CHAPTER 1
INTRODUCTION

1.1 Background of Study

Friction Stir Welding (FSW) is a newly developed, innovative, simple, welding or joining process that was originally invented and patented at The Welding Institute (TWI) at Cambridge, England in 1991.

The reason for the invention was due to increasing interests in the use of lightweight materials in industries such as aluminium alloys for its high strength-to-weight ratio. However, they are not readily weldable and do not produce preferred mechanical properties if they were joined by conventional arc processes.

FSW uses a rotating tool into adjoining plates to generate heat which elevates the temperature of the local weld region high enough to plasticize or soften the material. The rotating tool also provide the 'stir' action to continue the hot working action, plasticizing the metal while transporting or mixing metal from the leading face of the pin to the trailing edges. As the tool moves through the material, the weld cools, thus joining the metals together. Because there is also no melting of the material, the weld produced is a solid phase joint and left in a fine grain wrought structure and other problems associated with liquid to solid transformation, such as residual stresses, porosity and cracking, are all minimized.

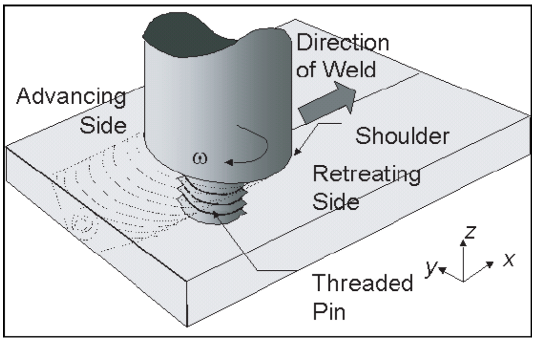

Figure 1 : Schematic diagram of FSW process[1]

1.1.1 Friction Stir Welding in Industry - Application

There are many industry sectors that have adopted the friction stir welding process for their commercial applications. Some of them are:

1. Shipbuilding and marine industries – joining panels for decks, sides, bulkheads, floors, platforms, masts and booms, and structural components.
2. Aerospace Industry – wings, fuselages, empennages, fuel tanks, military rockets, and structural components.
3. Railway Industry – high speed trains, underground carriages, trams, tankers, wagons and container bodies.
4. Land Transportation - Engine and chassis cradles, rims, truck bodies, mobile cranes, tail lifts, armour plate vehicles, fuel tankers and frames.
5. Other – Cooking equipments, gas tanks and cylinders, furniture and many other applications.

1.1.2 Friction Stir Welding – Advantages and Limitations

The process advantages result from the fact that the FSW process takes place in the solid phase below the melting point of the materials to be joined. The benefits therefore include the ability to join materials which are difficult to fusion weld, for example aluminium alloys. Friction stir welding can use purpose-designed equipment or modified existing machine tool technology. The process is also suitable for automation and adaptable for robot use. Other advantages are as follows:

- Low distortion, even in long welds as the method use a stable machine to do the welding. The fact that the material needs to be rigidly clamped also helps in keeping the distortion low.
- Excellent mechanical properties as there is no liquid to solid transformation, thus problems associated with the transformation are minimized.
- No arc because the method doesn’t use electric current to melt the materials.
- No fume because the method doesn’t use filler material that has flux. This advantage also is good for health.

- This method use non-consumable tool to perform the welding. This advantage can lower the cost of welding for massive production.
- No welder certification required as the welding is performed by machines.
- No grinding, brushing or pickling required in mass production.
- Excellent repeatability.

The limitations of the FSW process are being reduced by intensive research and development. However, the main limitations of the FSW process are at present:

- Workpieces must be rigidly clamped to minimize the distortion of the material, tool and weldline.
- Keyhole at the end of each weld, when the tool is withdrawn from the material.
- Cannot make joints which required metal deposition (e.g. fillet welds)
- Less flexible than manual and arc processes (difficulties with thickness variations and non-linear welds).
- Not for high-strength materials, as it will be harder to stir the materials together.

1.2 Problem Statement

Nowadays, FSW are becoming popular as a process of joining lightweight materials due to its ability to produce quality welds at a low cost. Because the FSW process is relatively new, there are not much recent publications concerning the process. So, a systematic investigation to study the mechanical properties of the weld produced by the FSW process is necessary to further improve the understanding of the process. In this project, the author is expected to conduct an experimental study on the strength of the FSW process.

1.3 Objectives and Scope of Study

By the end of this project, the author should be able to:

ii) Understand the concept of FSW process and technique.

iii) Fabricate the rotating pin tool.

iv) Analyze and test the end product with interest on its strength.

The author is however will be in the following conditions:

i) Material for the rotating pin tool is H13 steel while for the workpiece is aluminium alloys 5xxx series.

ii) CNC machines as the equipments needed to fabricate the rotating pin tool and perform the friction stir welding.

The time constrain of 1 year is a good time frame for this project to be completed.

CHAPTER 2
LITERATURE REVIEW

2.1 Theory of the Strength of Friction Stir Welding

The joint strengths of the friction stir welding are varied from 70% to 100% of the parent value, depending on the type of aluminium alloys. For such alloys, the main strengthening mechanism is through deformation hardening and the build up of high dislocation in the deformed microstructure. [1]

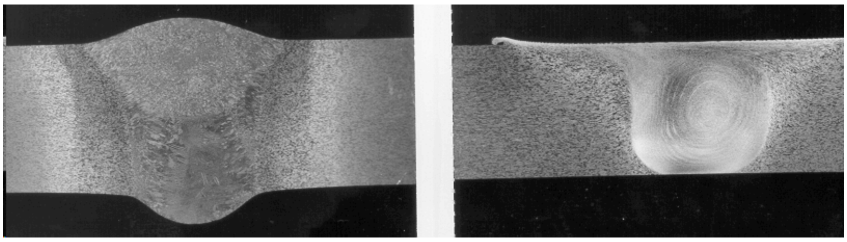

Figure 2 : Weld nugget cross section [2]

Due to the nugget zone undergoes a considerable amount of deformation, the final microstructure gets recrystallized. The majority of the grain boundaries within the nugget zone is high angle (misorientation between grains being greater than 15^{o}), and formed through dynamic recrystallisation during the stirring process. This provides for low dislocation density in the weld nugget, thus leading to the uniform strength and hardness across the weld zone.

In the aluminium alloys, the strength depends more on grain size (d), which has been expressed in terms of the Zener-Holloman parameter:

$$\log d = a + b \log Z$$

where a and b are empirical constants based on data from extrusion experiments. [3]

2.2 Rotating Pin Tool

The design of the tool is a critical factor as a good tool can improve both the quality of the weld and the maximum possible welding speed.

It is desirable that the tool material is sufficiently strong, tough and hard wearing, at the welding temperature. Further it should have a good oxidation resistance and a low thermal conductivity to minimise heat loss and thermal damage to the machinery further up the drive train. Hot-worked tool steel such as AISI H13 has proven perfectly acceptable for welding aluminium alloys within thickness ranges of 0.5 - 50 mm [4] but more advanced tool materials are necessary for more demanding applications such as highly abrasive metal matrix composites [5] or higher melting point materials such as steel or titanium.

The nib may have a diameter one-third of the cylindrical tool and typically has a length slightly less than the thickness of the workpiece [6].

The majority of tools have a concave shoulder profile which acts as an escape volume for the material displaced by the pin, prevents material from extruding out of the sides of the shoulder and maintains downwards pressure and hence good forging of the material behind the tool. The Triflute tool uses an alternative system with a series of concentric grooves machined into the surface which are intended to produce additional movement of material in the upper layers of the weld.

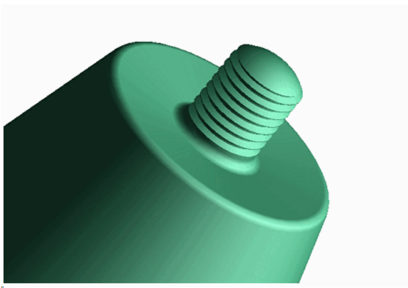

Figure 3 : Typical Weld Tool Profile

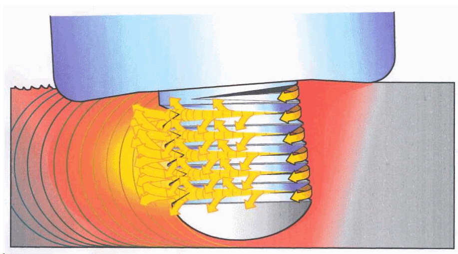

Figure 4 : Cross section of tool during stir action takes place [7]

2.2.1 Heat treatment

Heat Treatment is the controlled heating and cooling of metals to alter their physical and mechanical properties without changing the product shape. Heat Treatment is often associated with increasing the strength of material, but it can also be used to alter certain manufacturability objectives such as improve machining, improve formability, restore ductility after a cold working operation. Thus it is a very enabling manufacturing process that can not only help other manufacturing process, but can also improve product performance by increasing strength or other desirable characteristics[10].

Metallic materials consist of a microstructure of small crystals called "grains" or crystallites. The nature of the grains (i.e. grain size and composition) is one of the most effective factors that can determine the overall mechanical behaviour of the metal. Heat treatment provides an efficient way to manipulate the properties of the metal by controlling rate of diffusion, and the rate of cooling within the microstructure[11].

Steels are particularly suitable for heat treatment, since they respond well to heat treatment and the commercial use of steels exceeds that of any other material.

Figure 5 : A tube furnace

CHAPTER 3
METHODOLOGY

For this experimental study, the methods for doing the project were mainly divided into 4 parts, which is:

3.1 Research and Literature Review

A thorough search was made through the internet and the library to collect all available information in the shape of articles, journals and books regarding the Friction Stir Welding, strength and machines and methods that is relevant with the FSW.

3.2 Fabricate Rotating Pin Tool

With the detail design of the rotating pin tool already been supplied by the supervisor, the author need to do a little alteration in the design so that it can be use in the UTP's Mazak Variaxis 630 5-X machine during the experiment. Then, the author need get the material for the tool, which is an AISI H13 steel with the dimension of 50mm in diameter and 200mm long, and fabricate the tool using the Mazak Integrex 200-III CNC Turning machine. After the tool is fabricated, the tool needs to undergo heat treatment process. The pin tool was inserted into the tube furnace and was pre-heated slowly until reaching 732 – 760 ^{o}C for two hours. Then, the temperature was raised until 1000 ^{o}C for 1 hour. Finally the pin tool been cooled down to room temperature (24 ^{o}C) for another 2 hours. The detail design of the pin tool is available at the appendices.

Figure 6: The tool steel after heat treated

3.3 Experiments

After the tool is completely fabricated, the experiment study for the strength of the FSW can be started and aluminium alloys as the workpiece. The tool is inserted into the spindle shank. The parameters for the experiment, which are the traverse speed ranging from 15mm/min – 100 mm/min, and spindle speed ranging from 450rpm-3000rpm, are adjusted in order to compare with each other and finally achieve the optimum result of FSW. The details during the experiments of FSW that have been done are available at the Chapter 4: Results and Discussions.

3.4 Analyze

After the experiments, the author needs to analyze the result with interests on its strength using the test equipments that are available in UTP. The proposed test technique to analyze the strength of the joint is the tensile (pull-to-break) test, using UTP's 100kN Universal Testing Machine. The standard test procedure for this testing will be according to the ASTM E8-00b standard. The results of each experiment with different parameters will then be compared with each other in order to determine the relationship between the spindle speed and travelling speed with the maximum load of the end result.

3.4.1 Sample Preparation

Before the testing for the result of the Friction Stir Welding experiments can be perform, the sample need to be prepared as per required in the ASTM E8-00b standard. As the total length of the specimen is only 200mm and the distance between the two holes for clamping is 30mm, the dimensions of the specimen for the testing has been changed approximately as the following:

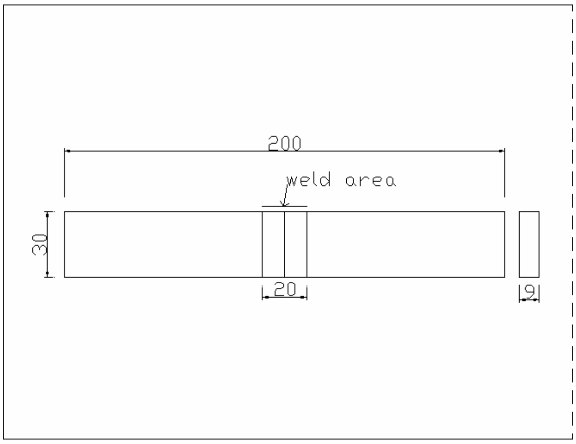

Figure 7: Testing Dimension (in mm)

The machine that was used to machine the sample to the specified dimension was a bend saw machine. Aside from machining the sample, the author also remove the splashing material out of the sample using the metal saw.

CHAPTER 4
RESULTS AND DISCUSSIONS

4.1 Friction Stir Welding Experiments

After completed the fabrication of the rotating pin tool, the next objective is to run the FSW experiment with different parameters. At the end of the semester, 6 experiments were done. Below are the details of the experiments that have been carried out.

For the first experiment dated 12th February 2009, the parameters were:

Spindle Speed = 450rpm

Traverse speed = 100mm/min

Plunge Depth = 2mm

Figure 8: Experiment 1

The figure shows that the aluminium alloy workpieces has been clamped at the each side and the tool will operate at the butt joint of the two workpiece.

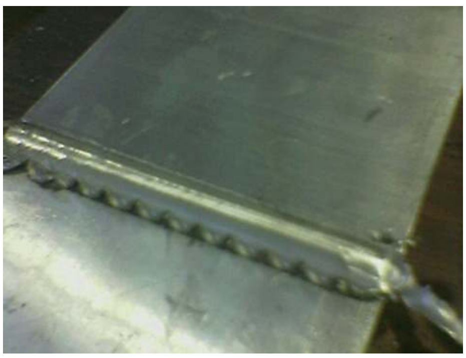

Figure 9: Experiment 1 - Result

From the observation, for the first 15mm of pin travel, the joint was a little bit coarse, probably because the material did not plasticize enough to perform the stir action due to the low spindle speed. It was also noted that some of the plasticized material went out from the joint line. This is because the shoulder of the pin tool did not close enough with the surface of the workpiece due to the low plunge depth. The workpieces were also a bit bent due to the clamping were not rigid enough.

For the second experiment, dated 20th February 2009, the parameters were:

Spindle Speed = 2500rpm

Traverse Speed = 15mm/min

Plunge Depth = 6mm

Figure 10: Experiment 2

The figure shows that the workpiece were clamped sideways, and in addition of 2 screws each attached to metal plate below to make the workpiece more rigid.

Figure 11: Experiment 2 – Result

From the observation, there were still some plasticize material went out from the joint line. Noted also that there was a large exit-hole detected at the end of the weld line. The previous problem of bending workpieces has been solved with a more rigid clamping system.

For the third experiment, dated 11th March 2009, the parameters were:

Spindle Speed = 3500rpm

Traverse Speed = 45mm/min

Plunge Depth = 8.1mm

The apparatus were setup like the previous experiment.

Figure 12 : Experiment 3 - Result

From the observation, there were still some plasticize material went out from the joint line even though the tool shoulder was well touched the workpiece surface. Further readings need to be done. The previous problem of large exit hole at the end of the weld line is still apparent.

After this experiment, five more experiments were carried out. Below are the details and parameters:

Table 1: Experiment's Parameters

Exp. Num.	Date	Spindle Speed (rpm)	Traverse Speed (mm/min)	Plunge Depth (mm)
4	3rd April 2009	3000	35	8.1
5	6th April 2009	3000	40	8.1
6	6th April 2009	3500	40	8.1
7	1st June2009	3000	45	8.1
8	1st June 2009	2500	40	8.1

Previous problems of materials splashing out of the weld zone and large key hole exit is still exists at all of these experiments.

After the experiments, the sample need to be machined to the dimensions stated in the earlier chapter as part of the method of preparation for the result testing. During the machining, a weld defect of discontinuities was detected at the near-bottom of the weld area of each of the sample.

discontinuities

Figure 13: Weld defect

The discontinuities happened because of the materials splashing out of the weld area during the stirring of materials. Since there were no filler materials involved, the materials inside the weld area were insufficient, thus discontinuities occurred in the weld area.

4.2 Tensile Test

For the tensile test, the procedure and method was referred to the ASTM E8-00b, Standard Test Methods for Tension Testing of Metallic Materials. 100kN Universal Testing Machine was used to conduct the pull-to-break test method to determine the tensile strength of the weld. The speed of the testing was set to be at 1.27 mm/min.

Below are the results for the experiments:

Experiment 3: 11th March 2009

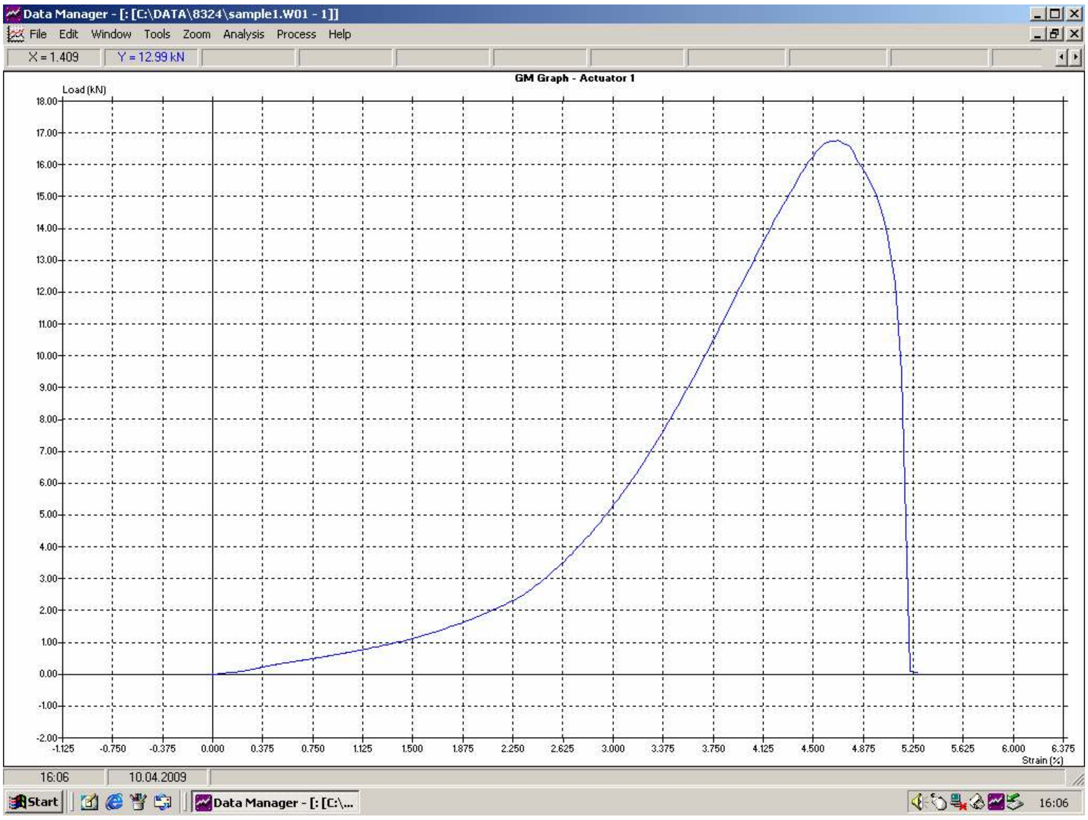

Figure 14: Experiment 3 - Test Result (Load vs Strain)

From the graph above, the highest peak represent the maximum load that the sample can withstand during the pull-to-break test. In this graph, the highest load is 16.76 kN.

From the value of the maximum load, we can also determine the Ultimate Tensile Strength of the weld. The ultimate tensile strength, UTS of a material of cross-sectional area *A* is given by:

$$UTS = F / A$$

where F is the tensile force (load) required to break the material. Given that the load is 16.76 kN and the actual A is 2.894 x 10^{-4} m, the UTS for this sample is 57.92 MPa.

Experiment 4: 3rd April 2009

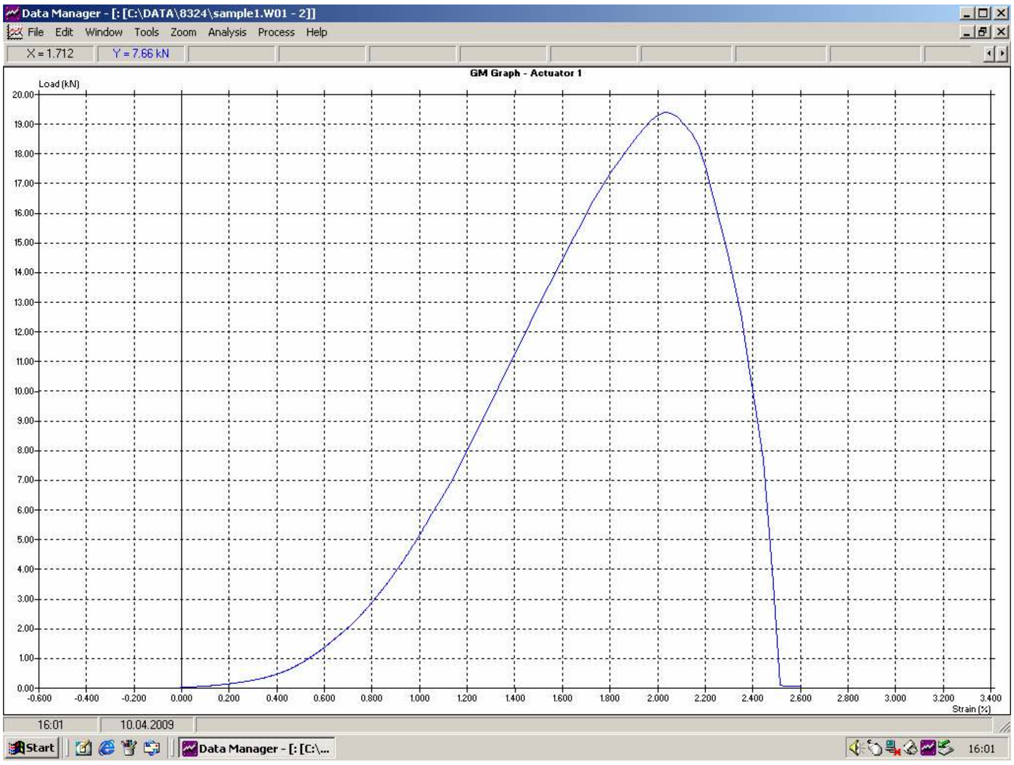

Figure 15: Experiment 4 - Test Result (Load vs Strain)

From the graph above, the highest peak represent the maximum load that the sample can withstand during the pull-to-break test. In this graph, the highest load is 19.4 kN.

Given that the load is 19.4 kN and the actual A is 3.066 x 10^{-4} m, the UTS for this sample is 63.28 MPa.

Experiment 5: 6th April 2009

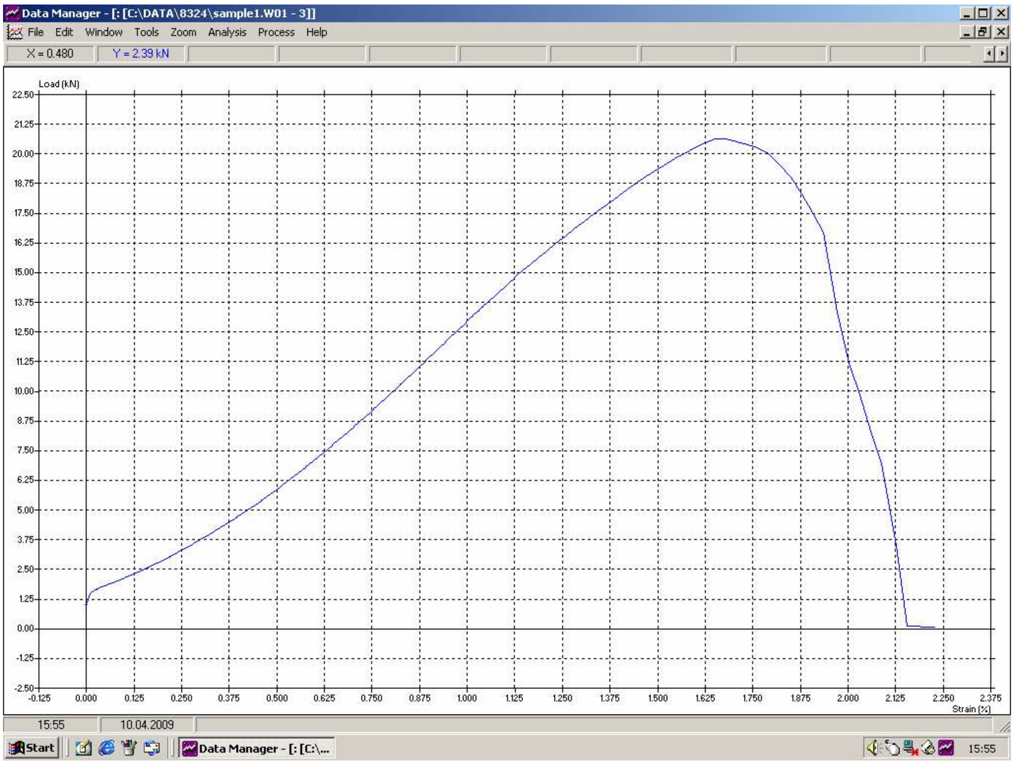

Figure 16: Experiment 5 - Test Result (Load vs Strain)

From the graph above, the highest peak represent the maximum load that the sample can withstand during the pull-to-break test. In this graph, the highest load is 20.48 kN.

Given that the load is 20.48 kN and the actual A is 2.809×10^{-4} m, the UTS for this sample is 72.91 MPa.

Experiment 6: 6th April 2009

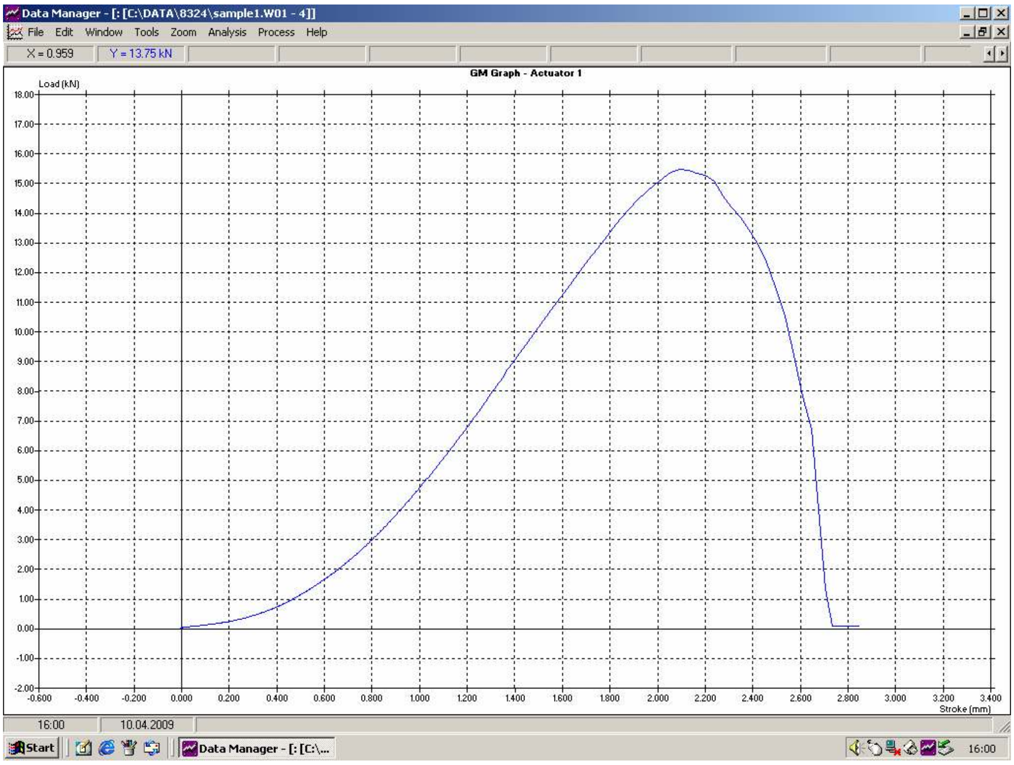

Figure 17: Experiment 6 - Test Result (Load vs Strain)

From the graph above, the highest peak represent the maximum load that the sample can withstand during the pull-to-break test. In this graph, the highest load is 15.52 kN.

Given that the load is 15.52 kN and the actual A is 2.894×10^{-4} m, the UTS for this sample is 53.64 MPa.

Experiment 7: 1st June 2009

Figure 18: Experiment 7 - Test Result (Load vs Strain)

From the graph above, the highest peak represent the maximum load that the sample can withstand during the pull-to-break test. In this graph, the highest load is 21.58 kN.

Given that the load is 21.58 kN and the actual A is 2.81×10^{-4} m, the UTS for this sample is 76.80 MPa.

Experiment 8: 1st June 2009

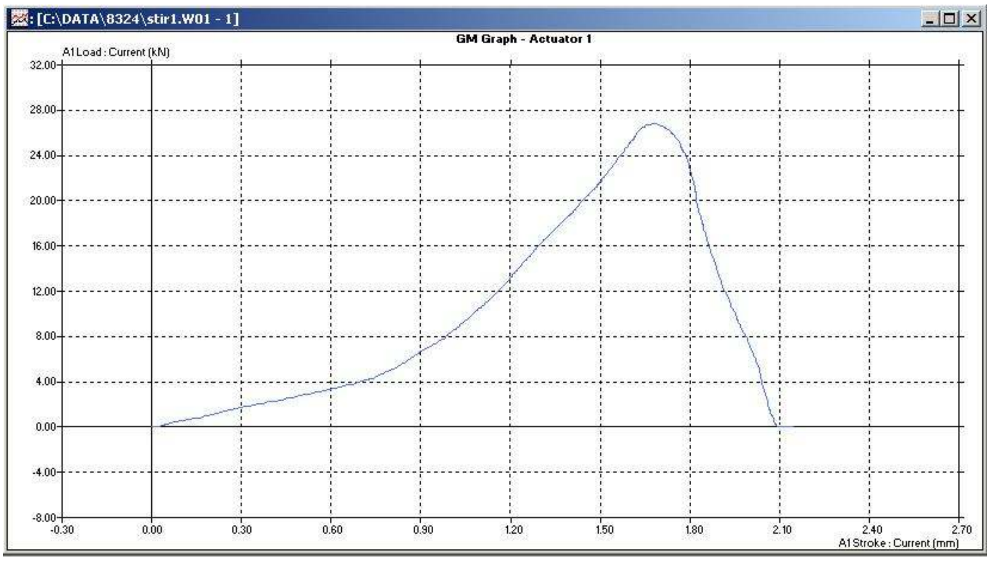

Figure 19: Experiment 8 - Test Result (Load vs Strain)

From the graph above, the highest peak represent the maximum load that the sample can withstand during the pull-to-break test. In this graph, the highest load is 26.89 kN.

Given that the load is 26.89 kN and the actual A is 2.52×10^{-4} m, the UTS for this sample is 106.71 MPa.

Result Summary

Table 2: Result Summary

Sample	Spindle Speed (rpm)	Travelling Speed (mm/min)	Depth (mm)	Load (kN)	UTS (MPa)
3	3500	45	8.1	16.76	57.92
4	3000	35	8.1	19.4	63.28
5	3000	40	8.1	20.48	72.91
6	3500	40	8.1	15.52	53.64
7	3000	45	8.1	21.58	76.8
8	2500	40	8.1	26.89	106.71

The data from the table can be divided into 2 sets of graphs, which is the 'Load vs Travelling Speed graph' and 'Load vs Spindle Speed' graph.

It is noted that the curve of the graphs were not uniform and different than the typical curve of a load vs strain curve. This is may caused by the discontinuities that occur inside the weld area that affecting the results.

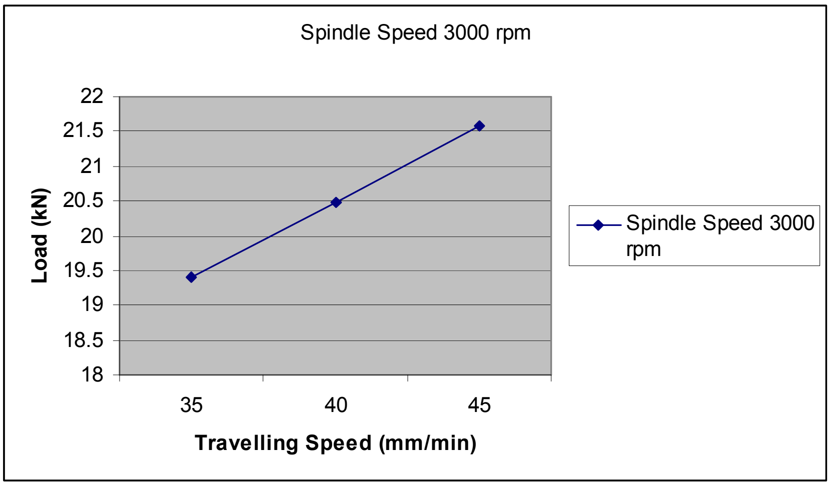

Figure 20: Load vs Travelling Speed graph with fixed Spindle Speed at 3000 rpm

This graph is used to determine the relationship between Load (kN) and the Travelling Speed (mm/min) with constant Spindle Speed (rpm) at 3000 rpm. From the graph, it is shown that the maximum load is proportional to the travelling speed. As the travelling speed increases, the maximum load increases as well.

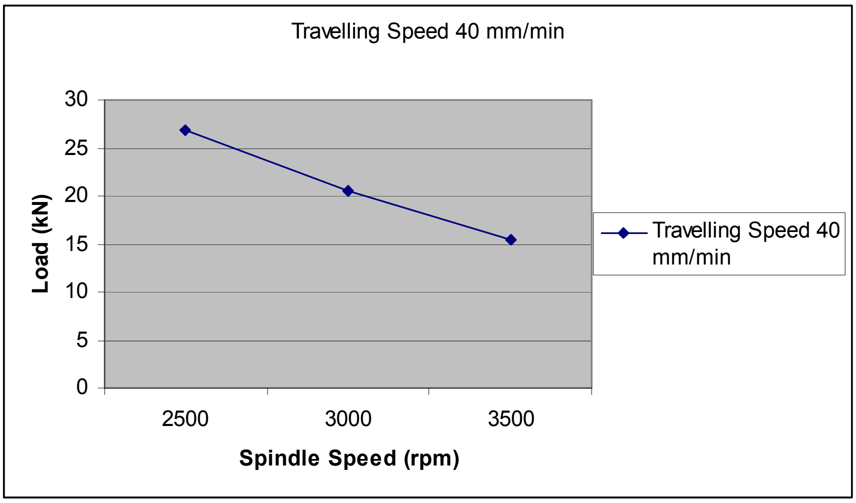

Figure 21: Load vs Spindle Speed graph with fixed Travelling Speed at 40 mm/min

This graph is used to determine the relationship between Load (kN) and the Spindle Speed (mm/min) with constant Travelling Speed (rpm) at 40 mm/min. From the graph, it is shown that the maximum load is inversely proportional to the spindle speed. As the spindle speed increases, the maximum load decreases.

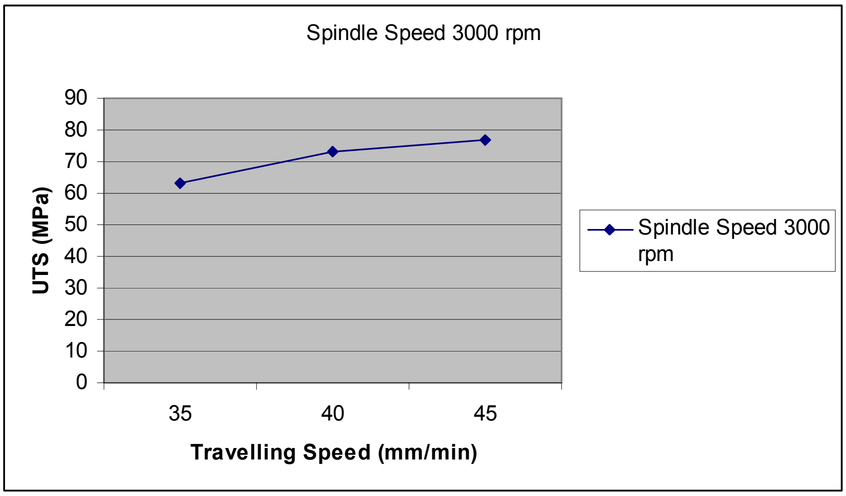

Figure 22: UTS vs Travelling Speed graph with fixed Spindle Speed at 3000 rpm

This graph is used to determine the relationship between UTS (MPa) and the Travelling Speed (mm/min) with constant Spindle Speed (rpm) at 3000 rpm. From the graph, it is shown that the maximum load is proportional to the travelling speed. As the travelling speed increases, the maximum load increases as well.

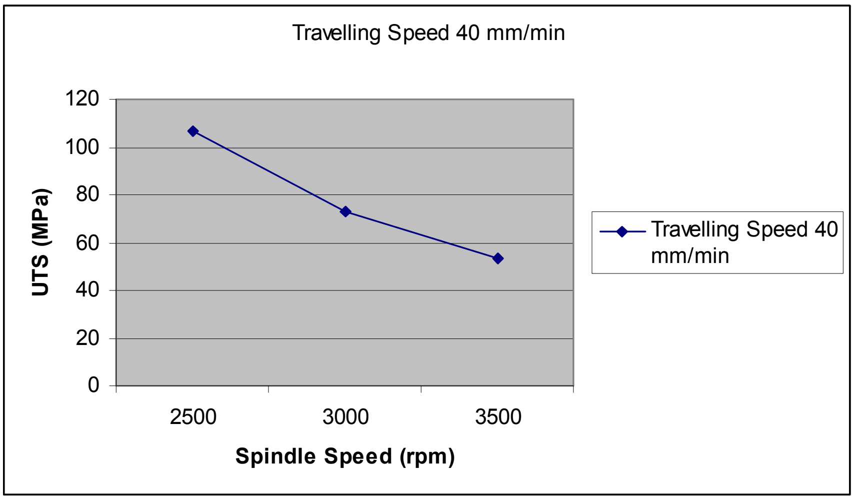

Figure 23: UTS vs Spindle Speed graph with fixed Travelling Speed at 40 mm/min

This graph is used to determine the relationship between UTS (MPa) and the Spindle Speed (mm/min) with constant Travelling Speed (rpm) at 40 mm/min. From the graph, it is shown that the maximum load is inversely proportional to the spindle speed. As the spindle speed increases, the maximum load decreases.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This project has described the basic understanding of the Friction Stir Welding process for joining lightweight materials such as, aluminium alloys. The author has managed to perform the friction stir welding process and analyze the end results using the equipment available in Universiti Teknologi Petronas.

From the results, the following conclusions are derived:

i) The maximum load and UTS are proportional to the travelling speed. As the travelling speed increases, the maximum load increases as well.

ii) The maximum load and UTS are inversely proportional to the spindle speed. As the spindle speed increases, the maximum load decreases.

FSW has the potential to play an important role in manufacturing industry in the future. Thus, necessary studies and improvement need to be done for this process. Therefore, various activities have been planned out by the author and supervisor throughout the semesters in order to achieve these objectives.

5.2 Recommendations

As for the recommendations for future works for continuation or expansion of the project, the author suggest the use of a more efficient rotating pin tool design in order to minimize the splashing of materials out of the weld zone which brings to the discontinuities inside the weld zone. One way to solve this problem is to fabricate a pin tool that has a concave shoulder profile which can prevents material from extruding out of the sides of the shoulder and maintains downwards pressure.

Beside that, more experiments should be carried out with different parameters. This is to get more variations in the results and thus more accurate results.

The author also suggests that the test analysis should be conducted exactly or as close as possible with the standard test procedure which is the ASTM E8-00b, the Standard Test Methods for Tension Testing of Metallic Materials. This is to ensure the result obtained is accurate according to the standard.

REFERENCES

[1] Mandal, N.R., 2005, “Aluminum Welding – Second Edition”, Narosa Publishing House.

[2] http://www.ajt-inc.com/theprocess.html

[3] Nandan R, DebRoy T, and Bhadeshia H.K.D.H., 2008 “Recent Advances in Friction Stir Welding – Process, Weldment Structure and Properties”, Department of Materials Science and Engineering, Pennsylvania State University, University Park, PA 16802, USA and Department of Materials Science and Metallurgy, University of Cambridge, Cambridge CB2 3QZ, U.K.

[4] Nelson, T; Zhang, H; Haynes, T (2000). "friction stir welding of Al MMC 6061-B4C". *2nd International Symposium on FSW*

[5] Reynolds, AP (2000). "Visualisation of material flow in autogenous friction stir welds". *Science and technology of welding and joining*.

[6] Chao, Y.J., and Qi, X., 1998, “Thermal and Thermo-Mechanical Modeling of Friction Stir Welding of Aluminium Alloy 6061-T6”, University of South Carolina, USA.

[7] http://www.ajt-inc.com/theprocess.html

[8] http://www.idc-shanghai.com/Popular%20Technology/machining/Turning.htm

[9] Kalpakjian, S; Schmid, S (2006).”Manufacturing Engineering and Technology”, Prentice Hall.

[10] http://www.efunda.com/processes/heat_treat/introduction/heat_treatments.cfm#Hardening

[11] Reed-Hill, R (1994). "Principles of Physical Metallurgy" 3rd edition. PWS Publishing, Boston.

APPENDICES

Gantt Chart for Semester Jan09