical Application of Scales
B	1.588 mm ball diamond	100	red	Copper alloys, soft steels, aluminium alloys, malleable iron, etc.
C	diamond	150	black	Steel, hard cast irons, pearlitic malleable iron, titanium, deep case hardened steel, and other materials harder than B100.
A	Diamond	60	black	Cemented carbides, thin steel, and shallow case-hardened steel.
D	diamond	100	black	Thin steel and medium case hardened steel, and pearlitic malleable iron.
E	3.175 mm ball	100	red	Cast iron, aluminium and magnesium alloys, bearing metals.
F	1.588 mm ball	60	red	Annealed copper alloys, thin soft sheet metals.
G	1.588 mm ball	150	red	Malleable irons, copper-nickel-zinc and cupro-nickel alloys. Upper limit G92 to avoid possin=ble flattening of ball.

Rockwell hardness test is performed at the stir zone of the five FSW joints fabricated as per ASTM using tester shown in Figure 24. Similar with microstructural analysis, Rockwell hardness test is carried out on the three specimens that sectioned from each FSW joints. Hence, there will be 15 specimens in total for Rockwell hardness test. According to Table 8, Rockwell hardness scale B is selected to perform on the specimens. The Rockwell B Harness (HRB) values are collected and analysed.

Figure 24: Rockwell Hardness Machine

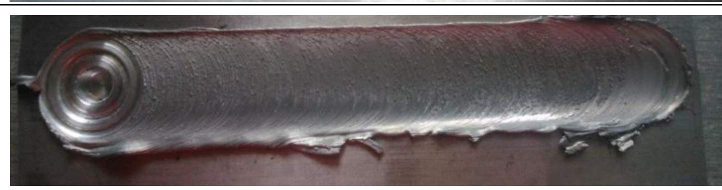
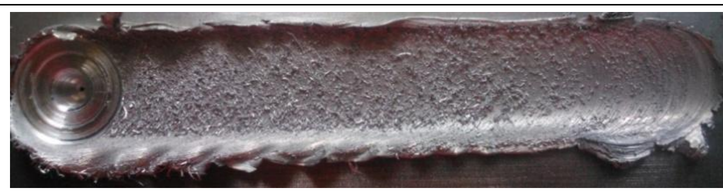
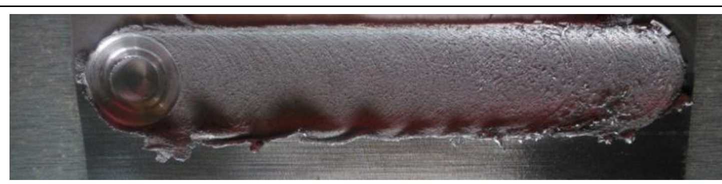
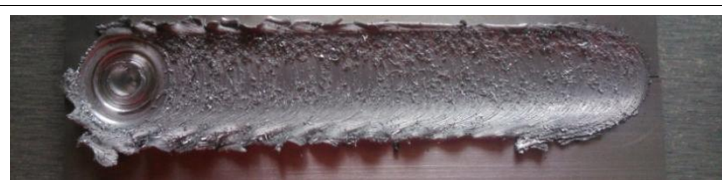
CHAPTER 4

RESULT and DISCUSSION

4.1 Visual Investigation

Five FSW tools with pin profiles of straight cylindrical, threaded cylindrical, tapered cylindrical square and triangle are used in the fabrication of AA6061-T6 aluminium alloy FSW joints. All the joints are fabricated with constant welding parameters in which rotational speed and traverse speed are 1100rpm and 40mm/min respectively. Table 9 shows the FSW joint fabricated by different pin profiles.

Table 9: FSW Joints Fabricated by the Five Tools

Tool Pin Profiles	FSW Joints
Straight Cylindrical	
Threaded Cylindrical	
Tapered Cylindrical	
Square	
Triangle	

Based on Table 9, it is observed that all the FSW joints have defect in visual appearance which is the formation of weld flash. Formation of weld flash on the FSW joint is due to the excess heat input [11]. Besides that, formation of weld flash may also due to the 1mm step between shoulder and pin of the tools. During the FSW process, the step pushes the material away from the pin and hence causes defect on FSW joints [4]. By comparison, threaded cylindrical produced the best quality in term of visual appearance while FSW joint fabricated by straight cylindrical has the largest mass of flash weld. Moreover, it is observed that tool with square pin profile produces the second best quality joint among the five tools.

As shown in Figure 25, wormhole or void defect is identified from the visual investigation at the end point of FSW joint produced by straight cylindrical and tapered cylindrical pin profile. This could be related to less heat input and insufficient stirring as well as insufficient flow of the plasticized metal. During FSW process, the plasticized material flow from the advanced side to the retreated side. Straight cylindrical and tapered cylindrical pin profiles have less stirring action and thereby causing insufficient flow of plasticized material that means insufficient material comes back to the advanced side resulting wormhole on the joints [12].

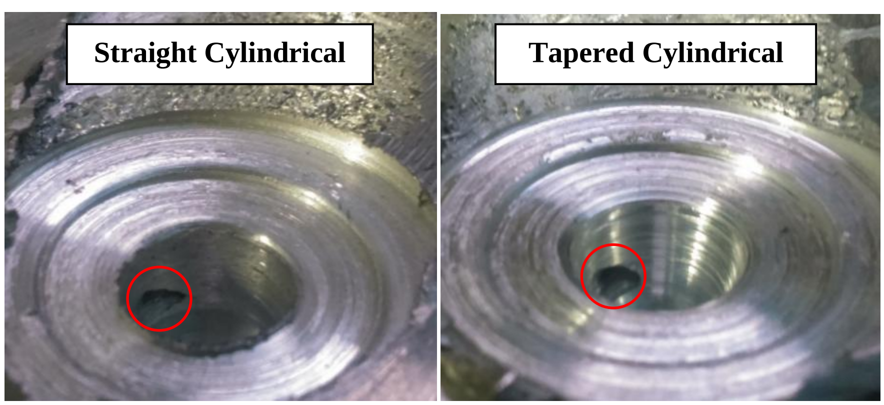


Figure 25: Wormhole Defect

After the joints are sectioned for the preparation of metallographic analysis, visual check is performed on the cross section of the joints. The defects which visually identified from the five FSW joints fabricated by different tool pin profiles and also the probably reason for the defect are listed in Table 10. At the rotational speed of 1100rpm and traverse speed of 40mm/min, cross section of FSW joint fabricated by straight cylindrical, tapered cylindrical and triangle pin profiled tool are identified to have visible pin hole at the bottom portion at the retreating side, whereas square pin profile tool produces joint with tunnel in the root of weld. There is no visible defect is detected on the cross section across the joint produced by threaded cylindrical pin profiled tool. For the case of straight cylindrical and tapered cylindrical pin profiles, the probably reason for the defect is the insufficient flow of plasticized material due to low driving force. Meanwhile, the probably reason for the joints produced by square and triangle pin profiles to have defect is the excess flow of plasticized metal due to high driving force.

Table 10: Visual Inspection on Cross Section of FSW Joints

Tool Pin Profiles	Cross Section of Joints	Defect	Probably Reason
Straight Cylindrical		Visible pin hole defect at the bottom portion at the retreating side	Insufficient vertical flow of the plasticized metal due to low driving force
Threaded Cylindrical		No visible defect	Adequate heat input and sufficient working of plasticized metal
Tapered Cylindrical		Visible pin hole defect at the bottom portion at the retreating side	Insufficient vertical flow of the plasticized metal due to low driving force
Square		Tunnel in the root of weld	Excess turbulence of plasticized metal due to high driving force
Triangle		Visible pin hole defect at the bottom portion at the retreating side	Excess turbulence of plasticized metal due to high driving force

4.2 Microstuctural Analysis

Three sections including rear, middle and front region from each five joints fabricated are examined under SEM to view the microstructure of stirred zone. Table 11 indicates the three microstructure of stirred zone in which the rear, middle and front region are shown in column 1, 2 and 3 respectively. The microstructure on the stirred zone of the five joints fabricated is compared according to the grain.

Table 11: Microstructure of Stirred Zone of Five FSW Joints

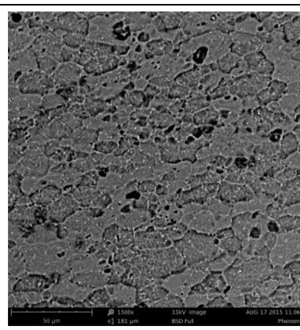
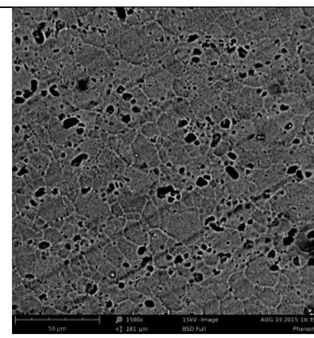
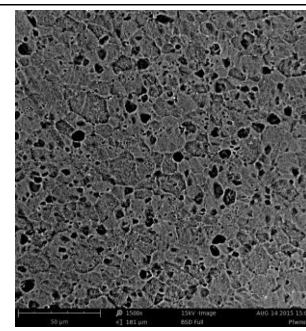
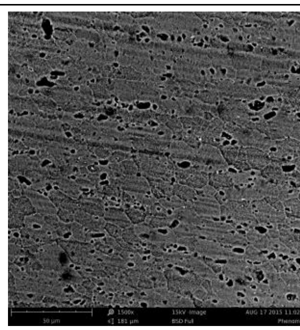
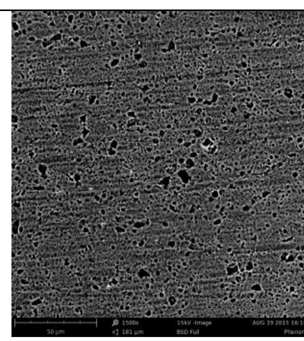
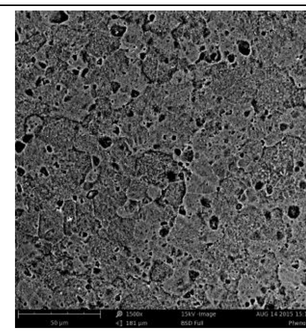
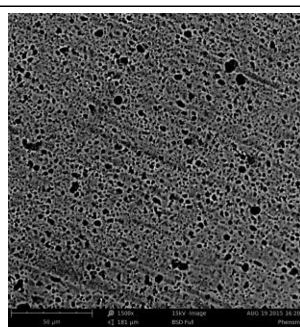
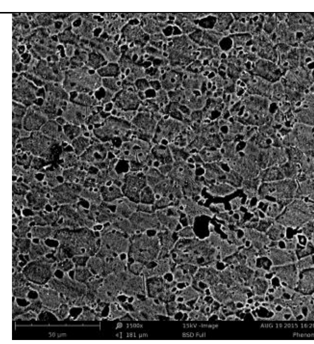
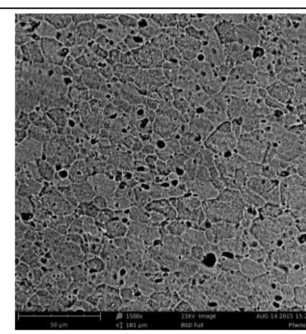
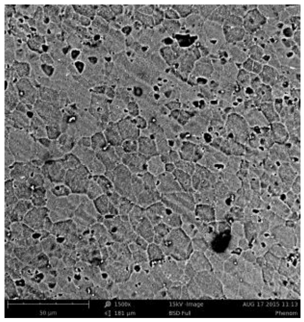
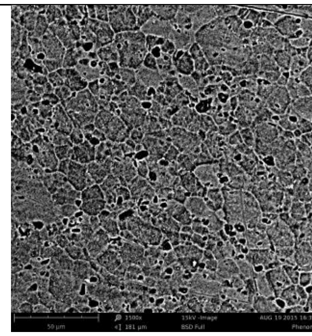
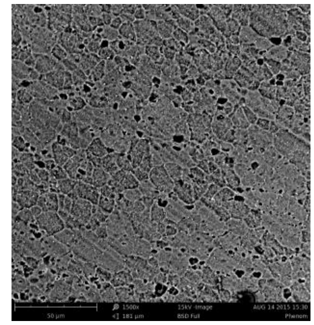
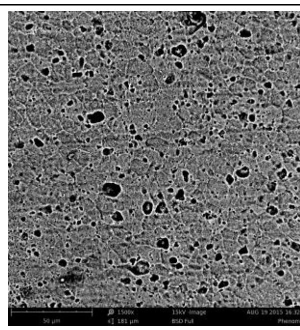
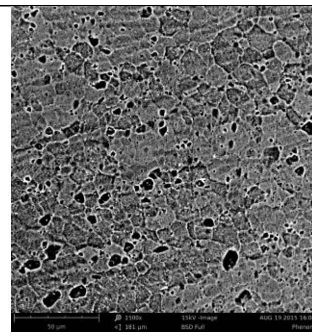
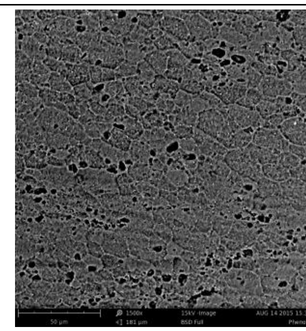
Tool Pin Profiles	Microstructural View		
	1	2	3
Straight Cylindrical			
Threaded Cylindrical			
Tapered Cylindrical			

Table 11: Microstructure of Stirred Zone of Five FSW Joints (Cont.)

Tool Pin Profiles	Microstructural View		
	1	2	3
Square			
Triangle			

From Table 12, it is observed that the microstructure of stirred zone at the cross section of FSW joints fabricated by straight cylindrical and threaded cylindrical pin profiled tools consist of coarse grain with more bundle of black precipitates. Meanwhile, tapered cylindrical, square and triangle pin profiled tool fabricates FSW joints with fine grain and less bundle of black precipitates at the stirred zone. By comparing the microstructural view, square pin profile produces the finest and most uniform grain at the stirred zone, while the straight cylindrical profile produces stirred zone with the coarsest grain.

Furthermore, square and triangle pin profiled tool which consists of flat faces produce smaller and finer grain compared to others pin profiled tools. Due to the flat faces, square and triangle pin profiled tool have more intense stirring and mixing of material during FSW process and result in improving the microstructural evolution, thereby producing fine grain.

Pin profile with flat faces such as square and triangle are correlative to eccentricity. This eccentricity allows incompressible material to pass around the flat faces pin profile. Eccentricity of the rotating object is related to dynamic orbit due to eccentricity. The relationship between the static volume and dynamic volume decides the flow of plasticized material from the leading edge and trailing edge of the rotating tool [13 and 14]. The ratio of dynamic volume to static volume of the pin profiles is presented in Table 12. Pin profile with higher ratio of dynamic volume to static volume generates finer grain at stirred zone. However, Table 12 shows that square pin profile produce the finest grain of stirred zone out of the five pin profiles, although with a lower ratio of dynamic volume to static volume than tapered cylindrical and triangle pin profiles.

Table 12: Ratio of Dynamic Volume to Static Volume

Tool Pin Profiles	Static Volume (mm^3)	Dynamic Volume (mm^3)	Dynamic Volume/Static Volume
Straight Cylindrical	589.05	589.05	1.00
Threaded Cylindrical	589.05	589.05	1.00
Tapered Cylindrical	309.62	589.05	1.90
Square	750.00	1178.10	1.57
Triangle	243.53	589.05	2.42

In addition, the microstructure of stirred zone produced by square and triangle pin profiled tool shows finer grain compared with others pin profiled tool. Square and triangle produce pulsating stirring action due to the flat faces. In the case of straight cylindrical, threaded cylindrical and tapered cylindrical pin profiles, there is no such pulsating stirring action during FSW process [13-15]. At the rotating speed of 1100rpm, square and triangle pin profiles produce 73.33pulses/s and 55pulses/s respectively. In comparison, square pin profile which has higher pulsating stirring action generates finer grain of stirred zone than triangle pin profile.

4.3 Hardness Test

Rockwell hardness, B scale test is performed on the stirred zone of each five joints fabricated. Similar with microstructure analysis, three sections including rear, middle and front region of the joints are performed hardness test. The result is listed in Table 13. Moreover, average Rockwell B Hardness (HRB) value is calculated and comparison of HRB between the five joints is presented in Figure 26.

Table 13: Rockwell B Hardness at Stirred Zone of Five FSW Joints

Tool Pin Profiles	Rockwell Hardness, B Scale (HRB)			
	1	2	3	Average
Straight Cylindrical	28.1	29.1	28.4	28.5
Threaded Cylindrical	29.2	31.8	32.7	31.2
Tapered Cylindrical	33.1	34.6	33.8	33.8
Square	37.8	36.2	36.5	36.8
Triangle	35.4	36.3	35.8	35.8

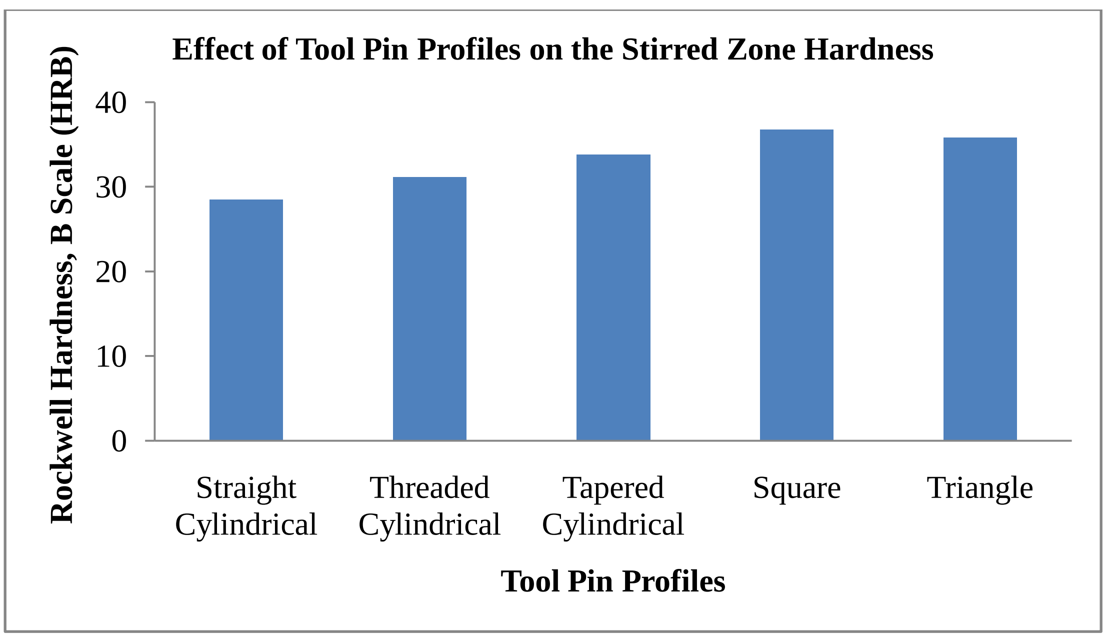


Figure 26: Effect of Tool Pin Profiles on the Hardness of Stirred Zone

Based on the result, tool pin profile is proven to have effect on the hardness at stirred zone of FSW joint. All the five FSW joints fabricated have lower hardness compared to the base material which has 60HRB. Out of the five FSW joints, the highest hardness value of 36.8HRB has been recorded in the joint fabricated by square pin profiled tool. Table 13 and Figure 26 also show that straight cylindrical pin profiled tool produces stirred zone with the lowest hardness value which is 28.5HRB. Moreover, hardness of joint produced by tapered cylindrical pin profile is higher than that of threaded cylindrical pin profile and this is probably due to joint fabricated by tapered cylindrical pin profile has finer grain. Similarly, the result tabulated indicates that the joint with fine grain produce harder stirred zone of the joint compared with tool without flat faces.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

FSW joints of AA6061-T6 fabricated by different pin profiled tool are investigated. Based on visual investigation on the five FSW joints, visual appearance defect such as formation of weld flash is observed. Threaded cylindrical and square pin profiles produces better quality of FSW joint in term of visual appearance compared to the others. Furthermore, visual inspection on the cross section across the joints shows visible pin hole is detected on the joints fabricated by straight cylindrical, tapered cylindrical and triangle, and tunnel is detected on the joints fabricated by square pin profiled tool. The probably reason is due to the low driving force of straight cylindrical and tapered cylindrical pin profiles, and high driving force for square and triangle pin profiles.

Out of the five FSW joints fabricated in this project, joint fabricated by square pin profiled tool consists of finer and uniform grain at the stirred zone and also has the highest hardness which is 36.8HRB. The coarsest and lowest hardness value joint is produced by straight cylindrical pin profiles tool. The pulsating stirring action experienced by square and triangle pin profiles fabricates finer microstructure and in turn yields higher hardness joint compared with straight cylindrical, threaded cylindrical and tapered cylindrical.

5.2 Recommendation

Throughout this project, there are some recommendations for future improvement such as:

- Design a tool with concave shoulder instead of convex or add feature on the convex shoulder to prevent plasticized material escapes from the pin and formation of defect.

- Include effect of FSW process parameters in the study on effect of tool pin profile on FSW of aluminium alloy. So that, both optimum pin profile and process parameter are identified for respective aluminium alloy.
- Carry out FSW and dissimilar metal FSW study on others aluminium alloys in order to broaden the FSW technique in the lightweight construction industry.

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APPENDICES

Table 2: Studies Performed on FSW of Aluminum Alloys [13, 14 and 16-18]

References	[13]	[14]	[16]	[17]	[18]
Material welded	300 × 150 × 6mm AA6061	300 × 150 × 6mm AA2219-T62	300 × 70 × 5mm AA1050-H24	400 × 100 × 12mm AA2219-T62	100 × 8mm AA6082-T6
Tool material	High carbon steel	High carbon steel	Tool steel	H13	High speed steel
Pin profile	Cylindrical; threaded cylindrical; tapered cylindrical; square; and triangular	Cylindrical; threaded cylindrical; tapered cylindrical; square; and triangular	Cylindrical; threaded cylindrical; and triangular	Threaded and tapered with three spiral flutes; and threaded and tapered with triangle	Cylindrical threaded; triflute cylindrical threaded; and cylindrical without featured shoulder
Pin diameter (mm)	6	6	6	11.8 (root); and 5.9 (head)	Not specified
Pin length (mm)	5.5	5.7	4.7	11.7	7.8
Shoulder diameter (mm)	15, 18 and 21	18	15	26	Not specified
Shoulder Feature	No	no	No	No	Spiral groove
Concavity (°)	0	0	10	0	0
Tilt angle (°)	0	0	3	2.5	1.5
Rotational speed (rpm)	1200	1600	1500	300; 400; and 500	710
Welding speed (mm/min)	75	22.2; 45.6; and 75	100; 400; and 700	60; 80; and 100	900
Axial force (kN)	7	Not specified	Not specified	Not specified	Not specified
Remarks	Welds produced by square pin has finer microstructure and exhibits superior tensile strength. Tool with ratio of 3 produced higher strength welds.	Square tool pin with 45.6mm/min produces higher hardness and finer grains and superior strength of welds.	Tool shape is not significantly influence on welds quality	Spiral flutes produce finer and disperse grain size and particle. Tool pin profile has less effects of tensile strength.	The tools used influences the mechanical properties of welds.

Table 3: Studies Performed on FSW of Aluminum Alloys [7 and 19-22]

References	[7]	[19]	[20]	[21]	[22]
Material welded	300×50×5mm AA7039-T6	300×100×3mm 6005A-T6	200×200×6mm AA6061	3.7mm thick Al-Mg-Er	6mm thick Al-Zn-Mg-Cu
Tool material	Not stated	Cr12MoV	High speed steel	Tool steel	Steel
Pin profile	Tapered cylindrical	Cylindrical	Cylindrical; and square	Threaded cylindrical	Threaded and tapered triangular
Pin diameter (mm)	6	3	7.2	5	10(root); and 6(head)
Pin length (mm)	4.7	Not specified	5.7	3.4	5.75
Shoulder diameter (mm)	16	12	18	12	20mm
Shoulder Feature	No	No	No	No	No
Concavity (°)	0	0	0	0	Angle not specified
Tilt angle (°)	2.5	2.5	0	2.5	2.5
Rotational speed (rpm)	410; 540; and 635	1200	2000	400; 800; and 1200	350; 650; and 950
Welding speed (mm/min)	75; 120; and 190	100; 200; and 400	20	100; 200; and 400	50; 100; and 150
Axial force (kN)	Not specified	Not specified	Not specified	Not specified	Not specified
Remarks	Both grain size and hardness decreases on increasing welding speed and decreasing rotary speed.	Low welding speed increase hardness of welds.	Cylindrical tool pin produce weld with maximum micro-hardness value.	Grain size increased with increasing rotary speed or decreased with decreasing welding speed. Hardness is not significantly influenced after welding speed reach 200mm/min.	Fine grains produced. Grain size decreased with increasing in welding speed and increasing in tool rotational speed.