Experimental studies on strength of friction stir spot welding (FSSW)

By

Mohd Syazwan Akmal Bin Yaccob

Dissertation submitted in partial fulfillment of

the requirement for the

Bachelor of Engineering (Hons)

(Mechanical Engineering)

JUNE 2009

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

ABSTRACT

Friction Stir Spot Welding (FSSW) is a derivative of the friction stir welding (FSW), novel variant of the "linear" FSW process. It creates a spot, lap-weld without bulk melting with vertical movement of a non-consumable tool during the welding operation on overlapping sheet metal with small range of thickness for soft metal like aluminium. It has been used in the production of aluminum doors, engine hoods, and deck lids in the Japanese automotive industry, aerospace, transportation, and automotive industry globally [2]. It has the benefits of operation and investment cost savings, weight reduction, high repeatability and consistence, low maintenance, better work environment, environmental metal joining and recyclability versus other aluminum spot joining method [2]. This dissertation Final Year Project on Friction Stir Spot Welding (FSSW) reports the experimental study on strength of overlapping Aluminum 1100 sheet metal which applies the welding method. CNC Mazak Integrex 200-III is used to fabricated tool steel while CNC Mazak Variaxis 530 5-X is used for implementing the welding technique. Pull to break test is used to obtain maximum load (N) before break for the overlapping sheet correspond to lap-shear force. Overall result obtained shows that the lap-shear strength of overlapping sheet decreases by increasing or decreasing tool rotational speed and penetration rate beyond the optimum combination.

TABLE CONTENT

LIST OF FIGURES

LIST OF TABLES

LIST OF GRAPHS

CHAPTER 1: INTRODUCTION

1.1 Background Study

One of aluminium main disadvantages is the limitation imposed by its welding method compare to steel. Several reason for this exist; aluminium requires more joint preparation prior to welding rather than steel, and the heat of welding reduces the strength of soft metal while it is opposite way for steel. Traditional arc welding used for joints made between butting aluminium parts usually requires that material first be removed from the joint, thereby creating a groove into which special filler material is redeposit under an inert shielding gas with an electric arc. This is especially inefficient for aluminium because aluminium production is so energy intensive and arc welding requires most of the material in the joint be produced twice.

Welding limitation are also particularly disadvantages for aluminium since the largest commonly produced aluminium structural shapes are smaller than carbon steel. When larger structural are needed, built-up shapes must be made by welding together plates or smaller shapes.

A new process, however, shows promise in helping to overcome these hurdles. One of the technicians at The Welding Institute (TWI) in England was cutting plastic pipe with a dull saber saw and notices that the pipe tended to melt back together behind the blade due to friction-generated heat. In 1991[1], TWI filed a patent for friction stir welding (FSW), which uses frictional heat generated by a rotating, non-consumable tool that is plunged into the interface between two closely abutted parts. The heat plasticized the material and bonds it, producing welds with low heat input and, hence, little distortion and good properties in the weld area.

Friction-stir welding (FSW) is a solid-state joining process (meaning the metal is not melted during the process) and is used for applications where the original metal characteristics must remain unchanged as far as possible. This process is primarily used on aluminium, and most often on large pieces which cannot be easily heat treated post weld to recover temper characteristics. It was invented and experimentally proven by Wayne Thomas and a team of his colleagues at The Welding Institute UK in December 1991 [1]. TWI holds a number of patents on the process, the first being the most descriptive [1]. In addition to the development of welding technique, a new process which is a derivative of Friction-stir welding (FSW) has been developed by TWI which is Friction-stir Spot Welding (FSSW).

(FSSW) is generally used in automotive industry where the efforts to reduce vehicle weight and improve crash performance have resulted in increased application of advanced high strength steels (AHSS) and a recent focus on the weldability of these alloys. Resistance spot welding (RSW) is the primary sheet metal welding process in the manufacture of automotive assemblies. Integration of AHSS into the automotive architecture has brought renewed challenges for achieving acceptable welds. The varying alloying content and processing techniques have further complicated this initiative. Furthermore, a relationship between chemistries and hardness is produced. The effect of strain rate on the joint strength and failure mode is also an important consideration in the design of welded structures.

Up to now, most of the production applications have focused on non-automotive means of transportation such as trains, airplanes and boats. Tremendous results have been realized including dramatically improved production, quality, uptime and flexibility. Most production applications have been used outside the automotive industry. This has been happening due to high capital investment, but the advent of lower cost, FSW equipment now eliminates this impediment. It is now the automotive industries time to exploit this process to the fullest. The key enabler is the development of the hardware, software and process parameters which make it possible to use a standard industrial robot. Aluminium, aluminium alloys, and magnesium in a variety of joint types can now be successfully joined. Typical automotive components being designed for FSW and FSSW include: chassis, crush horns, body enclosures, hoods, suspension links and gas tanks. In these types of applications, significant cost reductions have been realized as well as dramatic improvements in mechanical properties [2].

1.2 Problem Statements

Conventional welding has been used to joint dissimilar or similar material in producing the desired shape of many products; commonly on metal to metal. The principle lies on the conventional welding is by melting the workpiece and adding a filler material to form a pool of molten material (the weld puddle) that cools to become a strong joint. Disadvantages of conventional welding are more on space, skill, and cost whereby it suit in wide fabrication area, joining in high strength material, but not to soft and thin metal like aluminium in producing light weight end product. Nowadays new technology has been introduced on Friction Stir Spot Welding (FSSW), which uses friction concept to initiate heat generated into the weld area where it is sufficient enough to permit dissimilar or similar material to joint each other. In this final year project, the strength of the overlapping aluminium sheet metal is analyzed using this friction stir spot welding (FSSW) technique by means of soft metal which is Aluminium 1100 and H13 tool steel as a tool using CNC Mazak Integrex 200-III. The results are useful for future references for soft metal joining at low cost solid-state joining welding methodology. This project is significant since locals market is quite new on this new technology especially on transportation and automotive industry.

1.3 Objectives

At the end of this project, the following objectives should be achieved towards completing this project which are:

1. Fabricate H13 tool steel which suit in-campus facility for FYP 1.
2. Analyze, test, and report the result on strength of workpiece for FYP 2.

1.4 Scope of Study

The study of Friction Stir Spot Welding (FSSW) in Final Year Project 1 covers:

1. H13 tool steel manufacturing procedure.
2. Gathered information needed in performing the manufacturing processes such as:
    a. CNC Mazak Integrex 200-III related information.
    b. CNC Mazak Variaxis 530 5-X related information.
    c. Data sheet of the tool steel material.
    d. Data sheet of the overlapping sheet metal material.
3. Literature review of FSSW technology in locals and international.

The study of Friction Stir Spot Welding (FSSW) in Final Year Project 2 covers:

1. The analysis on strength of specimen using FSSW.
2. Design clamping assembly which suit for FSSW to apply in-campus facility.
3. Machine operatibility regarding the variables involves.
4. Pull to break test to measure maximum load in Newton (N) before specimen break.

CHAPTER 2: LITERATURE REVIEW

Friction stir spot welding (FSSW) is a derivative process of friction stir welding (FSW) in which a solid-state joint is made between adjacent materials at overlap configuration. Feasibility studies of the FSSW process have been performed for more than a decade for materials applied in the automotive, transportation and aerospace industries. However, for a mass production environment, the selection of optimum process parameters is rather less discussed. Principle lies on the FSSW is an improvement step element added from FSW. Given that the FSW process uses a moving tool, the process is flexible [2]. It can be used to weld many different joint configurations [2]. The process can also be used to weld in any orientation (e.g. overhead), as gravity has no effect on the process. The simplicity of the process allows FSW to have significant operating cost advantages over other processes. Likewise, the lack of melting allows the process to have numerous quality advantages over other traditional fusion joining methods, such as Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW), Plasma Arc Welding (PAW), Laser Beam Welding (LBW) or Resistance Spot Welding (RSW). It is said to be cost advantages result because it requires no consumables elements such as gas, wire, or fasteners are required, less repair and rework occurs, little to no material preparation is needed, and there is a reduced need for environmental protection because there is no noise, fumes, UV light, and spatter. The quality related advantages of FSW include weld geometry and penetration consistency, improved yield and tensile strength, as well as improved fatigue life. Furthermore, the process avoids many of the problems with traditional processes. Typical fusion welding problems include poor weld penetration, low weld, poor welding uptime, propensity for weld cracking and porosity, and excessive distortion. The quality improvements versus the traditional processes are more pronounced in harder to join materials, such as 2xxx and 7xxx series aluminium.

Friction Stir Welding (FSW) has become established as a method of making high quality joints in a number of materials in both butt and overlap configurations. A range of materials and thicknesses has been successfully welded under experimental conditions and in production. Recently the increasing use of high strength steels and dissimilar material combinations in high productivity manufacture has encouraged the development and adoption of new joining techniques capable of meeting the quality, reliability and cost requirements in the automotive and other industry sectors, including rail and other transport structures. The FSW process is inherently simple, with few variables. The basics of the process are illustrated in Figure 2.1:

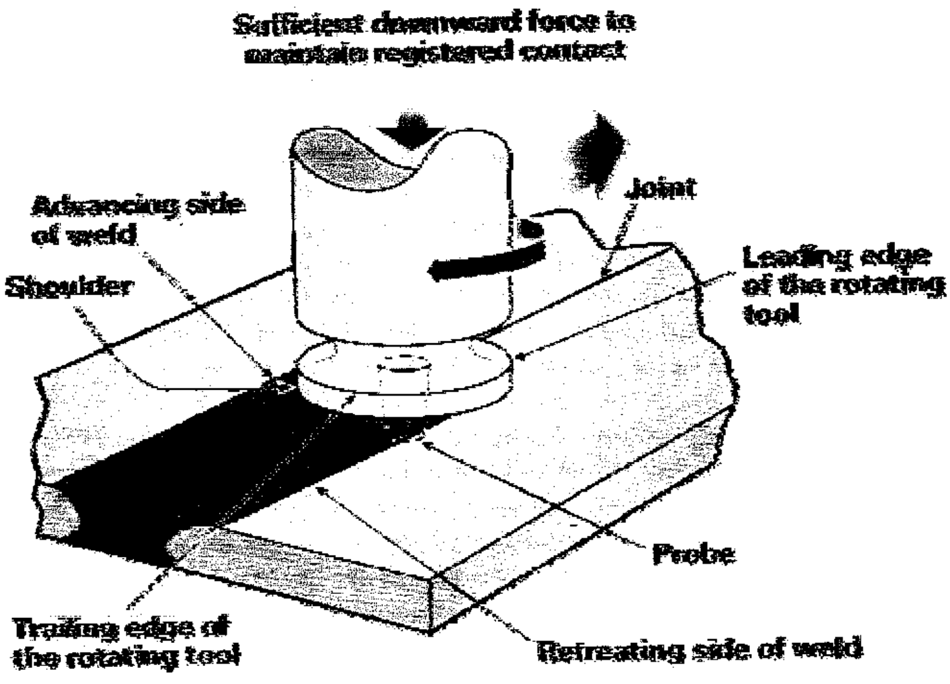


Figure 2.1: Basic principle of Friction-stir Welding [2]

A non-consumable, rotating FSW tool with a specific geometry is plunged into and traversed through the material. The two key components of the tool are the shoulder and the pin (probe). During welding, the pin travels in the material, while the shoulder rubs along the surface. Heat is generated by the tool shoulder rubbing on the surface and by the pin mixing the material below the shoulder. This mixing action permits the material to be transferred across the joint line, allowing a weld to be made without any melting of the material. The only variables in the process are the rotation speed, travel speed, FSW tool design, and tool orientation and position. Once the proper tool design, rotation speed, and travel speed are selected, this simple process ensures high quality, repeatable welds. Other than the linear process described above, another major variation of the process is Friction Stir Spot Welding (FSSW). The FSSW process involves only the plunge and retraction of the FSW tool. The traverse part of the process is eliminated. The FSSW process mimics the Resistance Spot Welding (RSW) process and can be used in place of RSW, riveting, clinching or any other single point joining processes in many applications. The FSSW process has two major variants; one which uses a single sided tool which is comparable to what is known as RSW "Poke" welding and the other involving a C-Frame, which is more like traditional RSW. The main advantage of the C-Frame FSSW process is that fixturing can be reduced because there is now no need to resist any significant force on the part. The C-Frame FSSW process also makes it a lot easier to use any large robot because there is no longer the need to have precise force control. Resistance spot welding, toggle-lock, rivets, and self-piercing fasteners are the primary methods used today for single point joining. All of these processes have inherent disadvantages that are overcome with Friction Stir Spot Welding (FSSW). [2] Challenges with RSW include:

1) The need to chemically clean the aluminium within 8 hours of welding,
2) Excessive electrode mushrooming causing poor welds to be made
3) Process variability and
4) Shunting problems which require greater spacing of the welds.

Challenges with the rivets include:

1) High cost for fasteners,
2) Potentially higher downtime due to feeding issues and
3) Need for other operations (e.g. drilling) for non self-piercing rivets.

Processes such as Toggle-Lok are simple and cheap but have less strength than RSW, especially in the tensile ('cross-tension') direction [2]. In addition, they experience high die wear, which can lead to further degradation of mechanical properties, unless frequent preventative maintenance is done. FSSW is not saddled with the problems that are cited above due to the unique nature of the process. There is no consumable so this makes the process simpler. The tool has excellent life and is not mated to a die, so preventative maintenance is reduced. The speed of the process is competitive with RSW but is much more consistent because FSSW is not as sensitive to changing material conditions (e.g. oxides) and surface conditions (contamination such as forming lubricants).

Friction Stir Spot Welding (FSSW) has already seen limited production use for joining aluminium in the automotive sector and has great potential in high productivity manufacture. So far, little has been published on FSSW of high strength steels, but the data available is encouraging. Recent internal studies have independently shown promising results with several tool materials, and it is now appropriate to develop the process further to enable industry to consider this process for adoption. This final year project aims to study the characteristics and performance of the FSSW process for appropriate low cost soft metal, and to further develop it to achieve the quality and reliability required for large-scale industrial application. This work will enable industrial companies to reach an informed decision on the merits of the process, and its potential for commercial use.

There are four basic steps that involve in FSSW method which is tool rotation in contact with the specimen, plunging tool rotation with load manipulation into the specimen, stirring the tool with a preset time where gives quite enough time for the specimen to join together, and finally drawing out the tool from the molten specimen spot area to cool down to room temperature.

These four basic steps are essential in making the welding spot using FSSW technique where the strength of the end product is more than conventional spot welding. It is observed that all of the above process involves five basic variables which play its own role when combine together as one technique. Below listed are the expecting variables involves in FSSW operation which can be manipulate to get a diversify result:

1. Depth of penetration
2. Rotating tools
3. Lap-shear strength
4. Process time
5. Applied load

Pure FSSW use friction as an element in joining overlapping sheets with respect to the tool pin where thickness of the sheets should be within length of the pin (about 80% thickness of sheet is the length of the pin). The control elements are the rotation speed (rpm) and tool penetration rate (mm/min). The rotating tool with a pin at its tip is in contact with the top surface of upper layer of overlapping sheet metal for certain time to generate frictional heat and plunged into the overlapping sheet metals which cause plastic flow formation between upper layer and lower layer of overlapping sheet metal. The shoulder role as a compressive forging pressure against the sheet metal surface and moves down into the overlapping sheet surface with certain period of dwelling time. The rotating tool is retracted at the end of process with solid-state phase bond between upper and lower sheet of overlapping sheet metal. The process summarize below:

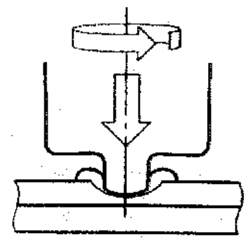


Figure 2.2: Plunging phase [5]

The rotating tool with pin in contact to the top surface rotates at certain rotational speed and dwelling for certain time to generate frictional heat where lower part backing up upper part from downward force. Friction heat generated causes plastic flow to the overlapping sheet.

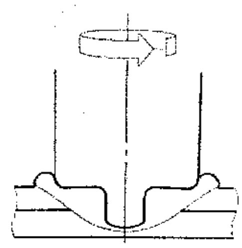


Figure 2.3: Stirring phase [5]

The rotating tool plunged into plastic flow formation accompany with tool shoulder in contact to the upper part sheet surface. The shoulder provides uniform force distribution to the welded area and compressive forging pressure generated in overlapping sheet.

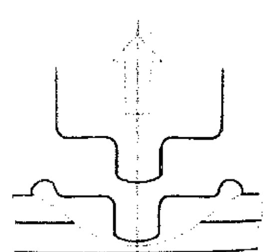


Figure 2.4: Drawing out phase [5]

The rotating tool retracted at the end process after certain dwelling time. The overlapping sheet metal cool down to the room temperature and a solid phase bond is made between upper and lower sheet.

In applying FSSW, there are two basic operations which are load control method and displacement control method where development of both method have been done as early as year 2000 till recently and involve manipulation of variables involves. Below are the schematic diagrams of load-control and displacement control of FSSW process [3]:

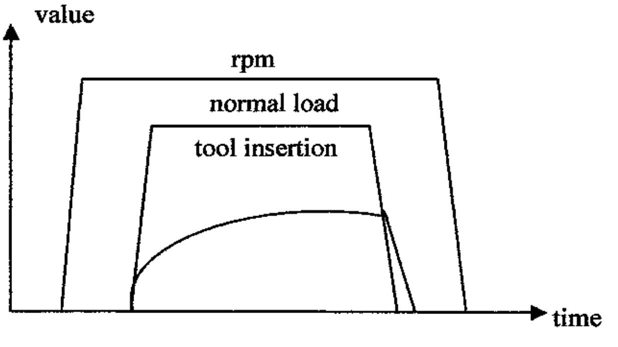


Figure 2.5: Schematic diagram of a load-controlled spot friction welding process [3]

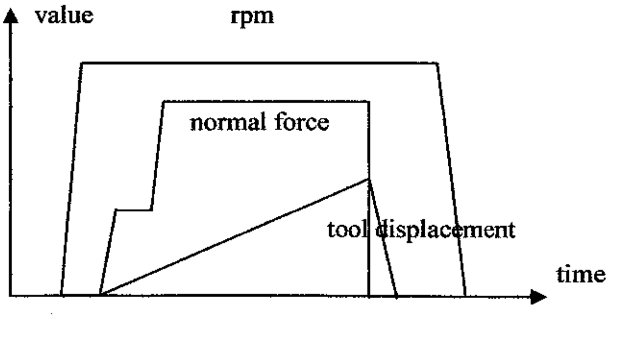


Figure 2.6: Schematic diagram of a displacement-controlled spot friction welding process [3]

The development process of FSSW shows that in manipulating three basic variables involve which are process time, rotating tool, and plunge rate, the lap-shear strength of the end product will reach up to 4kN with 1mm/1mm thickness plate. This value is more than riveting spot welding RSW. Below are the studied that have been conducted on FSSW until recently by SAE technical paper literature review [3]:

1. FSSW process controls
2. Development of process parameters
3. Fracture behaviors
4. FSSW metallurgy
5. Temperature during FSSW
6. Tool geometry
7. Material flow during FSSW
8. FSSW of:
   a. Dissimilar metal
   b. Magnesium
   c. Steel
   d. Adhesive(weld bonding)

There are many benefits using the FSSW technique compare to other conventional welding technique, which are [3]:

1. Reduced energy consumption
2. Reduced equipment investment
3. Improved work environment
4. Long tool life
5. No concern about weld spacing
6. Little welding deformation
7. No foreign substance and consumables
8. High repeatability
9. No preparation
10. Shot cycle time compare to RSW

Comparing between FSSW and RSW in term of advantages and disadvantages aspect differ on the overall strength result that both technique produce at the end of welding. Studies that have been conducted [2] show that FSSW have more overall strength and benefit rather than RSW can give. Some of the RSW advantages are efficient energy use, limited workpiece deformation, high production rates, easy automation, and no required filler materials. When high strength in shear is needed, spot welding is used in preference to more costly mechanical fastening, such as riveting. While the shear strength of each weld is high, the fact that the weld spots do not form a continuous seam means that the overall strength is often significantly lower than with other welding methods such as FSSW technique, limiting the usefulness of the process. It is used extensively in the automotive industry; cars can have several thousand spot welds.

There are numerous applications for both FSW and FSSW, especially in the transportation industry, employing aluminium structures. Any application that is currently riveted, toggle-locked, or spot welded (RSW) can often have FSSW substituted with little difficulty. Examples include automotive body panels, truck trailer bodies, truck chassis and suspension components, golf carts, and pleasure boats. A short list of possible applications in various industries is shown in Table 2.1. Most of the listed applications concentrate on the joining of aluminium, as the FSW process is most advanced in this area and with other lower melting point materials. Other materials that can be joined include magnesium, copper, lead, titanium, and steel. The applications can range from 0.5 mm in thickness to over 50 mm in thickness.

To determine if FSW or FSSW is acceptable for use in an application, one of the first steps is to do a thorough cost analysis. The output of the cost analysis is typically a part cost or a cost per distance of weld for the product to be manufactured. The inputs of the analysis are typically limited to costs that are well defined or easy to obtain. The known cost inputs are capital equipment, labor, and consumables (FSW tools, electricity, shielding gas, weld wire, contact tips). There are several other cost inputs, which can have significant impact, including maintenance, production uptime, rework, scrap and repair. When enough experience with the new technology has been achieved, these inputs can then be included. One also needs to consider the more difficult to measure, but very real costs related to the process being more environmentally friendly. As a general rule, for medium to high volume automotive production, FSW welds cost 20% less than arc welds and FSSW costs 25% less than RSW. If indirect costs are considered (post weld operations, rework, repair, distortion) then the costs of FSW are dramatically less than GMAW.

Table 2.1 - Typical Applications for FSW [2]

Industry Category	**Specific Application**	**Present Process**	**Advantages of FSW**
Electrical	Heat sinks-welded laminations	GMAW	Higher density of fins-better conductivity
Electrical	Cabinets, enclosures	GMAW, RSW	Reduced cost, Weld through corrosion coatings
Batteries	Leads	Solder	Higher quality
Military	Shipping Pallets	GMAW	Reduced cost
Extrusions	Customized extrusions	Not done today	Can customize, reduces need for large press
Boats	Keel, Tanks	Rivet, GMAW	Stronger, Less Distortion
Golf Cars	Chassis, Suspension	GMAW	Less distortion, Better fatigue life
Tanks, Cylinders	Fittings, Long & Circum Seam	GMAW	Higher quality - less leaks, higher uptime
Aerospace	Floors, wing spars	Rivets	Higher quality, cheaper(no rivets & holes)

CHAPTER 3: METHODOLOGY

The project encompasses some methodologies within the requirement in order to achieve the project objectives stated in previous chapter. With respect to the methodology, there are several combination methodology needed before the strength of weld area could be tested such as tool preparation, overlapping sheet preparation, specimen clamping design, friction stir spot welding (FSSW), pull to break test and evaluation on strength.

3.1 H13 Tool Steel Preparation

The project starts with tool steel preparation where it is a non-consumable tool which can sustain high temperature generated by friction during the FSSW operation. With respect to project objectives, H13 steel is a suitable candidate as FSSW tool since the material properties fit the aluminium material properties in applying the FSSW technique. Figure 3.1 below shows the methodology followed in fabricating the FSSW tool steel:

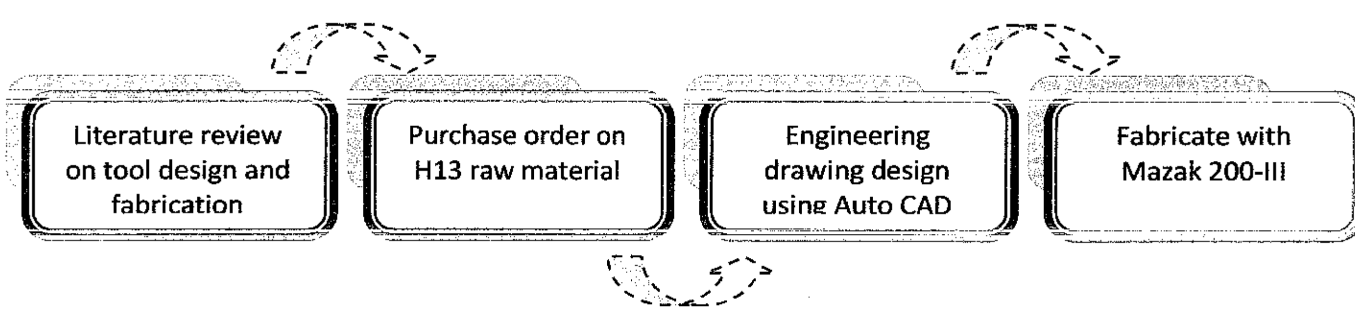


Figure 3.1: H13 tool steel methodology

The project starts with literature review on tool design and fabrication to suit the in-campus facility in order to achieve project objective. The project focus on pure FSSW technique where pin and shoulder type tool in fabricating the tool steel. As for tool steel fabrication, Computerized Numerical Control (CNC) Mazak Integrex 200-III machine is used in manufacturing the tool steel with respect to the Revision 1 of H13 tool steel engineering drawing (the Auto CAD and CATIA drawing is listed in Appendix 3.1). The dimension of H13 raw material is 25mm x 305mm (diameter x length) and it is suit to CNC Mazak Integrex 200-III which require 25mm as minimum diameter for the raw material to be machine which is in line with the raw material that have been purchased. As for the machine, all calculation and input regarding the fabrication variables such as feed rate, machine rotation, chips control, coolant use in fabrication, and tool spindle rate have been set as default in existing module software. The coolant used for the machine is soluble oil which is the combination of oil and water coolant while the insert used for cutting and shaping the tool steel is coated carbide tool. The H13 data properties are listed in Appendix for references.

3.2 Heat Treatment

Once the tool has been completely fabricated using the Mazak Integrex 200-III, it needs to undergo the heat treatment; a method used to alter the physical, and sometimes chemical, properties of a material. Heat treatments are also used in the manufacturing of many other materials, such as glass. Heat treatment involves the use of heating or chilling, normally to extreme temperatures, to achieve a desired result such as hardening or softening of a material. Heat treatment techniques include annealing, case hardening, precipitation strengthening, tempering and quenching.

It is noteworthy that while the term heat treatment applies only to processes where the heating and cooling are done for the specific purpose of altering properties intentionally, heating and cooling often occur incidentally during other manufacturing processes such as hot forming or welding. For this project, the procedures of the heat treatment are as follows:

1) The welding tool is inserted in the Tube Furnace and preheated initially for two (2) hours to raise from 0 – 1350°F [-17.78 – 732°C]

2) Next, the welding tool is continued preheated; slowly from 1350 – 1400°F [732 - 760°C] for another two (2) hours

3) Then the temperature will be raised to 1800°F [1000°C] for one (1) hour

4) Finally it will be cooled down to room temperature 75°F (24°C) for two (2) hours

3.2 Overlapping Sheet Preparation

Friction Stir Spot Welding (FSSW) is suitable for small range thickness for joining two overlapping sheet metal. In achieving the project objective, designing suitable overlapping sheet metal which suit engineering assembly design is the key to get a good quality welding. In this work, the overlapping sheet metal is 1mm in thickness and 30mm x 100mm (width x length) which have hole each sheet for clamping purposes.

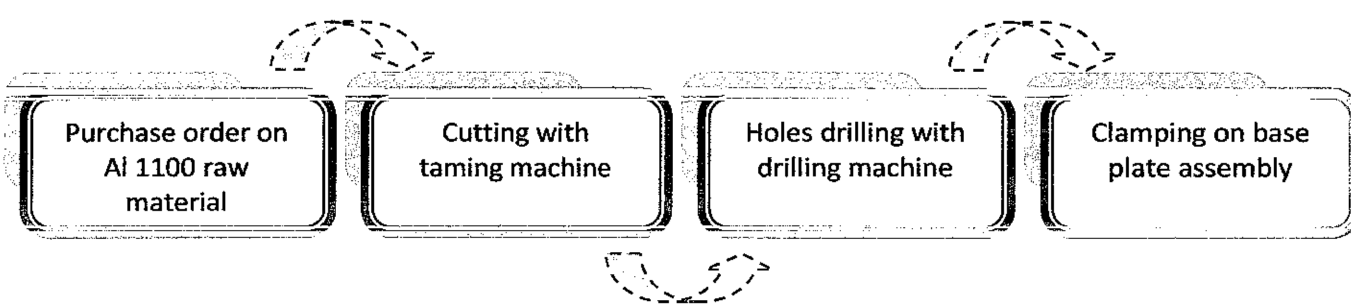


Figure 3.2: Overlapping sheet methodology

The workpiece is cut through taming machine according to engineering drawing dimension. Next step is to drill 8.5mm diameter hole using drill machine for each aluminium sheet which suit the base plate clamping design. Each sheet is label accordingly since the base plate assembly consists of three sheets for each experiment. Two sheets act as an overlapping sheet to undergone FSSW technique while the third sheet act as lining to achieve better quality welding (the Auto CAD and CATIA design for base plate clamping design is listed in Appendix 3.2).

3.3 Base Plate Clamping Assembly

Force distribution on soft metal like aluminium is quite high during the welding operation which requires the overlapping aluminium sheet to be clamped tightly for quality welding. The base plate clamping assembly has been designed to suit the welding purposes which clamp the overlapping aluminium sheet in Mazak 530 5X (the Auto CAD and CATIA for base plate clamping design is listed in Appendix 3.2). The base plate is 130mm x 250mm (width x length) and 20mm thickness where holes of 10mm diameter for the purpose of L angle and holes of 8mm diameter for the purpose of overlapping aluminium sheet is drilled on the base plate. The hole of 10mm is threaded with 1.5mm and hole of 8mm is threaded with 1mm according to ASME threading table. The screw used is hexagonal 10mm diameter and 8mm diameter for respective holes. Next step is L angle with 8.5mm diameter holes which restrict the movement of overlapping aluminium sheet in horizontal direction. Final step is setting the base plate clamping assembly to get the origin point (0, 0, 0) in the Mazak 530 5X with overlapping aluminium sheet. Figure 3.3 shows the methodology used for preparing the base plate clamping assembly:

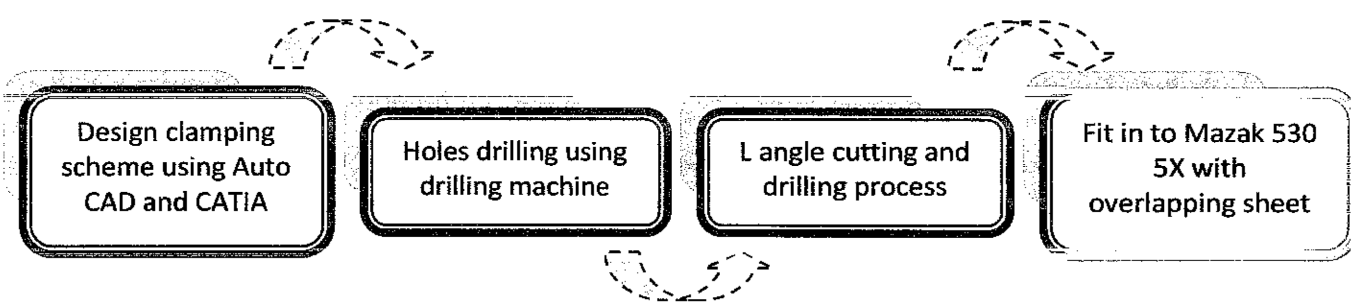


Figure 3.3: Base plate clamping assembly methodology

3.4 Friction Stir Spot Welding (FSSW)

The project uses CNC Mazak Variaxis 530 5-X to implement the FSSW on aluminium 1100 overlapping sheet. The base plate clamping assembly comprises overlapping aluminium sheet, base plate, and mounting hole for L angle. The machine is compatible with Auto CAD 2004 and the design can be read to generate the machine command using master-cam software integrated with the machine. The specimen need to be mounted using base plate since the thickness of 1mm is not well-suited to be operated in the machine due to small range of thickness. In addition, the base plate which is 20mm thickness is used and suitable enough to be mounted tightly during the welding. A screw is used to mount an 8mm holes and the thread drilled is 7mm which suit perfectly when the threading process is completed.

The friction stir spot welding (FSSW) technique is ready to run after the tool steel preparation and overlapping Aluminium 1100 sheet metal completed. For this project, Mazak Variaxis 530 5-X is used to apply the welding technique since the machine module is suitable for applying the FSSW concept which is plunging, stirring, and drawing out. The dwell time used for the welding is five second stirring before drawing out. In order to determine the highest possible joining strength, there are two manipulative variables to control which is tool rotational speed of tool steel per minutes (rpm) and penetration rate in (mm/min). These two variables are arranged from low value up to the highest possible to get the variation of strength during the pull to break test. The tool rotational speed per minutes is ranging from 2000rpm and increment by 2000rpm until 6000rpm. The penetration rate is ranging from 45mm/min and increment by 15mm/min for each experiment until 85mm/min. Table 3.1 below summarize the manipulative variables used for each variable control during the FSSW technique:

Table 3.1: Manipulative variables for each FSSW technique

	55 mm/min	70 mm/min	85 mm/min
2000 rpm	✓	✓	✓
4000 rpm	✓	✓	✓
6000 rpm	✓	✓	✓

Throughout the welding technique, about nine specimens are qualified to undergone pull to break test to obtain the maximum load in Newton (N) before break by shear force.

Figure 3.4 below shows the methodology chart on friction stir spot welding (FSSW) technique:

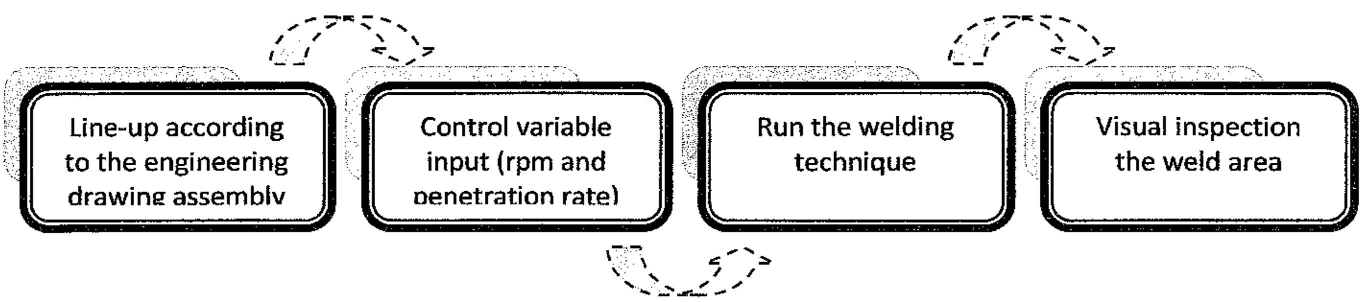


Figure 3.4: Friction stir spot welding methodology

3.5 Pull to Break Test

Pull to break test is a method used to obtain maximum load of the specimen before it breaks by applying shear force to the weld area. A total of nine specimens underwent the pull to break test to obtain the maximum load before break due to shear force applied to the weld area. The result regarding the test is discussed in result and discussion chapter. The specimen is clamped to the universal testing machine (UTM) and in order to prevent slip of clamping occur during the test, double sided tape has been used to increase the friction between the specimen and machine clamp holder. Initial test has shown some error regarding the clamping matter and yield non-clean break of the specimen with respect to the maximum load before break. Figure 3.5 below shows the methodology of the pull to break test:

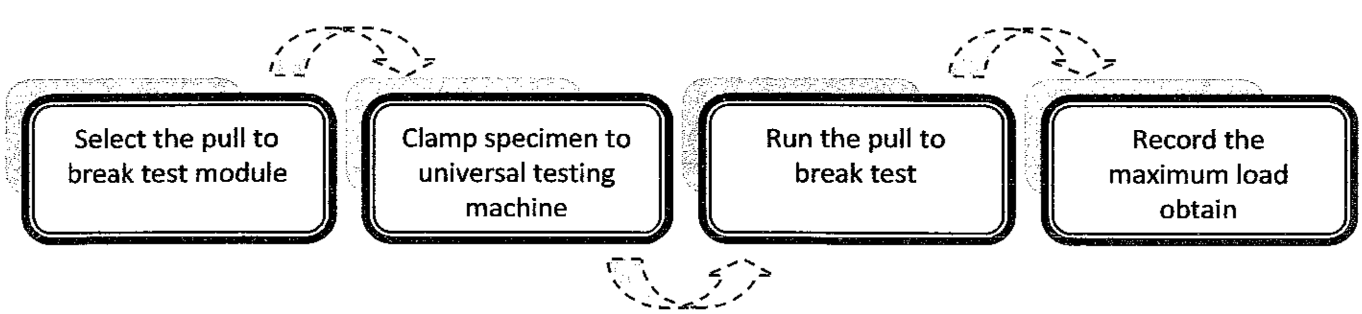


Figure 3.5: Pull to break test procedure

3.6 Experimentation & Procedure

The experimentation procedure conducted to obtain the maximum load before break is summarized in the diagram below:

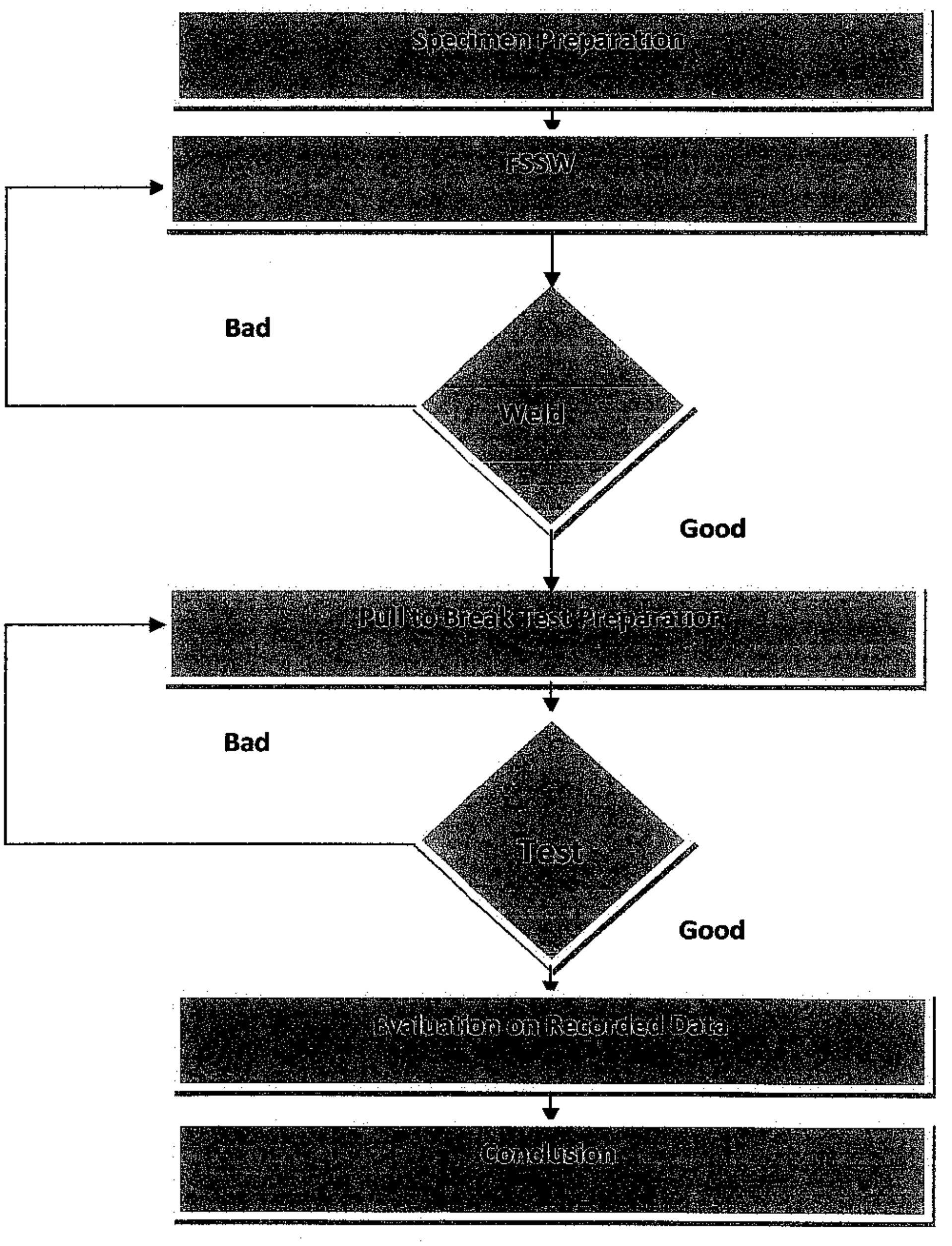


Figure 3.6: Diagram of experiment of lap-shear strength

CHAPTER 4: RESULT AND DISCUSSION

This chapter discussed the result with respect to the project objective. There are several subjects to be discussed upon obtaining the result before and after the FSSW technique such as H13 tool steel, Aluminium 1100 sheet metal, friction stir spot welding (FSSW) technique, pull to break test, Mazak Integrex 200-III, Mazak Variaxis 530 5-X, x-ray fluorescent (XRF).

4.1 H13 Tool Steel

The vendor that has been recognized which chould endow H13 tool steel raw material is Kim Win Metal Specialist located near the university campus. The H13 ordering information is according to American Standard and Testing Material ASTM A681. The class of material is categorized in hot work tool steel family. The type of equivalent standard is H13 where it describes the chemical composition, mechanical properties, physical properties, and heat treatment with tempering chart regarding the condition specified. The shape will be round bar cylinder shape raw material since it will be use in CNC Mazak Integrex 200-III as tool steel fabrication and as a tools in CNC Mazak Variaxis 530 5-X for FSSW purposes. The dimensions of the raw material are 50mm in diameter and 305mm in length where it is enough for four versions of tools with two bulk of raw material. Each tool consumes about 100mm of raw material after fabrication with CNC Mazak Integrex 200-III. The condition of the raw material would be annealed, hardened and tempered where it should be prepared by the vendor according to A681 standard and procedure.

The vendor provide the nearest matching requirement which is hot work tool steel 2344 / RDC 2V and it is equivalent with the H13 standard requirement. The product features is a chromium-molybdenum-vanadium steel which has outstanding toughness and high hot hardness. Below are the additional features of hot work tool steel 2344 / RDC 2V [9]:

1. Improved tool life which specially annealed to remove all intergranular carbide precipitation and allow a fine globular carbide distribution.
2. Higher toughness and hot hardness than H11 steels with chromium-molybdenum-vanadium element added to improve properties.

The product is suitable for listed applications, according to A681 and vendor suggestion [9].

1. Hot work tools subjected to temperature from 300 °C to 580 °C
2. Hot extrusion tools for light alloys: pressure discs, mandrels, stems, headers, centering and shearing mandrels, dies, and liners
3. Casting dies for light alloys: cores, ejectors.
4. Plastic molding dies: injection molding applications
5. Forging tools: dies, die insert, punches, mandrels.

For this project, hot work tools is subjected to temperature ranges from 300 °C to 580 °C. The temperature range meets the requirement since the FSSW technique which will be applied on Aluminium 1100 requires melting temperature in that range. Considering the raw material material properties, it is difficult to have one that match exactly according to the standard as needed. For H13, there are equivalent standards that match this project need and Wing Koh is in accordance with one of the requirement which is:

Table 4.1: Equivalent standard for tool steel requirement as A681.

WN	DIN	AISI	JIS
1.2344	X40 CrMoV 5 1	H13	SKD 61

For this part, it describes the gathered required data in analyzing the hot work tool steel properties. For the raw material, below is the chemical analysis in term of weight percentage:

Table 4.2: Chemical composition of H13 tool steel

C	Si	Mn	Cr	Mo	V
0.40	1.05	0.35	5.00	1.30	1.00

Looking at the chemical analysis, the data is in accordance with A681 standard where the required data for chemical composition which follow the standard is:

Table 4.3: Minimum and maximum element composition as H13 standard

UNS	Type	C		Mn		Si		Cr		V		Mo	
		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
T20813	H13	0.32	0.45	0.20	0.60	0.80	1.25	4.75	5.50	0.80	1.20	1.10	1.75

Furthermore, the weight percentage data provided by the vendor is in range with A681 standard which shows hot work tool steel 2344 / RDC 2V is an equivalent standard to H13 requirement. This shows that the raw material meet the project requirement as a tool steel for FSSW welding technique for the FYP 2 job scope. The vendor also provides the mechanical properties of the product where its hardness in annealed condition could go up to 229 HB max. According to the A681 standard, maximum Brinell hardness in annealed condition for H13 is 235BHN which around the figure with the data provided by the vendor. With data gathering, almost all related data required in preparing the tool steel for FSSW welding technique have met the requirement of the project.

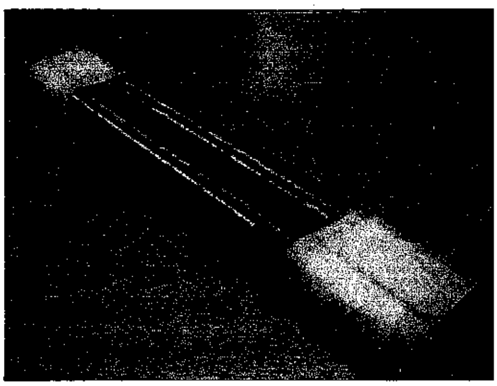


Figure 4.1: H13 hot work steel

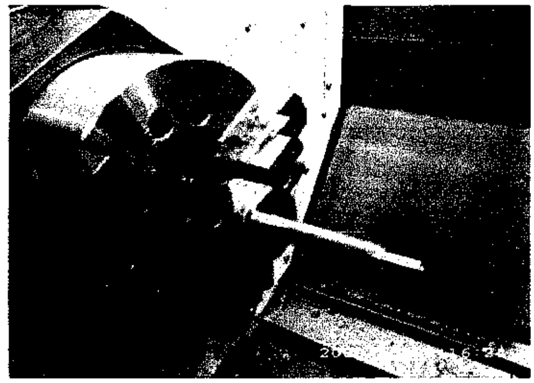


Figure 4.2: Tool steel fabrication

4.2 Aluminium 1100 Sheet Metal

Aluminium alloy 1100 contains a minimum of 99.00% aluminium, and is sometimes known as 'commercially pure aluminium'. It has excellent electrical conductivity, good formability, high resistance to corrosion, and is used where strength with lightweight product is needed. It has the low density and excellent thermal conductivity common to all aluminium alloys. Aluminium 1100 is commercial purity aluminium with a controlled content of copper. For this project, aluminum alloy 1100 is used for experimental study on strength to determine the highest lap-shear strength the joining could achieved by testing it using pull to break test. Table 4.4 and table 4.5 below shows the chemical composition and physical properties for aluminium 1100 respectively:

Table 4.4: Chemical composition of Aluminium 1100 [8]

Element	%	Element	%
Aluminium	99.00% min	**Manganese Zinc**	0.05 max
Copper	0.05 – 0.20	**Others, each**	0.10 max 0.05 max
Silicon + Iron	0.95 max		
		Others, total	0.15 max

Table 4.5: Physical properties of aluminium alloy 1100 [8]

Physical Properties						
Property	**At**	**value unit**	**Property**	**at**	**Value**	**unit**
Density	20°C	2,710 kg/m3	Mean Coefficient of Expansion	20°C	23.6	x 10-6 / °C
Weight	20°C	2.71 x thickness in mm	Thermal Conductivity	25°C	222	W / m.°C
Melting Range		643 – 657 °C	Electrical Resistivity	20°C	0.292	micro-ohm.m
Modulus of Elasticity			Electrical conductivity			
Tension	20°C	69 GPa	O temper (annealed)	20°C	59	% IACS
Torsion	20°C	26 GPa	H18 temper	20°C	57	% IACS

4.3 Friction Stir Spot Welding (FSSW)

Several experiments had been done to get an overview on friction stir spot welding (FSSW) before proceeding to experimental study on strength of solid-state joining between two overlapping aluminium 1100 sheet metal. The first FSSW technique run is the overlapping sheet metal in random series aluminium clamping to base metal without L angle and yield good solid-state joining but deviation in horizontal movement since there is no restriction in horizontal axis. After several revision of engineering drawing on the base plate clamping design, L angle bar is added to restrict the movement in horizontal axis during the welding operation in Mazak Variaxis 530 5-X. The second experiment is done based on a new revision of base plate clamping assembly in the company of random series of aluminium overlapping sheet metal to test the clamping design and the result yield good weld area with better quality rather than the first experiment. Next experiment implement the usage of specific overlapping sheet metal material since the overlapping sheet metal used in previous two experiments are in random series without data sheet where it is important for strength analysis after pull to break test. In the final experiment, aluminium 1100 is used as a specimen with several considerations have been taken into account to predict other attributed such as dwell time and stirring time with respect to the tool rotational speed and penetration rate gives that higher lap-shear strength after solid-state joining. As discussed in methodology chapter, a total of nine specimens of overlapping aluminium 1100 sheet metal are prepared to be tested using pull to break test with variation of tool rotational speed and penetration rate.

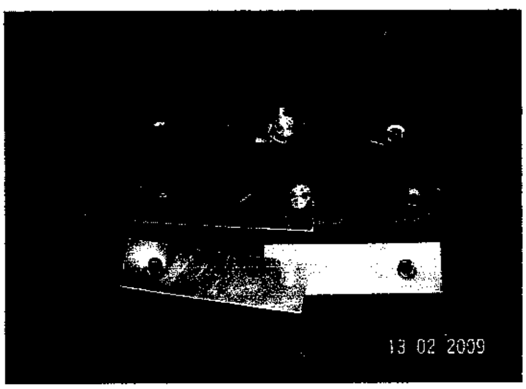


Figure 4.3: First try FSSW technique

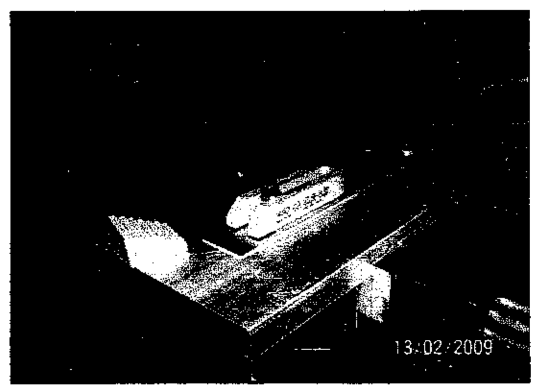
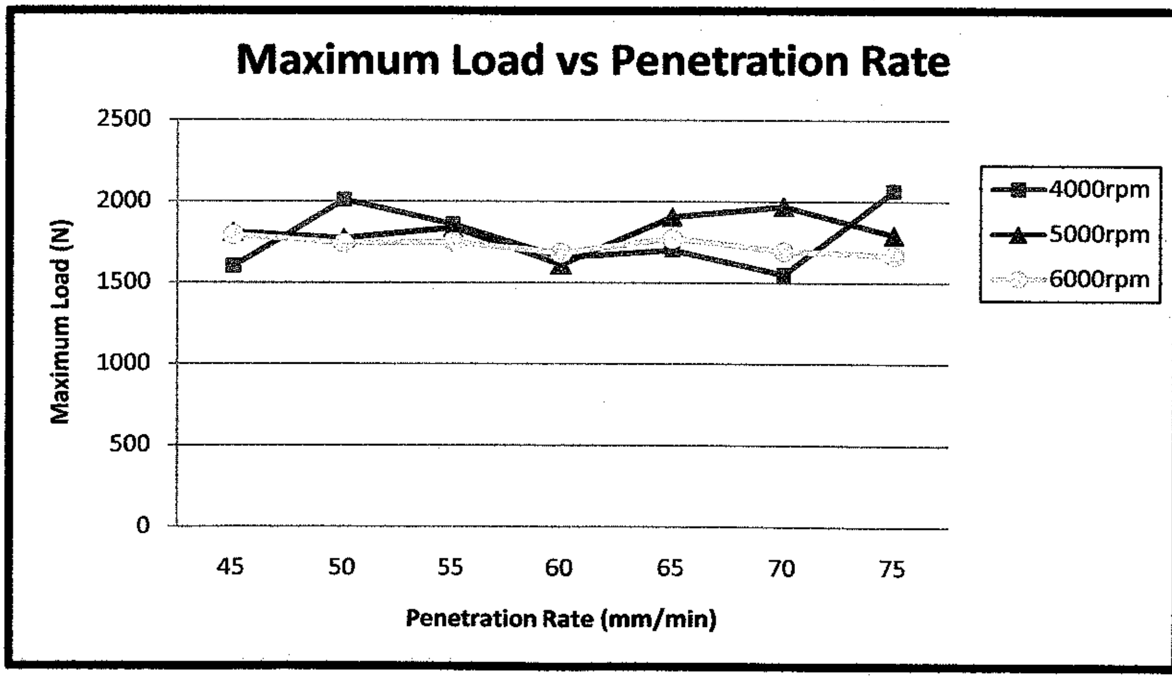


Figure 4.4: base plate clamping with jig

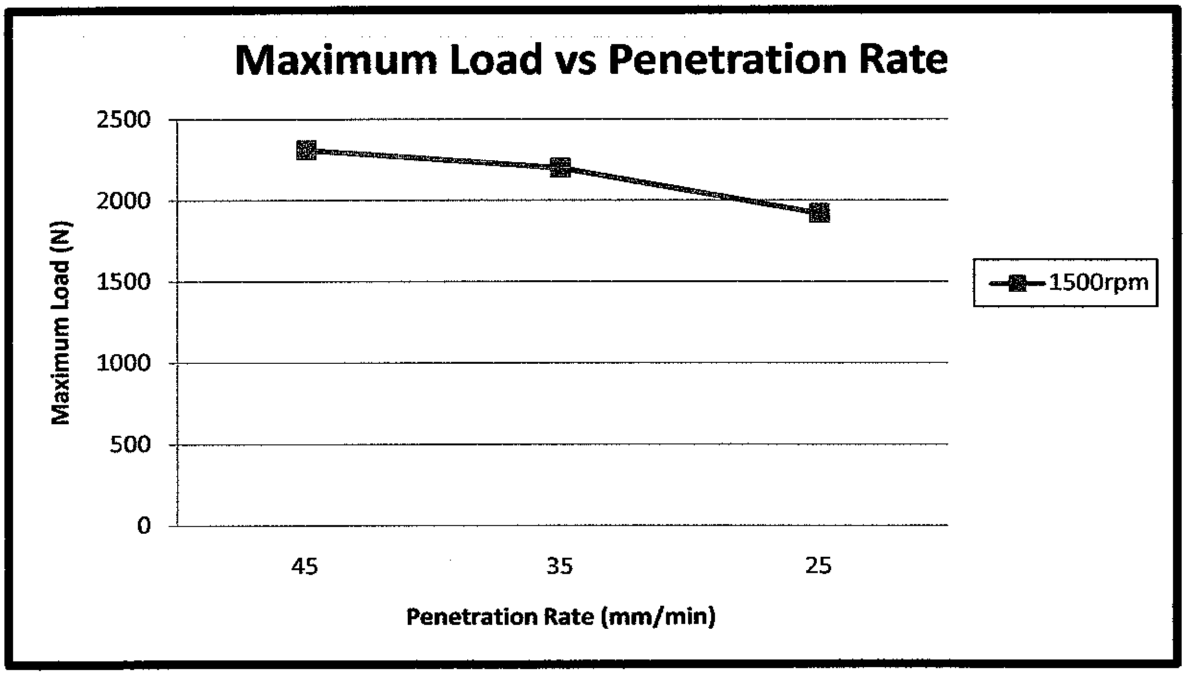
4.4 Pull to Break Test

Pull to break is used to determine the maximum lap-shear force that can be achieved after the overlapping sheet metal joint together in solid-state phase using FSSW. The result recorded could be used to study the trend of lap-shear strength using FSSW in evaluating the maximum load before break of the weld area. The test will deform the weld area until the specimen breaks which caused by shear load applied to the weld area. The force is required to break the specimen and the maximum load at which the break occurred are measured. The recorded graph 4.1 below shows pull to break test result for variation in penetration rate ranging from 45 mm/min to 75 mm/min with three different tests in tool rotational speed variation for 4000 rpm, 5000 rpm, and 6000 rpm. The maximum load is fluctuating but seems to be constant which ranging from 1500 N to 2000 N. This indicates that even the penetration rate is increased, there is not much effect on lap-shear strength since the variation of maximum load uniformly distributed between 1500N to 2000N. Based on the result, it gives an overview that with penetration rate is increased, maximum load achieved is uniformly distributed.



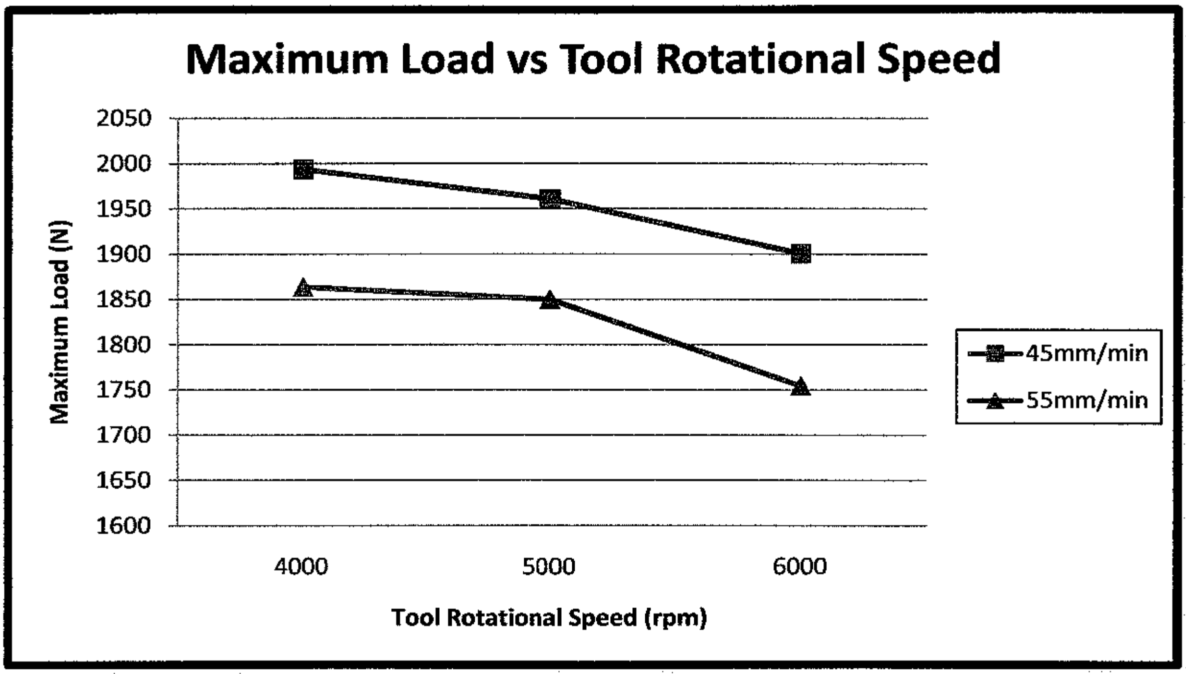
Graph 4.1: Maximum load versus penetration for high value of penetration rate and tool rotational speed.

Further experiment is conducted to determine the effect of lower value of penetration rate and tool rotational speed. Graph 4.2 shows the result of pull to break test in variation of penetration rate ranging from 45 mm/min to 25 mm/min with tool rotational speed constant at 1500rpm. The result indicates that with lowering penetration rate, the lap-shear strength trend decrease in maximum load rather than higher penetration rate. Based on the result, this shows that the optimum penetration rate in order to obtain high lap-shear strength of the overlapping sheet is at 45 mm/min. Previous result showed uniform distribution of maximum load since the operating value of penetration rate and tool rotational speed is at high value while graph 4.2 in lower value.



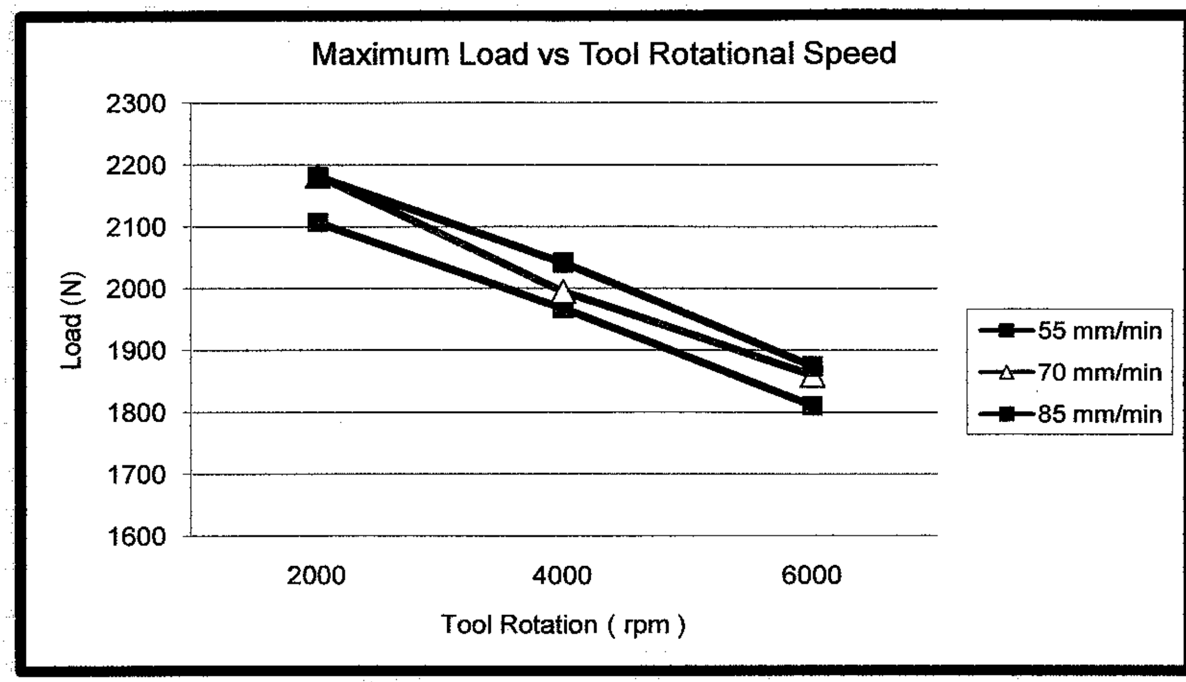
Graph 4.2: Maximum load versus penetration for lower value of penetration rate and tool rotational speed.

The recorded graph 4.3 below shows the result for maximum load versus tool rotational speed. Comparing this with previous result which varies in penetration rate, the trend for variation in tool rotational speed indicates maximum load decreases with increasing tool rotational speed. In addition, by increasing penetration rate, maximum load decreases from 2000N to 1850N and continue decreasing by increasing the tool rotational speed. It is reasonable since higher tool rotational speed decrease the amount heat generated in the overlapping sheet joint where the bonding is not uniformly distributed due to low value heat generated. With that, it affect maximum load before break for the specimen. Based on the result, it can be conclude that with increasing tool rotational speed, maximum load decrease. This indicates that lower energy is sufficient for the overlapping sheet to joint in solid-state bonding rather than higher energy to achieved high lap-shear strength.



Graph 4.3: Variation of tool rotational speed for 4000 rpm, 5000 rpm, 6000 rpm.

The final experiment used variation in both variables to see the trend of lap-shear strength. Graph 4.4 below shows the result of maximum load versus tool rotational speed with penetration rate ranging from 55 mm/min to 85 mm/min. The graph shows that the maximum load decreases by increasing the tool rotational speed and penetration rate. It is as expected since the previous result has showed that with increasing either one of the variables the lap-shear strength of the joining will decrease. Based on the result, it can be conclude that with the increasing of the energy beyond the optimum value to generate heat either by tool rotational speed or penetration rate will decrease the lap-shear strength joint using FSSW.



Graph 4.4: Pull to break test for specimen vary in rotational speed and penetration rate.

4.5 Machine Involvement

The project involves two major machines before experimental study on strength of overlapping sheet could be proceed. First major machine involved is CNC Mazak Integrex 200-III for H13 tool steel fabrication with pin and shoulder type tool to implement friction stir spot welding (FSSW) technique. This machine is suitable for H13 tool steel fabrication since the precision and accuracy is a requirement for FSSW tool steel where the pin dimension is 1.5mm with shoulder dimension 10mm diameter. This small range dimension play a big role for the tool since the pin and shoulder will undergo numerous number of FSSW operation amid no space for tool wear in order to achieve good solid-state joining of overlapping sheet metal. The second machine is Mazak Variaxis 530 5-X that is used for implementing the friction stir spot welding (FSSW) technique on overlapping aluminium sheet metal. This machine is suitable for the technique although the running cost is quite high where the vertical movement with dwell time is controllable. In addition, the precision and accuracy are also considered in selecting this machine for FSSW technique to implement. Variation of tool rotational speed in rotational speed ranging from 0rpm up to 35000rpm gives wide variety in controlling tool rotation variables while penetration rate ranging from 0mm/min up to 1000mm/min also gives wide variety in controlling tool speed rate. In seeking the optimum variable input that will gives highest lap-shear strength possible to the solid-state joining of overlapping aluminium sheet metal, lower rotational speed and penetration rate should generate higher heat generated rather than higher rotational speed and penetration rate.

Figure 4.5: Mazak Integrex 200-III

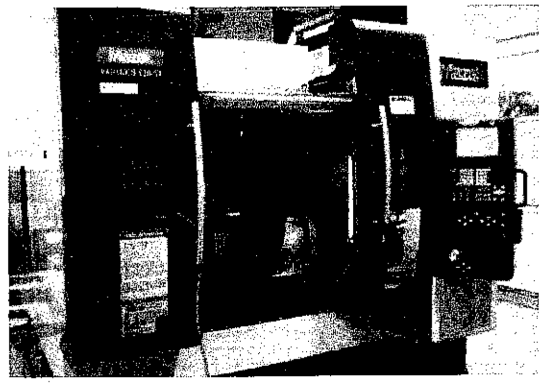


Figure 4.6: Mazak Variaxis 530 5-X

4.6 X-Ray Fluorescence XRF

The X-Ray Fluorescence (XRF) machine is employ for determining the material composition of overlapping sheet use during the early FSSW technique where the sheet metal was suspect as 6061 aluminium series since the sheet metal material composition is classified information on behalf of university policy. The X-Ray Fluorescence (XRF) machine use fundamental concept of the emission of characteristic "secondary" (or fluorescent) X-rays from a material that has been excited by bombarding with high-energy X-rays or gamma rays. The overlapping sheet material composition need to be investigated since it play significant role upon the strength analysis. This issue has been highlighted since the sheet metal from previous experiment not come with datasheet and grade listing documentation where deep analysis would require the information for clarification any related issue arise during the experiment and result obtain. Furthermore, the sample of 40mm diameter is prepared to be tested using XRF machine to determine the material composition.

The finding on using X-Ray Fluorescence (XRF) machine to obtain material composition of specimen use from previous experiment has lead the project to further analyze the composition since it is different grade as plan for early phase of the project where the expected material was Aluminium 6061. From the table it shows that the aluminium composition is 98.6% with several other elements which are contradict with 6061 requirement since it require zinc and chromium element. From the table of result it does not show any zinc and chromium element. Furthermore, from Material Science and Engineering Handbook shows that composition ranges for wrought aluminium alloys with 98.6% of aluminium composition is in 5000 series ranges but also contradict in other element whereby it require 1.4% Mg while there is no Mg element from the XRF result. Assumption has been made upon the highlighted issue which the result may have an error due to improper sample preparation. In addition, 5000 series seem in standard with the result obtain although not perfectly according to the requirement

The result obtains from XRF machine and material composition comparison between XRF result and Material Science and Engineering Handbook are listed below:

Table 4.6: Material Composition from X-Ray Fluorescence (XRF) machine

Element	Kilo Count Per Second KCps	Weight Percentage (%)
B	0.3	0.610
O	0.9	4.56
Al	4047.8	98.6
Si	2.5	0.202
S	0.2	0.00662
Cl	0.6	0.0437
Mn	4.9	0.0349
Fe	90	0.412
Ni	3.4	0.00530
Cu	32.5	0.0624
Ga	9.6	0.0139
Os	6.5	0.00958
Compton		1.20
Rayleigh		1.88
Sum		104.6

Table 4.7: Composition ranges for wrought aluminium alloys [7]

AA	Composition (%)							
Number	**Al**	**Si**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Other**
5005	99.2	—	—	—	0.8	—	—	—
5050	98.6	—	—	—	1.4	—	—	—
5052	97.2	—	—	—	2.5	0.25	—	—
5056	95.0	—	—	0.12	5.0	0.12	—	—
5083	94.7	—	—	0.7	4.4	0.15	—	—
5086	95.4	—	—	0.4	4.0	0.15	—	—
5154	96.2	—	—	—	3.5	0.25	—	—
5182	95.2	—	—	0.35	4.5	—	—	—
5252	97.5	—	—	—	2.5	—	—	—
5254	96.2	—	—	—	3.5	0.25	—	—
5356	94.6	—	—	0.12	5.0	0.12	—	0.13Ti
5454	96.3		—	0.8	2.7	0.12	—	—
5456	93.9	—	—	0.8	5.1	0.12	—	—
5457	98.7	—	—	0.3	1.0	—	—	—
5652	97.2	—	—	—	2.5	0.25	—	—
5657	99.2	—	—	—	0.8	—	—	—
Source: Data from ASM Metals Reference Book, Second Edition, American Society for Metals, Metals Park, Ohio 44073, p.292, (1984).								

4.7 Experimentation / Modeling

The experimentation done from the previous phase gives an overview and brief idea how FSSW technique works on the 1mm to 1mm thickness specimen. For pure spot FSSW, the joining part is quite good but need modification on base plate clamping design for the overlapping sheet metal. In-house step have been taken continuously in designing appropriate clamping scheme and the engineering assembly design is listed in Appendixes for references. From previous experiment it shows that spot welding area face a high load distribution and the specimen cannot withstand the tool rotating force which yield failure joining right after retracting tool process. The project has developed several engineering assembly designs using CATIA upon clamping scheme. The engineering assembly design and by part drawing is listed in Appendixes for references.

CHAPTER 5: CONCLUSION & RECOMMENDATION

5.1 Conclusions

As a conclusion, by increasing tool rotational speed and penetration rate, lap-shear strength joint of overlapping sheet decrease which indicates by maximum shear load before break by pull to break test. Base on the result obtained, the optimum combination of tool rotational speed and penetration rate which yield high lap-shear strength is at 1500rpm to 2000rpm for tool rotational speed and 45 mm/min to 55 mm/min for penetration rate. Beyond this optimum combination, lap-shear strength of overlapping sheet using FSSW will decrease either by non-uniform heat generated distribution for high value combination or not enough heat generated for low value combination.

5.2 Recommendations

The project can be developed further in the future by studying the strength for other family series of aluminium like 7xxx series which have other alloying element that may strengthen the solid-state joining using FSSW on the overlapping sheet metal compare with aluminum 1xxx. Furthermore, the technique may use other technique than pure FSSW like refill, swing, and stitch method to study the variation of lap-shear strength for each technique on the overlapping sheet metal. As for lap-shear strength analysis, other test method than pull to break test could be developed to further study the strength using FSSW by applying other type of force such as bending, vertical and torque force. The result obtained can be further developed by analyzing the result with microstructure analysis for better understanding on the trend of lap-shear joint using pull to break test. Finally yet importantly, the experimentation using CNC could be revised to further developed the sequence of tool movement during the welding operation for better understanding on the lap-shear strength on the overlapping sheet metal.

REFERENCES

1. J. Randolph Kissel, Robert L. Ferry, 2002, "Aluminum Structures: A Guide to Their Specifications and Design" *Part III Design Checks for Structural Components: Special Topics, Recent Development in Aluminum Structures, Friction Stir Welding.*

2. C. B. Smith, J. F. Hinrichs, P. C. Ruehl Friction Stir and Friction Stir Spot Welding - Lean, Mean and Green Authors: Friction Stir Link, Inc. W227 N546 Westmound Dr., Waukesha, WI 53186

3. Tsung-Yu Pan, 2007, "Friction Stir Spot Welding (FSSW) – A Literature Review," *SAE Technical Paper – reprinted from: welding & joining & fastening & friction stir welding, 2007 (SP-2139)* 2007-01-1702

4. A. Gerlich, P. Su, T.H. North, and G.J. Bendzsak, 2005, "Friction Stir Spot Welding (FSSW) of Aluminum and Magnesium Alloys," *Department of Materials Science and Engineering, University of Toronto*

5. Rajiv S. Mishra, Murray W. Mahoney 2007, "Friction Stir Welding and Processing"

6. *ASM Metals Reference Book, Second Edition*, American Society for Metals, Metals Park, Ohio 44073, p.292, (1984).

7. Shackelford, James F. et al "Composition of Materials" *Materials Science and EngineeringHandbook* Ed. James F. Shackelford & W. Alexander Boca Raton: CRC Press LLC, 2001

8. Jan 2005 Austral Bronze Crane Copper Limited ACN 008 466 840

9. Kenneth G. Budinski, Michael K. Budinski, 2004, *"Engineering Materials: Properties and Selection"* Eight Edition.

10. John Case, Lord Chilver, Carl T.F. Ross, 1999, "Strength of Materials and Structures" Fourth Edition.

11. K. Feldman, G. Kohn, A. Stern, *"Friction Stir Spot Welding"* JT Welding Technologies Ltd., Departments of Mechanical and Materials Engineering, Ben Gurion University of the Negev.

APENDIXES

1. Gantt chart for FYP 1 MAB 4012: An experimental study of strength of Friction Stir Spot Welding on overlapping sheet metal

No	Detail / Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of project topic	■	X						Mid Semester Break							
2	Preliminary research work		■	■	X											
3	Submission of preliminary report				■											
4	Project work			■	■	■	■	■								
5	Design welding tool of FSSW			■	■											
6	Submission of progress report									X						
7	Obtain tool steel of FSSW (H13)												X			
8	Fabrication welding tool using CNC lathe													X		
9	Undergo heat treatment on welding tool													X		
10	Submission of Interim report final draft														X	
11	Oral Presentation															X

Process	■
Suggested Milestone	X

2. Gantt chart for FYP 1 MAB 4012: An experimental study of strength of Friction Stir Spot Welding on overlapping sheet metal

No	Detail / Week	1	2	3	4	5	6	7	Mid Semester Break	8	9	10	11	12	13	14
1	***Project Work Continue***	■	■	■												
2	***Submission of Progress Report 1***				X											
3	***Apply FSSW (welding tool) on work piece***				■	■	■	■								
4	***Submission of Progress Report 2***									X						
5	***Seminar (compulsory)***										■	■	■			
6	***Pull to Break Test***									■	■	■	■			
7	***Poster Exhibition***											X				
8	***Submission of Dissertation (soft bound)***													X		
9	***Oral Presentation***														X	
10	***Submission of Project Dissertation (Hard Bound)***															X

Process	■
Suggested Milestone	X

Appendix 2.1: Data sheet H13 steel

Hot Work Tool Steel — 2344 / RDC 2V

PRODUCT FEATURES

2344 is a chromium-molybdenum-vanadium steel which has outstanding toughness and high hot hardness.

1. Improved tool life
   - Specially annealed to remove all intergranular carbide precipitation and allow a fine globular carbide distribution.
2. Higher toughness and hot hardness than H11 steels
   - Chromium-Molybdenum-Vanadium additions optimised to improve properties.

APPLICATIONS

- **Hot work tools subjected to temperatures from 300°C to 580°C**
- **Hot extrusion tools for light alloys:** Pressure discs, mandrels, stems, headers, centering and shearing mandrels, dies, liners
- **Casting dies for light alloys:** Cores, ejectors
- **Plastic molding dies:** Injection moulding applications
- **Forging tools:** Dies, die insert, punches, mandrels

EQUIVALENT STANDARDS

WN	DIN	AISI	JIS
1.2344	X40 CrMoV 5 1	H13	SKD 61

CHEMICAL ANALYSIS

Typical values (weight %)

C	Si	Mn	Cr	Mo	V
0.40	1.05	0.35	5.00	1.30	1.00

MECHANICAL PROPERTIES

Typical values

Hardness	Annealed (supplied condition)	229 HB max.

PHYSICAL PROPERTIES

Typical values

Thermal Expansion Coefficient

°C	20-100	20-200	20-300	20-400	20-500	20-600	20-700
10^{-6} °C^{-1}	10.9	11.9	12.3	12.7	13.0	13.3	13.5

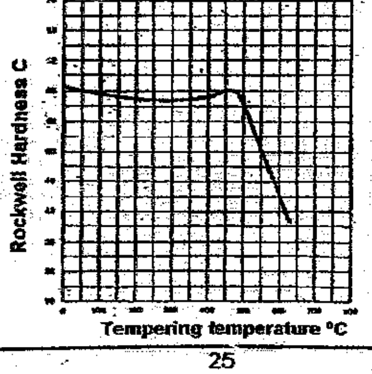
Thermal Conductivity

°C	20	350	700
W m^{-1} °C^{-1}	24.5	26.8	28.8

HEAT TREATMENT

Hardening Temperature	990 – 1050°C
Quenching Medium	Oil, Air
Tempering	Refer to tempering chart

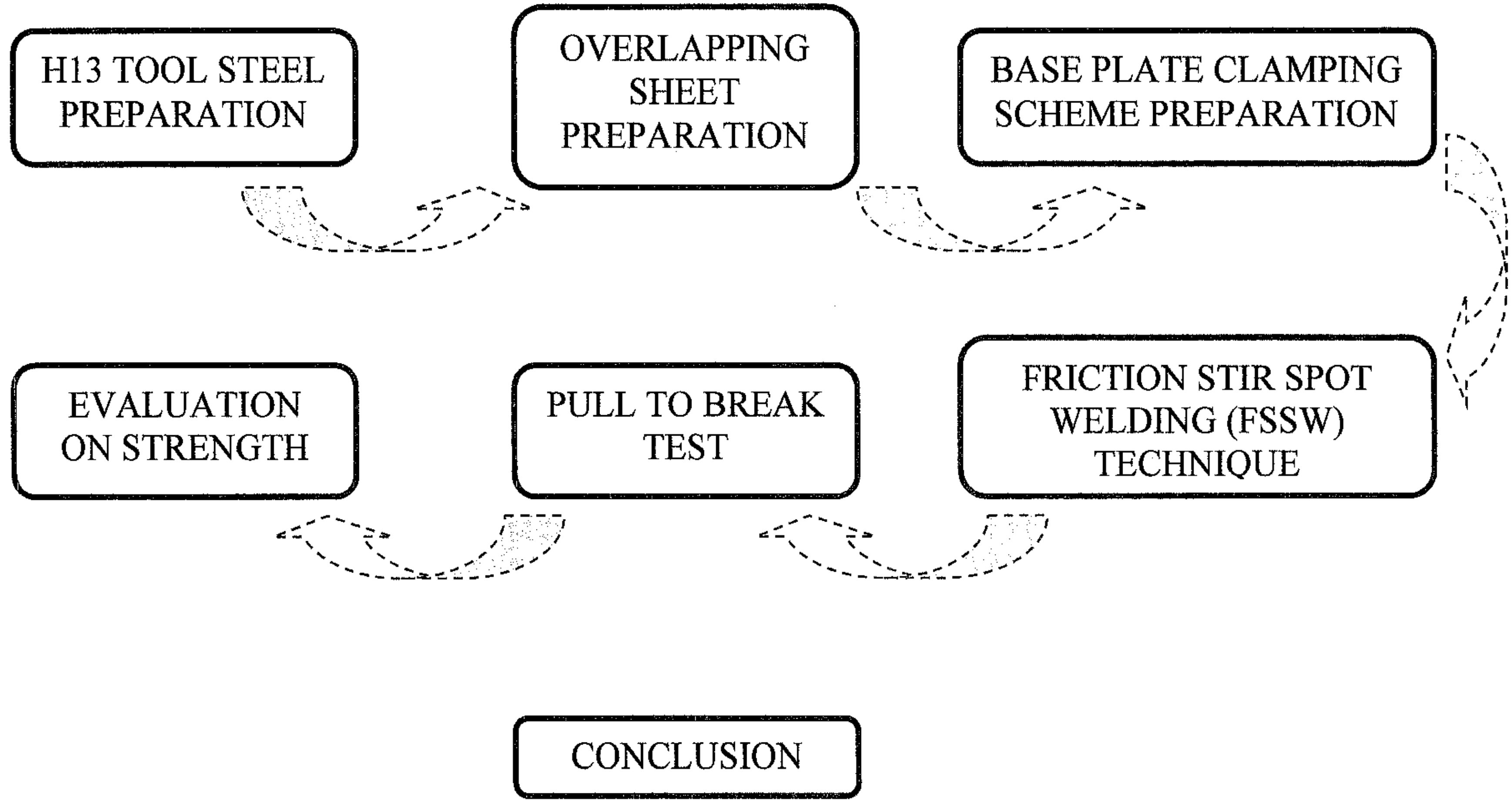
Tempering Chart



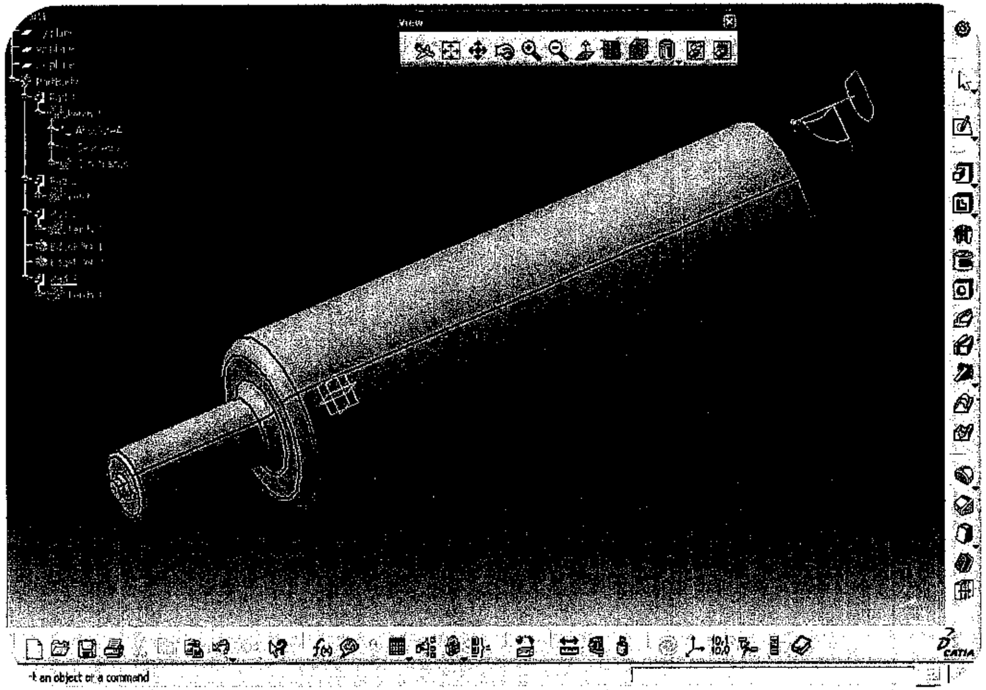
Quenched from 1020°C in air

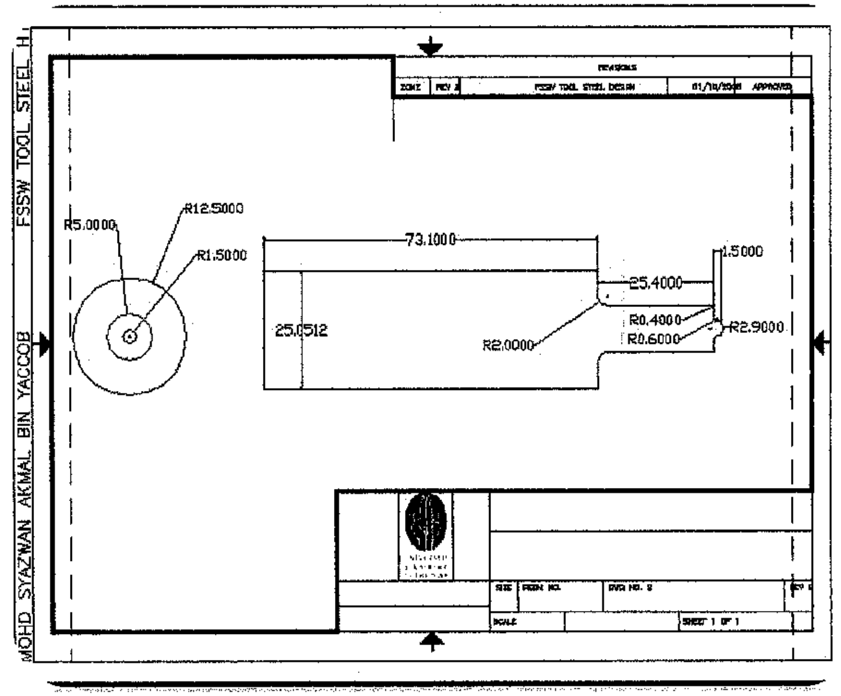
WINGKOH SPECIALTY METALS SDN. BHD.
(No. Syarikat: 209172-P)
8, Persiaran Perusahaan Kledang Utara 1/3,
Kawasan Perindustrian Chandan Raya,
31450 Ipoh, Perak.

Appendix 2.1: Project methodology

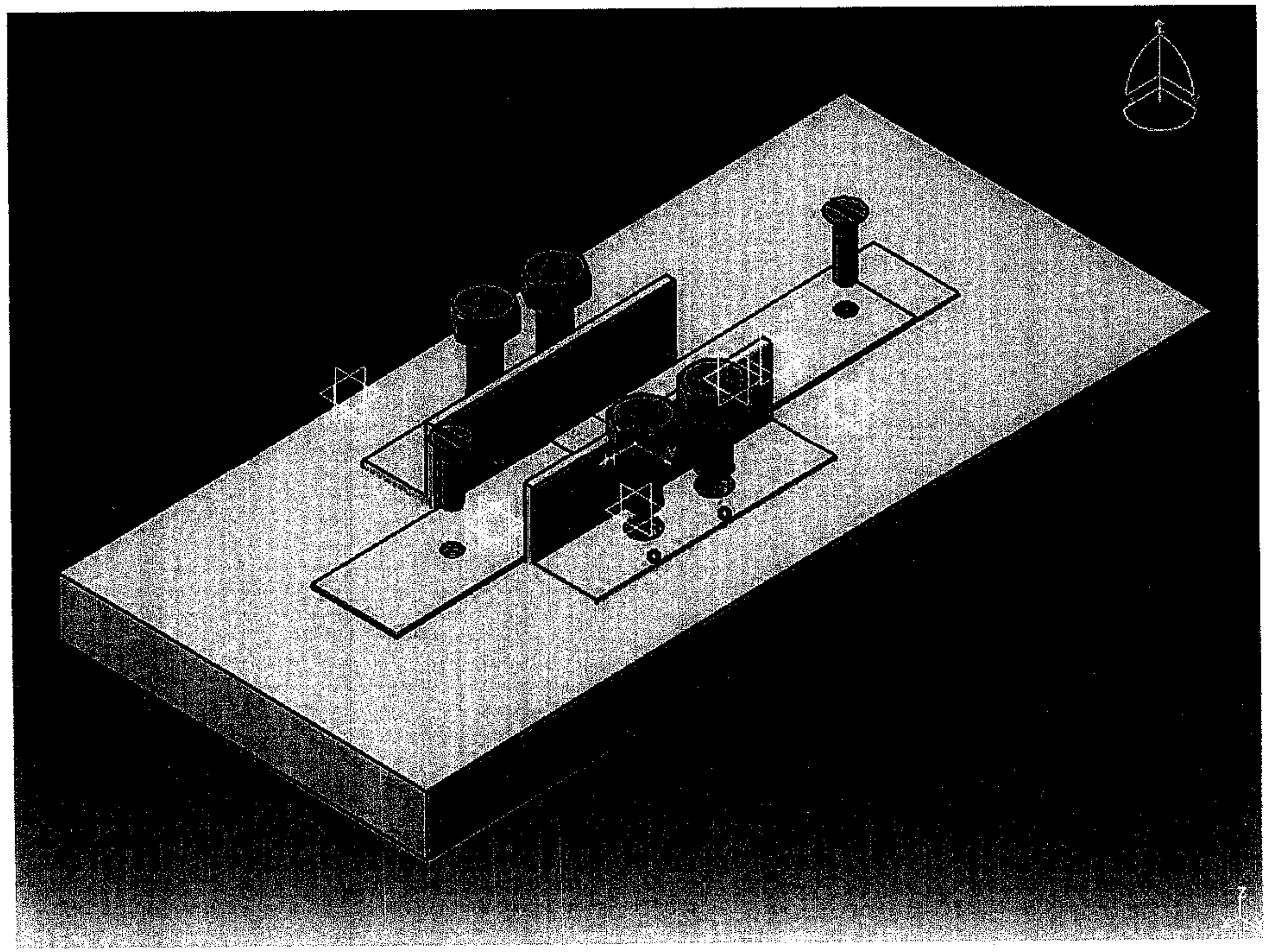


Appendix 3.1: H13 tool steel engineering drawing revision 1 (Auto CAD and CATIA)

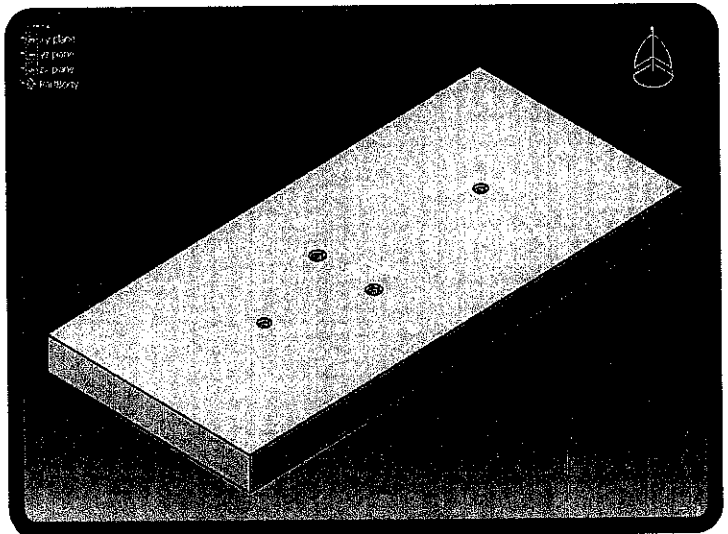




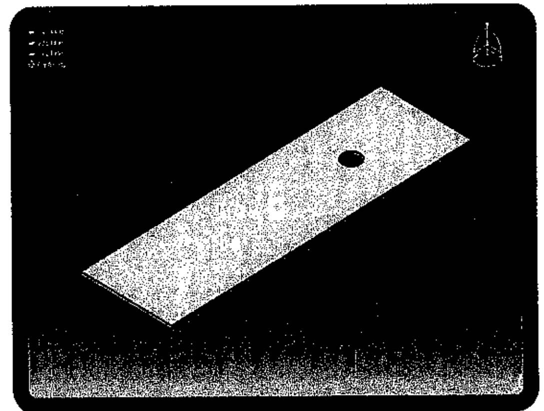
Appendix 3.2: Engineering Assembly Design Rev 2



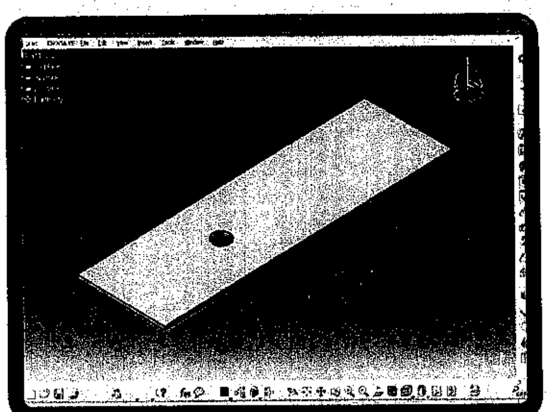
Appendix 3.3: Part Design Rev 0



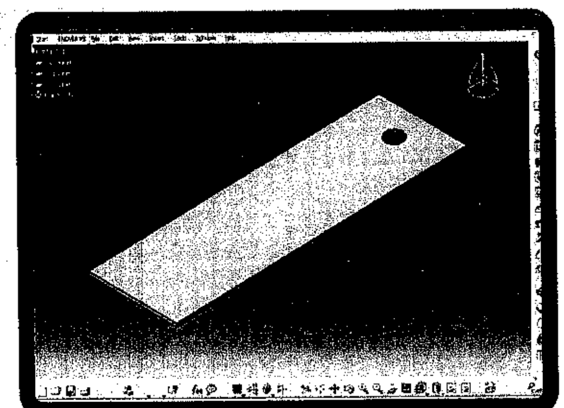
Base Plate with mounting hole



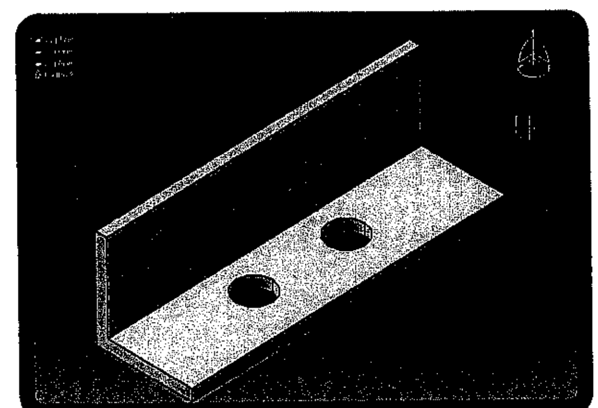
Overlapping Sheet 1



Overlapping Sheet 2

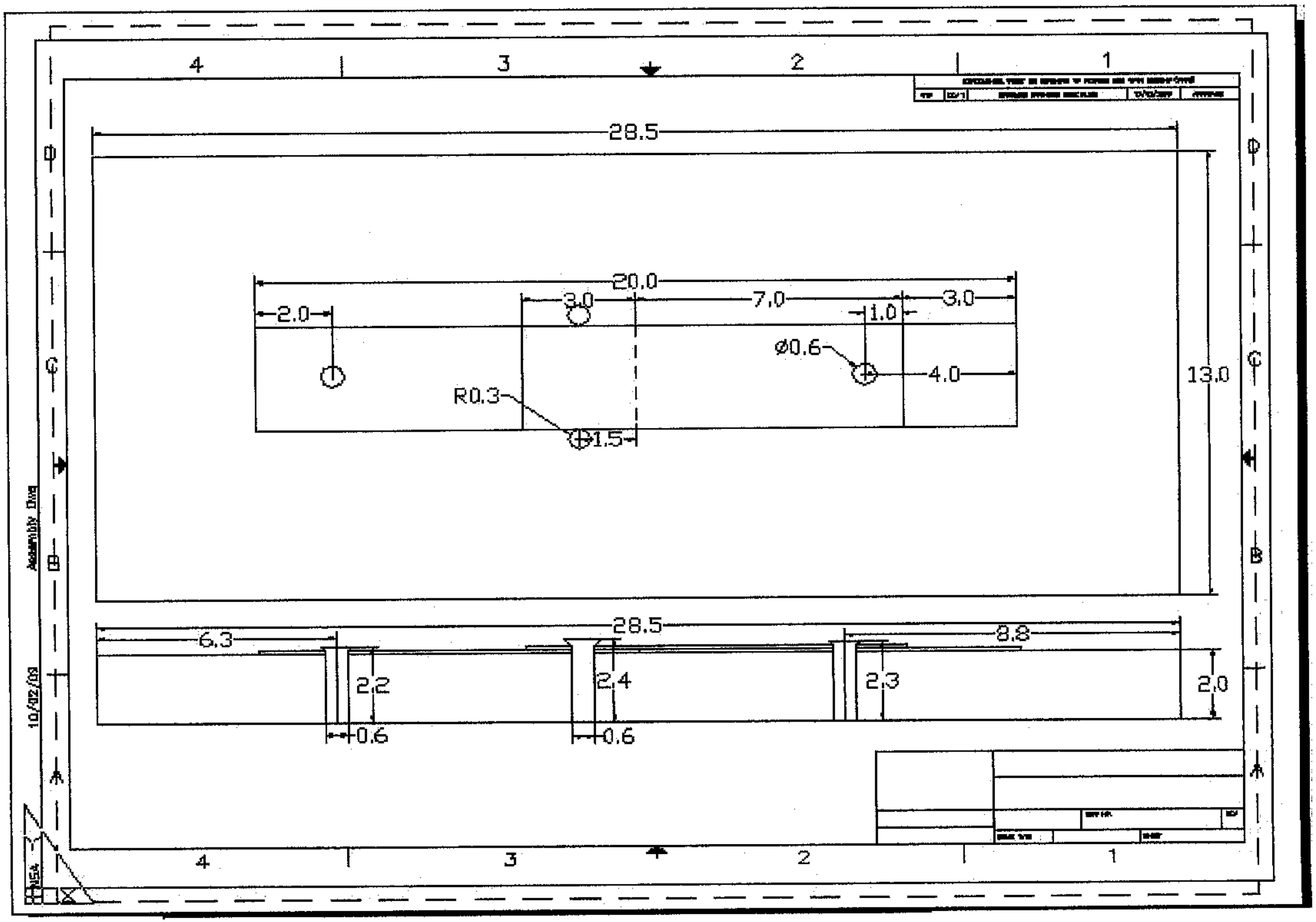


Overlapping Sheet 3



L angle Bar

Appendix 3.4: Assembly drawing Revision 1



Appendix 4.1: Pull to Break Test Result of 4000 rpm with penetration rate vary ranging 45 mm/min to 75 mm/min

Sample Reference	Maximum Load (N)	Deflection at Maximum Load (mm)	Work to Maximum Load (J)	Stiffness (N/m)	Load at Break (N)	Deflection at Break (mm)	Work to Break (J)
1	1602.044164	8.805801456	2.443501312	887810.2889	160.2044164	10.57785064	3.72102618
2	1184.023439	7.90970505	1.756623036	683492.1186	118.4023439	9.226474765	2.565195703
3	1860.975663	11.43196831	3.557984971	1051886.463	186.0975663	13.27879009	5.239146811
4	1654.438842	10.8717717	4.881255278	830517.8508	165.4438842	12.31223634	6.183936788
5	1702.79427	19.99319233	7.322633166	768398.5775	170.279427	21.673354	8.820857247
6	1550.64375	16.75213214	4.740896997	852168.4243	155.064375	18.28637265	5.920759695
7	0.170314675	16.82333262	-0.005715962	3054.312354	0.017031468	19.20325379	-0.005493006

Appendix 4.2: Pull to Break Test Result of 4000 rpm with penetration rate vary ranging 45 mm/min to 75 mm/min

	Maximum	Minimum	Mean	Median	Variance	Standard Deviation	TRUE
SamplePassed							100.00%
Speed	50.000 mm/min	50.000 mm/min	50.000 mm/min	50.000 mm/min	0.00%	0.00000 mm/min	
Preload							0.00%
Maximum Load	1861.0 N	0.17031 N	1365.0 N	1602.0 N	43.16%	589.19 N	
Deflection at Maximum Load	19.993 mm	7.9097 mm	13.227 mm	11.432 mm	32.30%	4.2717 mm	
Work to Maximum Load	7.3226 J	-0.0057160 J	3.5282 J	3.5580 J	62.93%	2.2202 J	
Stiffness	1050000 N/m	3050 N/m	725000 N/m	831000 N/m	43.14%	313000 N/m	
Load at Break	186.10 N	0.017031 N	136.50 N	160.20 N	43.16%	58.919 N	
Deflection at Break	21.673 mm	9.2265 mm	14.937 mm	13.279 mm	29.51%	4.4086 mm	
Work to Break	8.8209 J	-0.0054930 J	4.6351 J	5.2391 J	56.84%	2.6347 J	
Number of Rows that Passed	7						
Number of Rows that Failed	0						

Appendix 4.3: Pull to Break Test Result of 5000 rpm with penetration rate vary ranging 45 mm/min to 75 mm/min

Sample Reference	Maximum Load (N)	Deflection at Maximum Load (mm)	Work to Maximum Load (J)	Stiffness (N/m)	Load at Break (N)	Deflection at Break (mm)	Work to Break (J)
1	1774.341	7.262505	2.767967	907667.6	177.4341	9.386979	4.45785
2	1826.634	20.51426	6.375312	800172.1	182.6634	22.5992	8.310071
3	1612.44	15.61153	4.755671	871581.8	161.244	17.893	6.737974
4	1906.632	12.32939	6.697422	611884.5	190.6632	14.72204	9.404589
5	1732.25	11.93808	5.944038	515895	173.225	14.1453	7.812992
6	1793.239	20.48237	5.559385	734631.2	179.3239	22.65366	7.596707
7	1774.341	7.262505	2.767967	907667.6	177.4341	9.386979	4.45785

Appendix 4.4: Pull to Break Test Result of 5000 rpm with penetration rate vary ranging 45 mm/min to 75 mm/min

	Maximum	Minimum	Mean	Median	Variance	Standard Deviation	TRUE
SamplePassed							100.00%
Speed	50.000 mm/min	50.000 mm/min	50.000 mm/min	50.000 mm/min	0.00%	0.00000059605 mm/min	
Preload							0.00%
Maximum Load	1906.6 N	1612.4 N	1774.3 N	1783.8 N	5.07%	89.978 N	
Deflection at Maximum Load	20.514 mm	7.2625 mm	14.690 mm	13.970 mm	32.49%	4.7721 mm	
Work to Maximum Load	6.6974 J	2.7680 J	5.3500 J	5.7517 J	24.47%	1.3092 J	
Stiffness	908000 N/m	516000 N/m	740000 N/m	767000 N/m	18.76%	139000 N/m	
Load at Break	190.66 N	161.24 N	177.43 N	178.38 N	5.07%	8.9978 N	
Deflection at Break	22.654 mm	9.3870 mm	16.900 mm	16.308 mm	28.10%	4.7495 mm	
Work to Break	9.4046 J	4.4578 J	7.3867 J	7.7048 J	20.79%	1.5356 J	
Number of Rows that Passed	6						
Number of Rows that Failed	0						

Appendix 4.5: Pull to Break Test Result of 6000 rpm with penetration rate vary ranging 45 mm/min to 75 mm/min

Sample Reference	Maximum Load (N)	Deflection at Maximum Load (mm)	Work to Maximum Load (J)	Stiffness (N/m)	Load at Break (N)	Deflection at Break (mm)	Work to Break (J)
1	1795.095	11.10061	4.596534	784049.5	179.5095	14.10553	7.659766
2	1743.644	13.31213	6.07249	811455.7	174.3644	16.02785	8.802054
3	1751.778	14.04374	5.19188	657199.9	175.1778	16.6719	7.727066
4	1684.31	11.32284	3.809304	959589.5	168.431	14.00691	6.508496
5	1584.318	10.48866	5.707618	475598.5	158.4318	12.71059	7.522747
6	1694.97	18.02353	9.031023	605320.2	169.497	20.50781	11.30635
7	1668.521	18.80723	8.401206	494073.6	166.8521	20.95525	10.17154

Appendix 4.6: Pull to Break Test Result of 6000 rpm with penetration rate vary ranging 45 mm/min to 75 mm/min

	Maximum	Minimum	Mean	Median	Variance	Standard Deviation	TRUE
SamplePassed							100.00%
Speed	50.000 mm/min	50.000 mm/min	50.000 mm/min	50.000 mm/min	0.00%	0.00000 mm/min	
Preload							0.00%
Maximum Load	1795.1 N	1584.3 N	1703.2 N	1695.0 N	3.73%	63.471 N	
Deflection at Maximum Load	18.807 mm	10.489 mm	13.871 mm	13.312 mm	22.40%	3.1067 mm	
Work to Maximum Load	9.0310 J	3.8093 J	6.1157 J	5.7076 J	29.23%	1.7877 J	
Stiffness	960000 N/m	476000 N/m	684000 N/m	657000 N/m	24.00%	164000 N/m	
Load at Break	179.51 N	158.43 N	170.32 N	169.50 N	3.73%	6.3471 N	
Deflection at Break	20.955 mm	12.711 mm	16.427 mm	16.028 mm	18.18%	2.9865 mm	
Work to Break	11.306 J	6.5085 J	8.5283 J	7.7271 J	18.26%	1.5575 J	
Number of Rows that Passed	7						
Number of Rows that Failed	0						

Appendix 5.1: CNC Coding for the FSSW process used for the Mazak Variaxis 530 5X

```
(PROGRAM NAME – 1302091)
(DATE=DD-MM-YY – 13-02-09 TIME=HH:MM – 14:12)
N100G21
N102G0G17G40G49G80G90
(10.FLAT ENDMILL TOOL – 21 DIA. OFF. – 21 LEN. – 21 DIA. – 10.)
N104T21M6
N106G0G90G59X0.Y-50.A0.S2000M3
N108G43H21Z50.
N110Z10.
N112G1Z-.1F10.
N114Y50.F100.8
N116G0Z50.
N118M5
N120G91G28Z0.
N122G28X0.Y0.A0.
N124M30
```