UNIVERSITI TEKNOLOGI PETRONAS

FINAL YEAR PROJECT REPORT

MATERIAL FLOW BEHAVIOUR DURING FRICTION STIR WELDING (FSW) OF NYLON PLATES

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15000

MECHANICAL ENGINEERING MAJORING IN MATERIALS

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بِسْمِ ٱللهِ ٱلرَّحْمَنِ ٱلرَّحِيمِ

With the Name of Allah the Most Gracious, the Most Merciful

Praise to be to Allah The Almighty for the opportunity that He has given to further my journey in becoming an excellent engineer. First and foremost, I would like to express my deepest appreciation to Assoc.Prof Dr. Hj. Mokhtar Awang,who has shown great enthusiasm in coaching and mentoring. Blessed with wisdom and vast knowledge, Dr Mokhtar have shown that perseverance is the key in making this project a success. I really acknowledge his patience and the trust given to me throughout my final year duration.

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Apart from that, all of these would not have become a reality without my family members and friends who have been supporting me throughout my four years of degree programme. All of their efforts in ensuring the success and completion of this programme are really appreciated. Not forgetting, to my previous lecturers for their, excellent supervision along the assessment and the effort for allowing me to achieve an outstanding performance for my final year project will are deeply appreciated.

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ABSTRACT

Friction stir welding (FSW) have vastly experimented on thermoplastic material due to its wide engineering applications. FSW technique results in the material having low distortion and high joint strength as compared with other joining techniques. The purpose of this paper is to investigate the material flow pattern during FSW on Nylon -6 and conduct assessment on the effect of process parameters in the flow pattern. The method used to detect the material flow is by slotting blue-colored markers along the groove made prior the FSW process. The markers used were Paraffin Wax and blue-coloured Nylon material. Results show that although material flow can be seen, the blue colour makes up almost the entire stir zone. This makes it difficult to see the flow pattern of the blue coloured marker thus further improvements is needed on this technique. It also can be concluded that the material flow is influenced by the pin profile as well as process parameters. This paper shows that at different feed rates, the Nylon material shows different appearance that contributes to different material flow pattern.

CHAPTER 1: INTRODUCTION

Background

Friction Stir Welding (FSW) is a relatively new method in aluminium alloy welding patented by The Welding Institute, UK. It rose into the manufacturing industry in the year of 1991. This welding approach utilizes a non-consumable steel welding tool to develop frictional heating up to 80% the material's melting point. In addition, the forging pressure is mixed with the frictional heat to attain high-strength bonds nearly free of defects. Presently, the technique is applied in the aerospace, shipbuilding, air craft and automotive industries.

As compared to the conventional welding method, the FSW brings an important aspect which minimizes the number of process parameters to be controlled. In FSW, only three process parameters which need to be monitored: travel speed, rotation speed and pressure. On the contrary, purge gas, voltage and amperage, travel speed, shield gas and arc trap are some of the various process criteria need to be consider in executing fusion welding technique. These further complicates the welding process which could lead to increment in manufacturing cost. Moreover, material joined via FSW has proven to have welds of good mechanical properties with the ability to weld materials which are considered as "un-weldable" initially.

Researchers as well as manufacturers have all appreciate the advantages from the FSW technique. Therefore, various studies on the possibility of FSW being used on non-metallic materials such as plastic and composite. Currently, the demand of these non-metallic materials is relatively high due to their applications such as automotive and aviation industry. Additionally, efforts are being done to incorporate the existing metallic parts with plastic materials. Engineered plastic has several vital advantages over metal which favours manufacturers to utilize them. Here are the list of criteria which gives plastic the edge over metal.

- Higher strength to weight ratio that causes less energy for motion due to decreased in inertia. It aids in energy saving as well as providing fast motion.
- Ability to be designed as anisotropic.
- Tough viscoelastic materials which contributes to durability
- High resistivity towards the environment (UV stabilizers, Chlorine etc)
- Simple process which subsequently contribute to low cost of production
- Ability to be recycled after usage

A huge concern with regards in developing and improving new plastic materials is the inadequacy during fabrication processes for the final products. For the past years, it can be observed that the scope of joining processes for plastic has made the most enhancements. Joining process must be taken into serious consideration as it contributes to structural and high performance applications in spite the focus of producing large volumes of high quality plastic parts. Unfortunately, plastics can be difficult to join due to their low surface energies and the presence of release agents from previous processing steps. A good joining method should be able to meet basic requirements.(Nelson, Sorenson & Johns, 2004)

Problem Statement

Joining of materials is an essential process in manufacturing as it determine the structural strength of the final product. As mentioned, FSW which is a revolutionary method provides an array of positive effects in the manufacturing industry if it is applicable to all material. However, the technique patented by Thomas et al. was unfruitful due to obvious differences of properties between plastic and metal. Viscoelastic behaviour, low meting temperatures and several polymeric criterion caused the failure of joining polymeric material via FSW. Despite the unsuccessful first trial, the possibility of utilizing FSW on polymeric materials is high as manipulation of tools and procedure are the key factors in making the dream a reality. However, little knowledge is known towards the material flow behaviour of the polymer.

Objectives

1. To investigate the material flow pattern during Friction Stir welding (FSW) on Nylon.
2. To conduct assessment on the effect of process parameters in the flow pattern.

Scope of Study

In this project, nylon material will be the main polymer used in investigating the material flow behaviour. First, nylon plates will undergo FSW using a milling machine located at Block 21, Universiti Teknologi Petronas, Perak, Malaysia. A special tool head specifically for FSW is fitted on to the milling machine. Afterwards, the welded nylon plates section will be observed under SEM as well as undergoing several mechanical tests (flexural, tensile and impact) following the ASTM standards for polymeric materials. The collected data are essential in analysis of the material behaviour of nylon plates which have undergone FSW.

CHAPTER 2: LITERATURE REVIEW AND THEORY

A. Friction Stir Welding (FSW) with Threaded Pin Profile on Nylon 6

K. Panneerselvam and K. Lenin (2013) from the Department of Production Engineering, National Institute of Technology, Tiruchirappali, India had conduct a research on FSW used to join thermoplastic materials. In their research, Nylon 6 was chosen as the specimen due to its wide engineering application. Therefore, a study on Nylon 6 by FSW is necessary for expanding the knowledge on the subject matter. The table below illustrates the process parameters extracted from the study to perform FSW on Nylon 6 plate.

Table 1 Process Parameters for FSW on Nylon-6 Plates

Material Used	Nylon 6
Machine	Bridgeport CNC Milling Machine
Pin Profile	Threaded (cavity angle 60°, L= 10 mm, d= 6mm) D
Material of tool	Mild Steel
Dimension of Nylon Material	2 x (95 mm x 220 mm x 10 mm)
Temperature	Atmospheric conditions at 30°C
Tensile Strength	73. 44 MN/m ^2
Tool Rotational Speed	1000 rpm
Welding Feed	10 mm/min

A specially designed left handed threaded tool pin profile is used to butt-joint two nylon plates with thickness of 10 mm together. A Bridgeport CNC Milling machine was used in order to carry out FSW was carried out with tool rotational speed of 1000 rpm with welding feed rate of 10 mm/min. The objective of the study was to investigate the effect of the joint formation by the rotation of the threaded pin-profile in clockwise and counter-clockwise direction where the outcome is observing the effects of the tool direction on weld defects formation.

Results obtained showed that counter-clockwise tool rotation produced defect free welds and much better properties as compare to the nylon plate which undergoes the clockwise tool rotation. Upon inspection via optical microscopy, larger cavities appeared on the interior welded region when the tool rotates in the clockwise direction while smaller cavities can be seen when the tool rotates in the counter clockwise direction. Mechanical testing were carried out to further solidify the findings. The tabulated data shows the result of various mechanical testings where Nylon 6 which is used with the tool that rotates in the counter clockwise direction has higher tensile strength (34.8 MN/m), Shore-D hardness =(64 SD) and Charpy Strength (160.49 kN/m).

B. Friction Stir Welding (FSW) of Polymeric Materials

Nelson, Sorenson and Johns (2004) made a breakthrough research where their study revolves around conducting Friction Stir Welding (FSW) on polymeric materials. According to Callister and Rethwisch (2011) polymeric materials have a wide range of applications that we depend on our daily lives. Classifications of different types of polymers are always based on their end product usage. Plastics are the most number of polymers utilized in our ever changing world. Due to its high degree of structural strength, plastics generally being used for all purposes. A truly handy aspect of plastics is that their ability to have various combinations of properties which enables the material to suit with the demands of the consumers.

According to Nelson et. al (2003), the FSW technique plasticizes portion of a joint which opposes the non-consumable tool or probe that penetrates the joint region spawning heat energy between the probe and the opposed portions of the joint. Afterward, the plasticized portions were given time to solidify and join by removing or translating the probe along the joint. The study done by Nelson et. al (2003) is actually a patent invention which relates to a method and apparatus of joining thermoplastic materials. There are two objectives from this invention which are providing constraint surface which is stationary/moves independently of the pin and introducing energy by a system independent of the frictional energy produced by the tool. This led to the development of

Alumiminium-style tool with hot shoe tool design being used onto the thermoplastic. In this method, the constraining surface is in at least in part insulated to reduce the dissipation of the heat from the weld region. Process parameters were also being monitored (spindle speed, feed rate, profile tool) where by the analysis of each parameters are shown from the result obtained via mechanical testing. Based the result obtained, the optimal process parameters for conducting friction stir welding (FSW) on thermoplastic materials are as follow:

Spindle Speed >= 1000 rpm
Machine Feed rate: < 12 inches per minute
Tool Pin Diameter: Straight

This conclusion was supported by the fact that the specimens with the lowest average mechanical properties were welded with the low spindle speed at high feed rate, and with tapered pin.

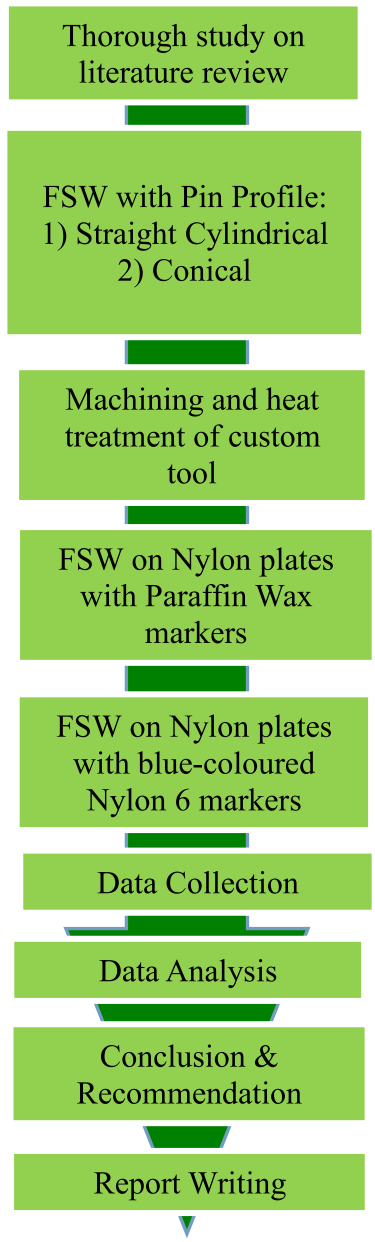
C. Material Flow Behaviour during Friction Stir welding of Aluminium

A famous welding research paper patent by K.Colligan (1991) regarding material flow behaviour during friction stir welding (FSW) of Aluminium (6061 & 7075) was chosen as the benchmark for this study. The objective of this study was to provide documentation on the movement of material during friction stir welding as means of developing conceptual model of deformation process.

In this breakthrough research, Colligan has instilled two methods in order to achieve the objective which are utilized Steel Shot Tracer Technique and “Stop Action Technique”. In the Steel Shot Tracer technique we observed the distribution of small steel ball embedded into the groove made into the material. The result shows that the material striking the pin on the advancing side (AS) will be swept around the rotating pin and deposits on the retreating side (RS) behind the pin while the material striking the pin on the RS will also be deposited on the RS behind the weld. Cross-sectional radiograph indicate most positions a lifting of the markers to points nearer the shoulder of the tool. The ‘Stop Action Technique’ is done to support the steel shot tracer technique where the tool is allowed to unwind its way out of the work piece very rapidly leaving behind a record of the material that was against the pin. These techniques gave rise to the idea of conducting this project

CHAPTER 3: METHODOLOGY

Project Flow Chart



Gant Chart and Milestones

Table 2 Final Year Project Gant Chart

	YEAR	2014								2015													
NO	TASK NAME	W8	W9	W10	W11	W12	W13	W14		W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
1	Literature review thorough study	■	■	■																			
2	Acquire nylon plates				■	■	■																
3	Conduct FSW with thermocouple								STUDY WEEK AND FINAL EXAM	■													
4	Conduct FSW experiment without marker											■	■										
5	Conduct FSW experiment with Paraffin Wax marker											■	■	■	■								
6	Conduct FSW experiment with blue-coloured nylon marker																	■	■	■			
7	Record and analyze data obtained																				■		
8	Preparation of final report and technical paper																					■	■

Table 3 Key Milestones

NO	TASK NAME	DEADLINE
1	Literature review thorough study	20/11/2014
2	Acquire nylon plates	16/1/2015
3	Conduct FSW with thermocouple	23/1/2015
4	Conduct FSW experiment without marker	30/1/2015
5	Conduct FSW experiment with Paraffin Wax marker	6/2/2015
6	Conduct FSW experiment with blue-coloured nylon marker	20/3/2015
7	Record and analyze data obtained	30/3/2015
8	Preparation of final report and technical paper	5/4/2015

Tool Fabrication

A) Tool Design

In this work, a custom made pin profile has fabricated as shown in Figure 1. The tool geometry plays a vital role in material flow and in turn controls the feed rate at which FSW can be conducted. An important aspect in making FSW is by altering the temperature during the process via the pin profile itself. For this particular experiment, the pin profile will be having two shoulders which the first having a diameter of 25 mm while the second having a diameter of 18 mm. The material used for making the tool is H13 steel because of its high hardenability, excellent wear resistance and hot toughness.

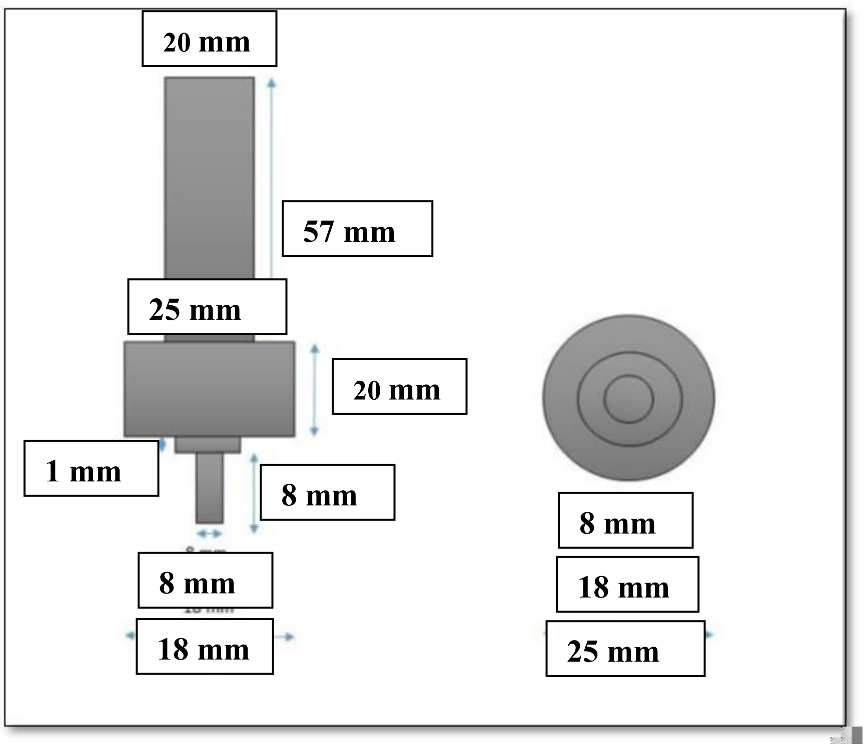


Figure 1 Tool geometry with two shoulders and a cylindrical pin profile

B) Machining of Tool and Heat Treatment

A cylindrical H13 steel (L=77 mm, D= 30mm) was machined using CNC Lathe machine equipped with iron carbide cutter to get the desired design. Next, the tool was put in the furnace for heat treatment to increase its hardness and toughness for a better FSW process.

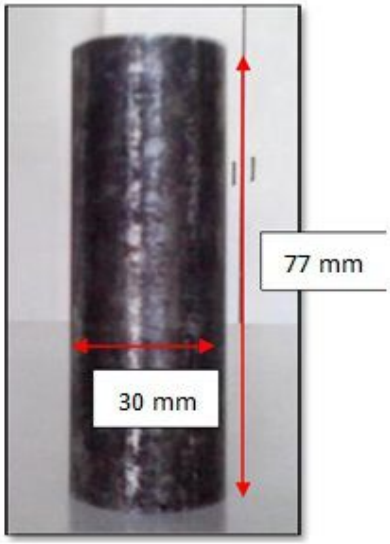


Figure 2 H13 Steel

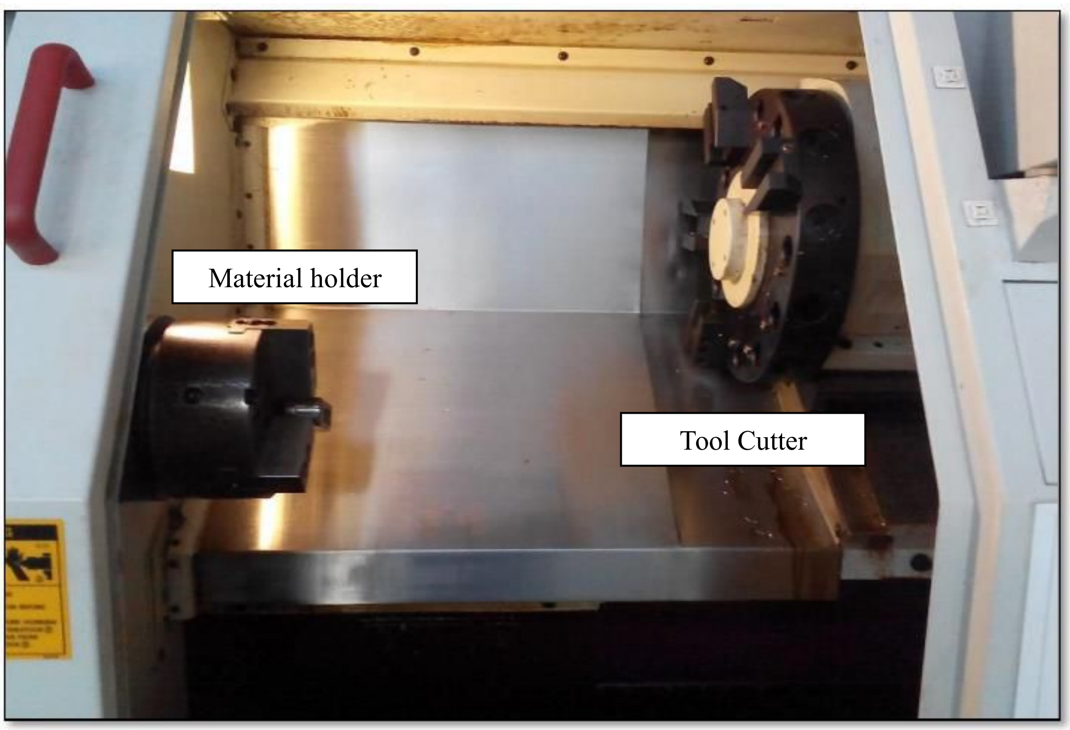


Figure 3 Utilizing CNC Lathe Machine for tool fabrication

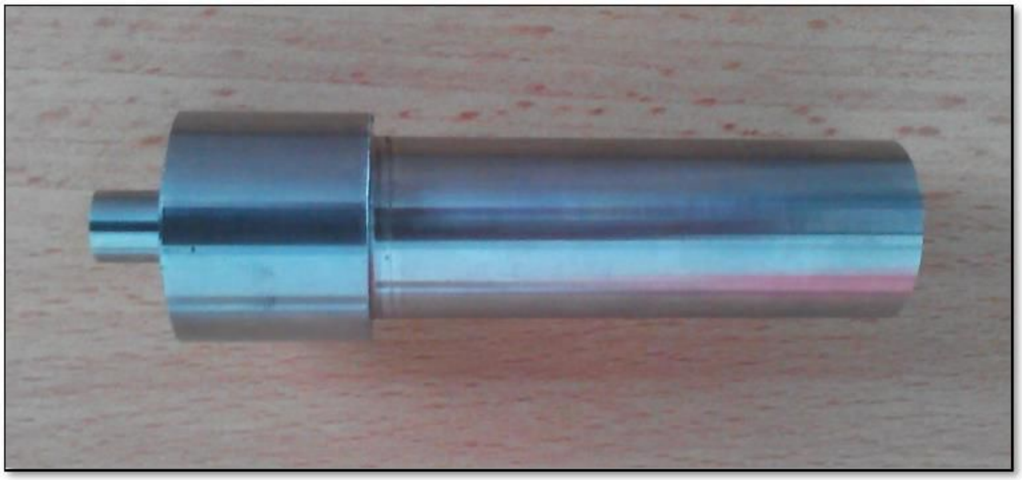


Figure 4 Fabricated Tool Side View

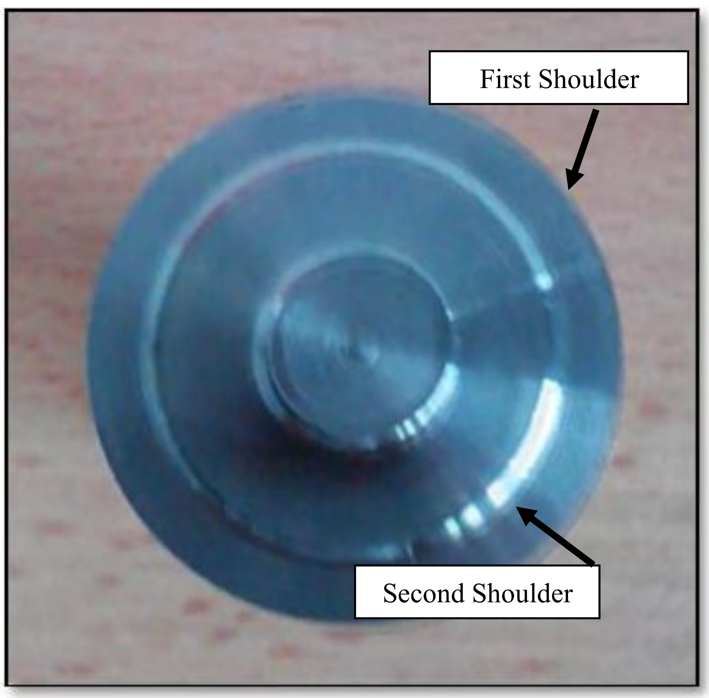


Figure 5 Fabricated Tool Top View

Figure 6 Furnace Unit for Heat Treatment Process

Figure 7 Fabricated Tool after Heat Treatment

Fabrication of FSW on Nylon Plates with Different Process Parameters

The friction stir welds have been carried out by using a specially designed clamping fixture that allows the user to fix the two nylon plates (95 mm x 220 mm) with the plate of 10 mm thickness to be butt welded on a CNC vertical milling machine. In this investigation, the base material, Nylon 6 plates were fabricated by inserting thermocouple wires on each of the reversing sides of the plates. A hole was drilled on each of the Nylon plates to insert the wires. The purpose of this method is to record the temperature of the Nylon plate during FSW process. Welding parameters used were based on the study by K. Pannerselvam and K Lenin (2013) where rotational speed is in the range of 800 rpm - 1000 rpm, welding feed rate ranging between 10 mm/min to 20 mm/min with two types of pin profile used. Figure 11 illustrates the experimental setup of the the FSW process while the table below shows the Mechanical properties of base material.

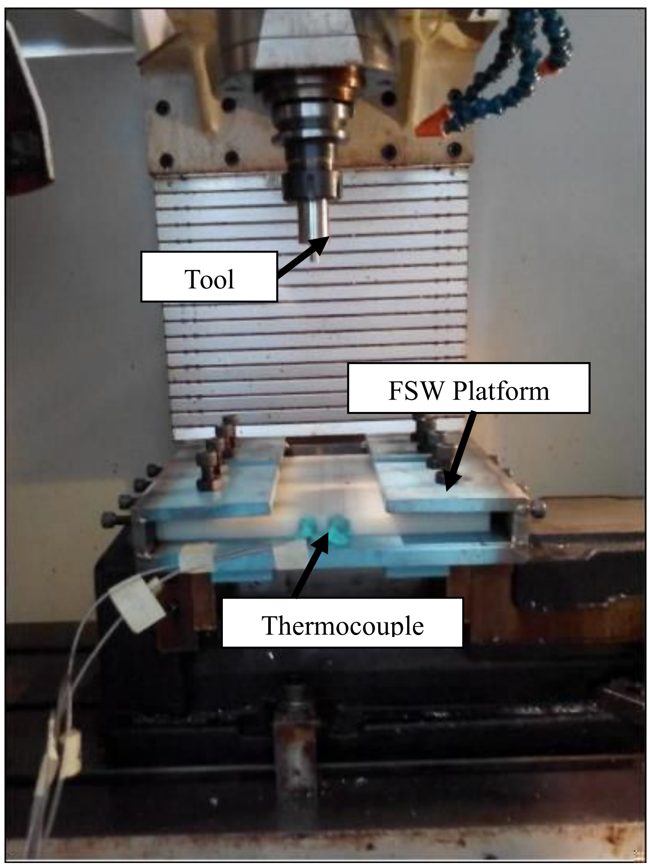


Figure 8 Experimental Setup of FSW on Nylon 6 Plates

Table 4 Mechanical Properties of Nylon-6

MATERIAL	YIELD STRENGTH (MPa)	MELTING POINT (˚C)	FRICTION COEFFICIENT
Nylon-6	85	220	0.4

The experiment setup was repeated twice using different tool pin profile which were straight cylindrical pin profile and conical pin profile. In the straight cylindrical pin profile, the rotational speed was set at 800 RPM with feed rate of 20 mm/min. On the other hand, the conical pin profile setup was setup at rotational speed of 1000 RPM with the same feed rate of 20 mm/min. The results are observed and recorded.

Experiment of FSW on Nylon Plates with Wax Markers

Next, experiment of FSW on Nylon plates with wax markers. Specifically, the marker used is paraffin wax with a melting point of 37˚C (99˚F) which will melt upon the heat produce during FSW. The markers were slotted at four different position in the groove (3 mm x 5mm x 220 mm) made prior the FSW. The experiment is repeated two times but with a slight change in the presence of the groove in between advancing side (AS) and retreating side (RS). In the first trial, grooves were present in between AS and RS, the rotational speed was set at 300 RPM with a feed rate of 25 mm/min. The pin profile for both trials were the tool with non-threaded cylindrical pin-profile prepared earlier. The results are shown in figure 12.

Figure 9 Nylon plate with paraffin wax slotted in the groove

Figure 10 Experiment Setup for Paraffin Wax Marker

Experiment of FSW on Nylon Plates with Blue-Coloured Marker

Afterward, the markers were changed to blue-coloured nylon material instead of parrafin wax. The decision to change the marker type is based on prediction of the effects of the paraffin wax upon FSW. Furthermore, it is more suitable to be having the marker material as Nylon-6 to ensure that the marker stirred homogeneously with the specimen. Originally, the marker has dimensions of (3mm x 70 mm x 190 mm) but it is then cut into eight smaller pieces with dimensions of (3mm x 5mm x 17mm) using a laser cutter. These markers are then slotted in the groove prepared at the Advancing side (AS) of the butt weld joint. This technique is repeated four times with different parameters in order to achieve the objectives of this experiment. Table 4 shows the different parameters being experimented.

Table 5 Parameters for the blue-coloured nylon-6 marker Technique

PARAMETERS	1st Trial	2nd Trial	3rd Trial	4th Trial
Spindle Speed (RPM)	300	300	300	300
Tilt Angle (˚)	0	0	0	0
Feed Rate (mm/min)	25	30	35	40
Pin Profile	Non-Threaded Cylindrical Profile with Double Shoulder			

Table 4 summarizes the parameters set for the experiment. The same pin profile was used for each experiments as the design is suitable for the application of FSW on Nylon-6 plates. The findings obtained are then photographed which illustrate the appearance of the nylon plates as a result of the FSW process. Next, hack saw machine is utilized to cut the joined nylon plates in obtaining the cross-section of the butt weld joint. The cross-section of each trials were grind and photographed to observe the markers' movement after FSW process.

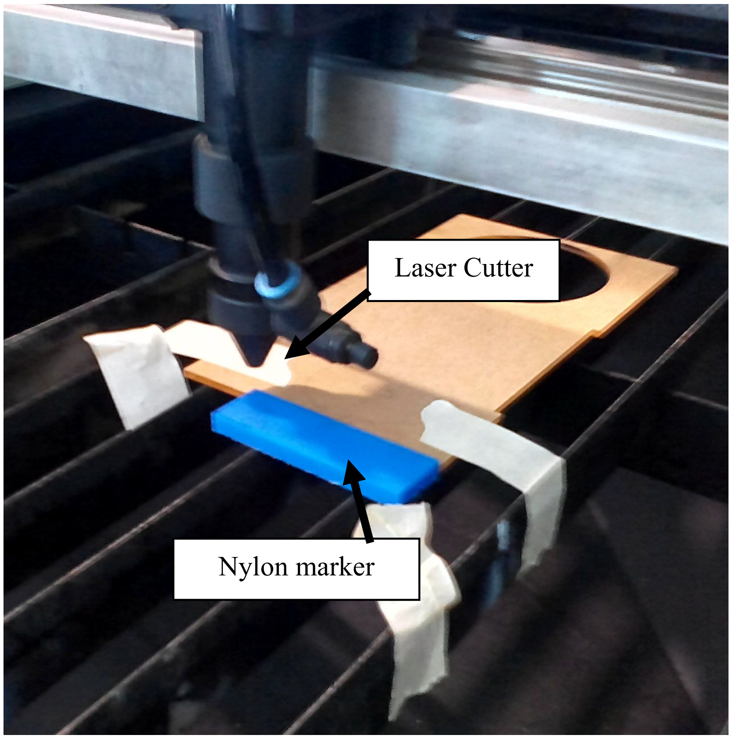


Figure 11 Laser Cutter Machine slicing the blue-coloured Nylon material

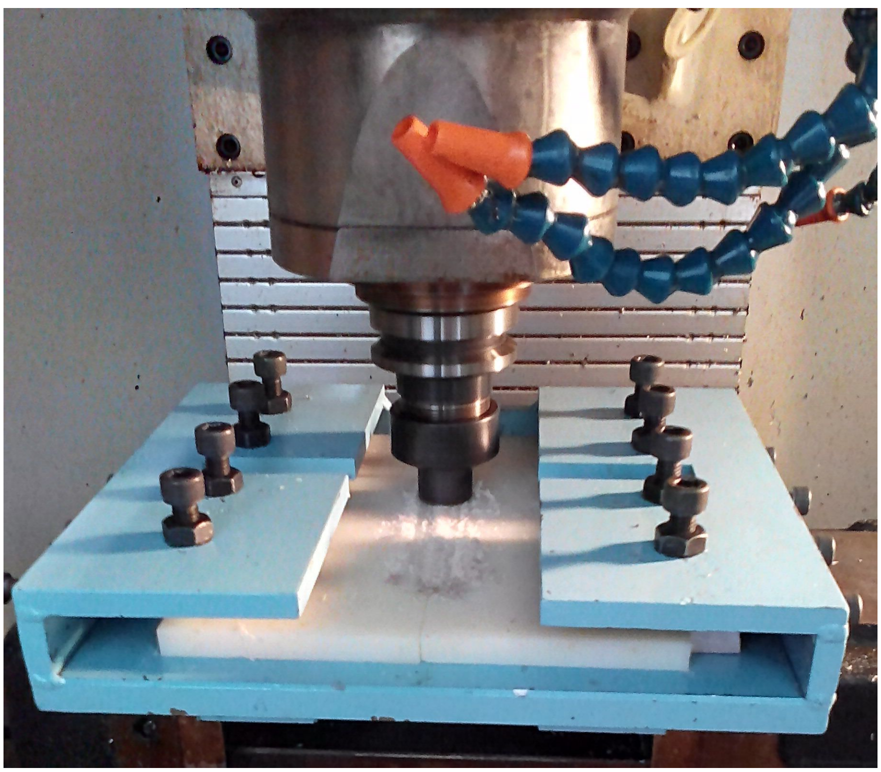


Figure 12 FSW with the presence of blue Nylon 6 Markers

Figure 13 Hack Saw Machine during the cutting the cross section of specimens

CHAPTER 4: RESULTS AND DISCUSSION

Experiment of FSW on Nylon Plates with Different Pin Profile

In this experiment, different pin profiles (straight cylindircial pin and concial pin) were used. A pair of thermo-couple was installed near the stir zone area to record the temperature of the nylon plates during FSW.

A) <u>Straight Cylindrical Pin</u>

The results show that the straight cylindrical pin broke at the beginning part of the FSW process. The pin was embedded in the Nylon-6 material but the process was kept going as the rotation of the shoulder merged the two plates together. It is suspected that the straight cylindrical pin profile is not suitable under the process parameters (800 RPM, 20 mm/min) that produced a high temperature which resulted in the tool breakage.

Figure 14 FSW with Straight Cylindrical Pin Profile

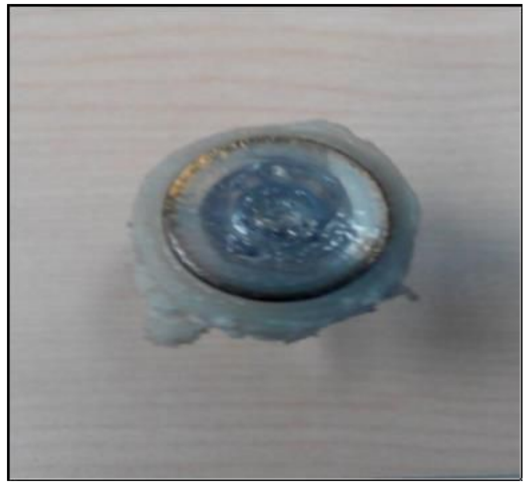


Figure 15 Pin Profile with breakage *Figure 16 Plan View of the breakage*

B) <u>Conical Pin Profile</u>

The result shows success of FSW process when the conical pin profile was being utilized. However, a massive amount of Nylon-6 material accumulated on the pin profile. It was proposed that a concave-like design must be fabricated on the shoulder of the pin profile to reduce the excessive accumulation. Figure 20 shows the result obtained.

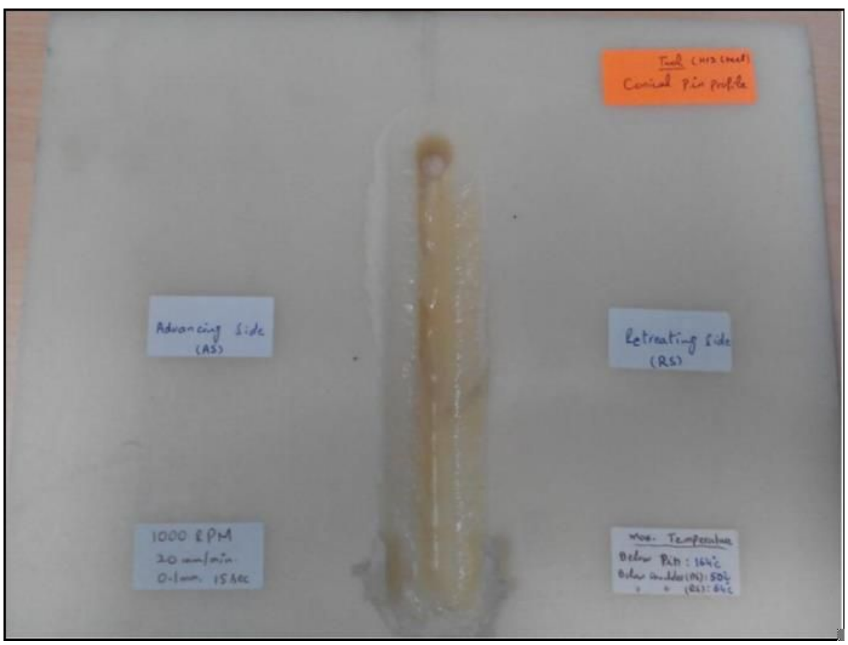


Figure 17 FSW with Conical Pin Profile

Figure 18 Accumulation of Nylon-6 material on conical pin profile

Experiment of FSW on Nylon Plates with Wax Markers

The experiment conducted is focusing on the material flow behaviour. Based on the results obtained, the suitable parameter as well as experiment setup needs to be decided before pursuing further on the material flow behaviour of the Nylon itself.

A) <u>Grooves on the Advancing Site and the Reversing Side</u>

The wax can be seen but the colour of the wax apparently became diluted thus making it difficult to observe the pattern of material flow. Due to the hollow part caused by the groove in between the butt-joint weldment area, the welding between the two nylon plates were not strong.

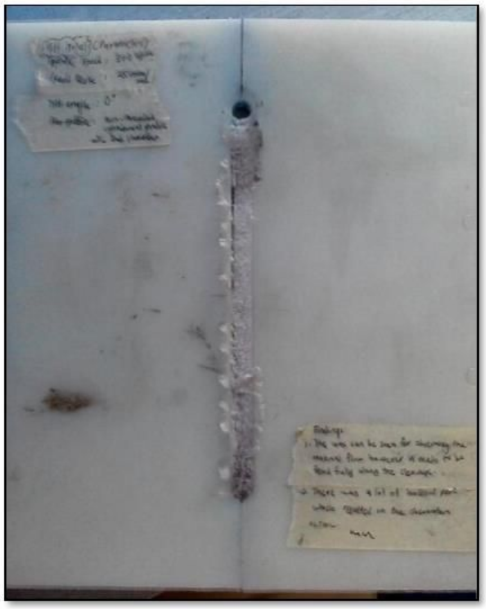


Figure 19 *First Trial of The FSW with Paraffin Wax Marker*

B) <u>Grooves on the Reversing Side</u>

The wax's appearance is still the same as the first trial. On the contrary, it proves to be stronger as compared to the first trial as the presence of only one groove in the butt weld joint provides enough strength to hold the two plates together.

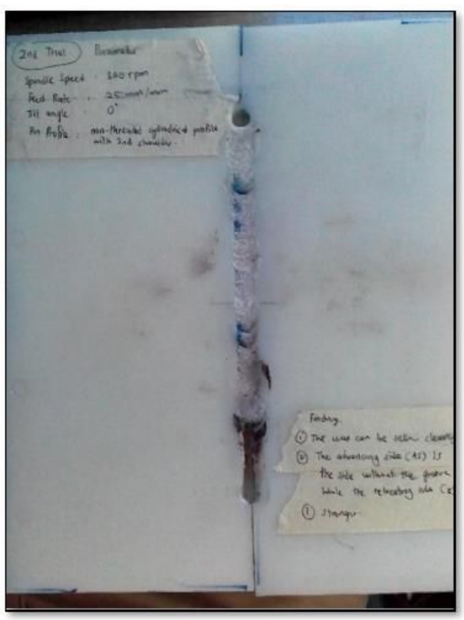


Figure 20 *Second Trial Of Material Flow Behaviour*

Experiment of FSW with blue-coloured Nylon-6 Marker

The whole FSW operation was conducted using the CNC Milling machine. A total of four experiments were carried with significant difference in the values of the feed rate. Below shows the result and discussion of each trials.

A) <u>Experiment 1</u>

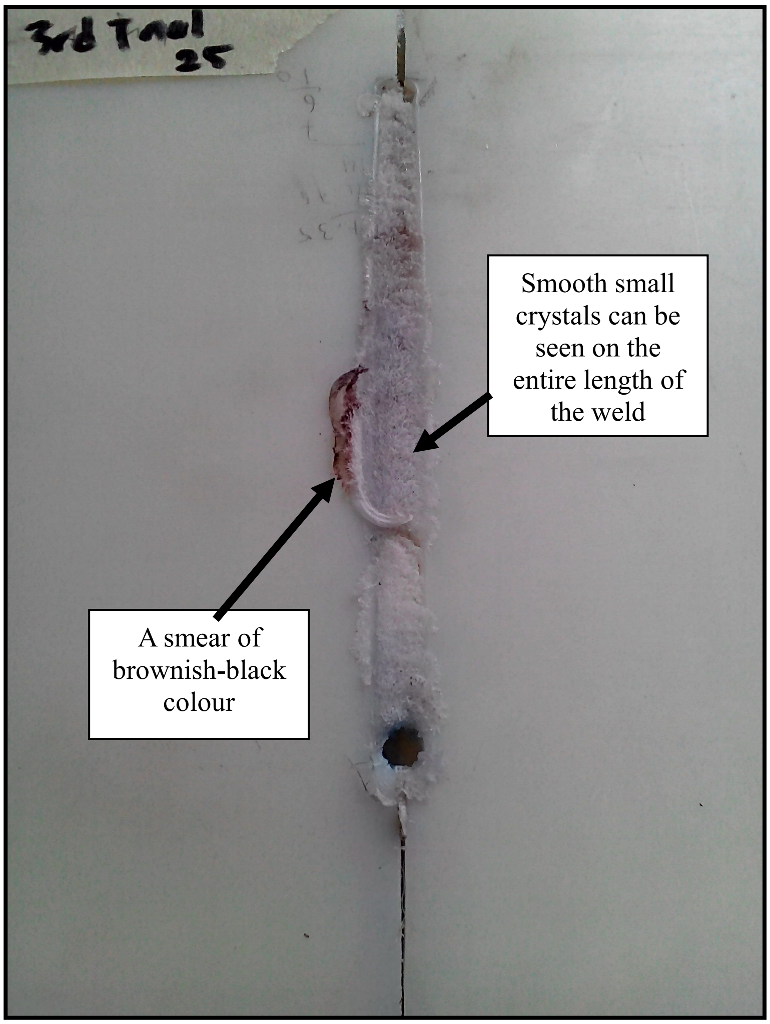


Figure 21 *Appearance of Nylon 6 Plates Welded at 25 mm/min*

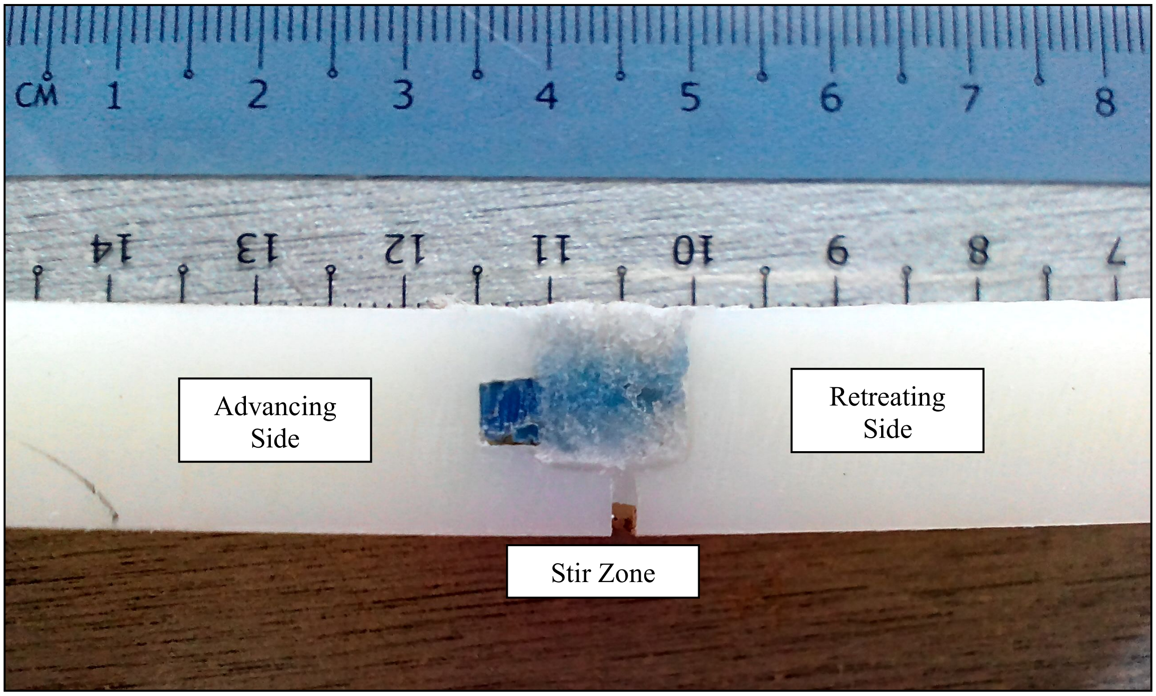


Figure 22 *Cross-section of the butt weld joint at 25 mm/min*

In this investigation, feed rate is the primary parameter that is manipulated over the course of four trials in order to observe any differences that might occur for comparison. The first feed rate was 25mm/min is investigated. Based on figure 24, a solid weld was produced where smooth small crystals can be seen on the entire length of the weld with a thin layer of material deposited on both advancing side as well as the reversing side. Here, a smear of brownish-black colour is noticeable on the deposited material located at the advancing side as this is due to the layer of dust on the tool. Inspection on the cross sectional view of the weld revealed that the material flow in a clock-wise manner as illustrated in Figure 25. As the tool penetrates and moves along the length of the joint, the blue coloured marker shows that the material moves from the advancing side towards the retreating side and moves back to the advancing side in a circular manner. As it moves upward in the stir zone, the shoulder of the tool pushed the material back down thus making it settle in the weld joint area.

B) Experiment 2

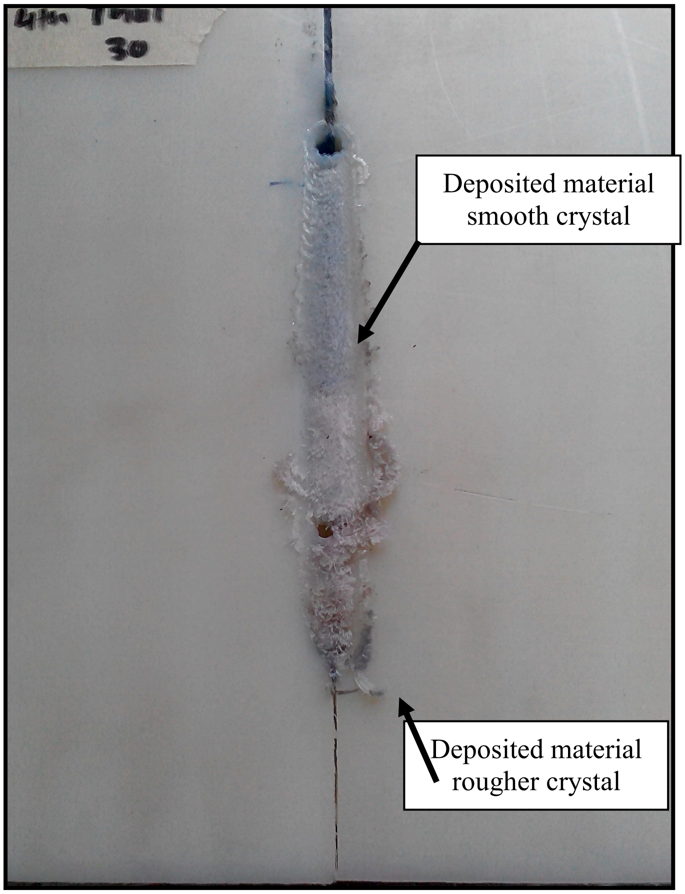


Figure 23 *Appearance on Nylon 6 Plates at feed rate of 30 mm/min*

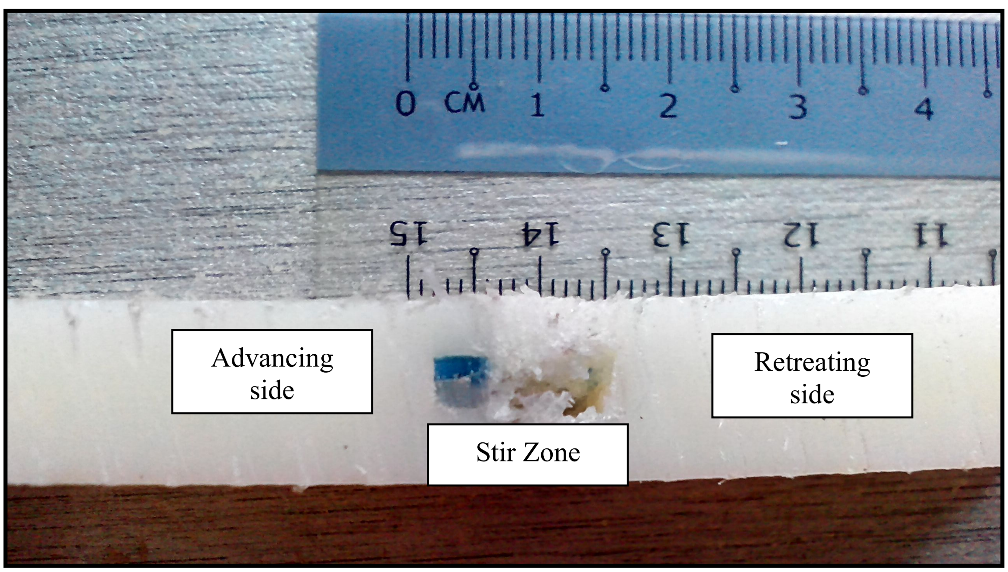


Figure 24 *Cross-section of the butt weld joint at 30 mm/min*

For this experiment, the weld produced is a complete welding which resembles the result obtained in the first experiment. However there's a significant difference between the beginning area of the weld length with the end. Deposited material on the beginning part of the weld length appears to be much rougher crystal as compared to the later part of the weld length. This is due to the additional dwell time needed for the tool to penetrate 80% of the depth of the butt joint which in this case is about 8 mm deep. Upon observation of its cross sectional area, the blue colour of the marker is not visible as a the presence of a gaping hole can be seen. The hole leads to a hollow path in the stir zone over a distance similar to the length of the entire weld. As bending stress is subjected to it, crackling sound can be heard and it breaks eventually. The breakage located at the panel of the Reversing side of the weld joint.

C) Experiment 3

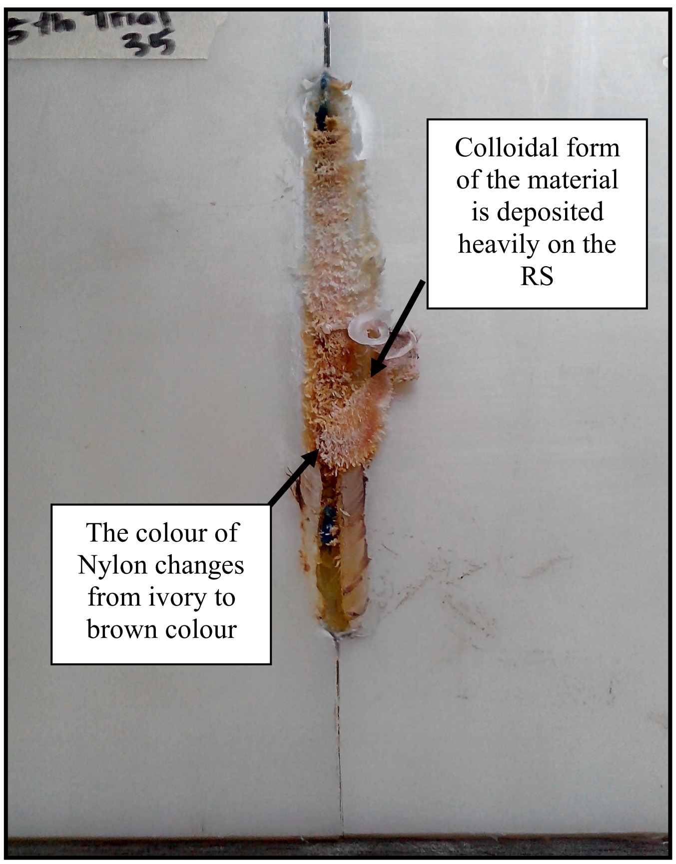


Figure 25 *Appearance on Nylon 6 Plates at feed rate of 35 mm/min*

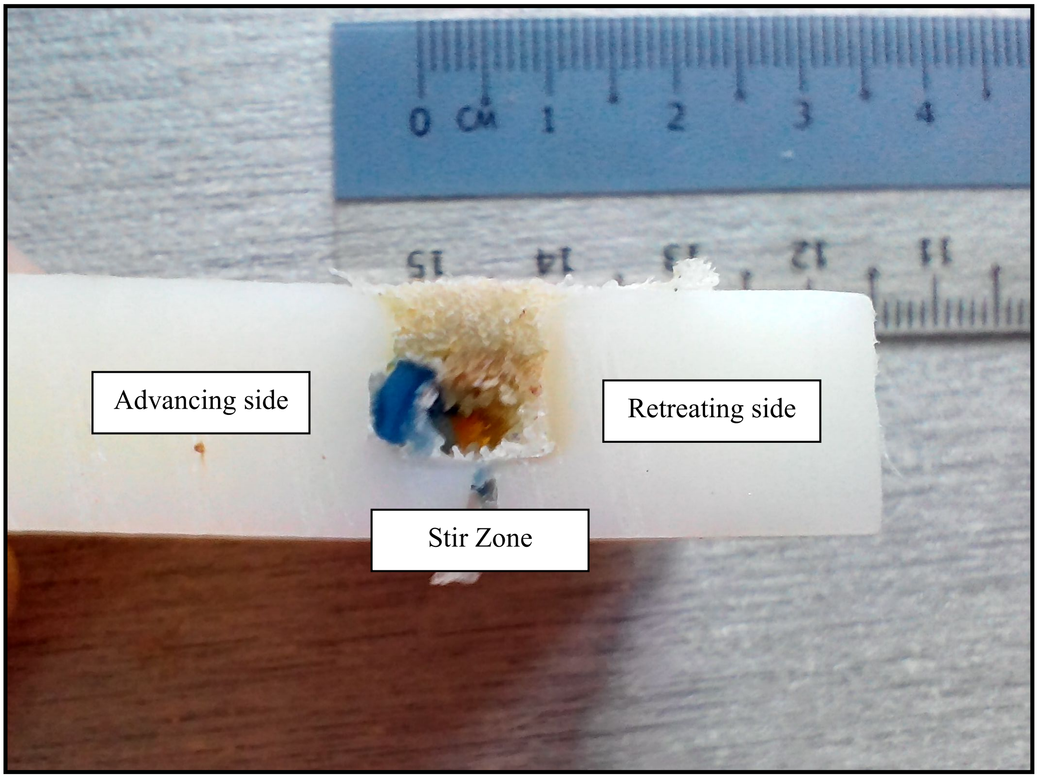


Figure 26 *Cross-section of the butt weld joint at 35 mm/min*

There is an obvious difference on the appearance of the weld joint in the third trial as compared to the previous trials. As the tool penetrates, there are white smoke from the stir zone with celery smell being detected throughout the process. Colloidal form of the material is deposited heavily on the retreating side of the weld joint. The colour of Nylon 6 material which occupy the space of the stir changes from ivory to brown colour. Excessive heating contributes to this colour change as the Nylon 6 material appears to be burnt from the heat produce at feed rate of 35 mm/min. For the cross sectional appearance, it is revealed that a rectangular hole about 0.4 mm thick can be seen at the stir zone which creates a hollow pathway along the whole length of the weld. Flow pattern of the material is difficult to detect as the blue colour of the marker deposits at the upper surface of the stir zone but with minimal visualization due to the changes in colour resulted via excessive heating.

D) Experiment 4

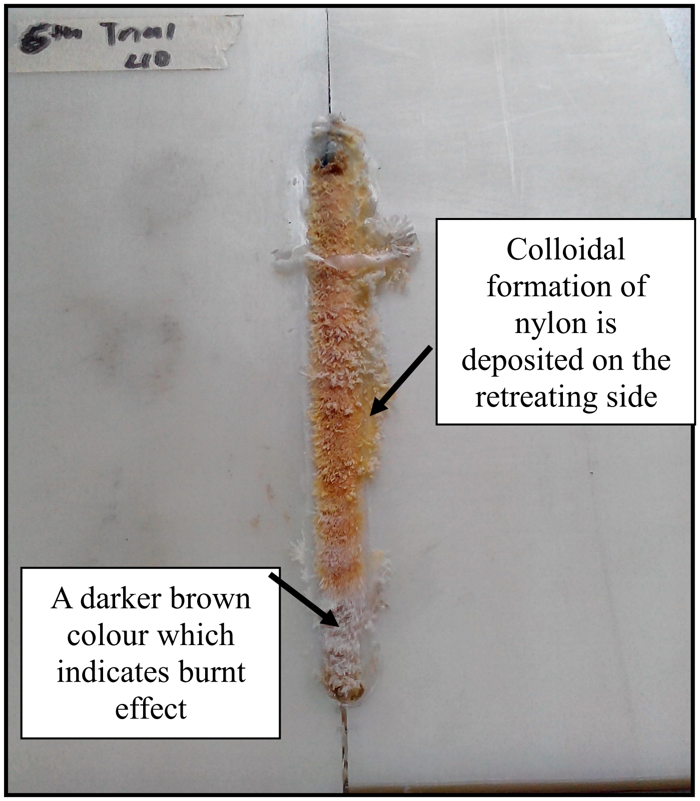


Figure 27 *Appearance on Nylon 6 Plates at feed rate of 40 mm/min*

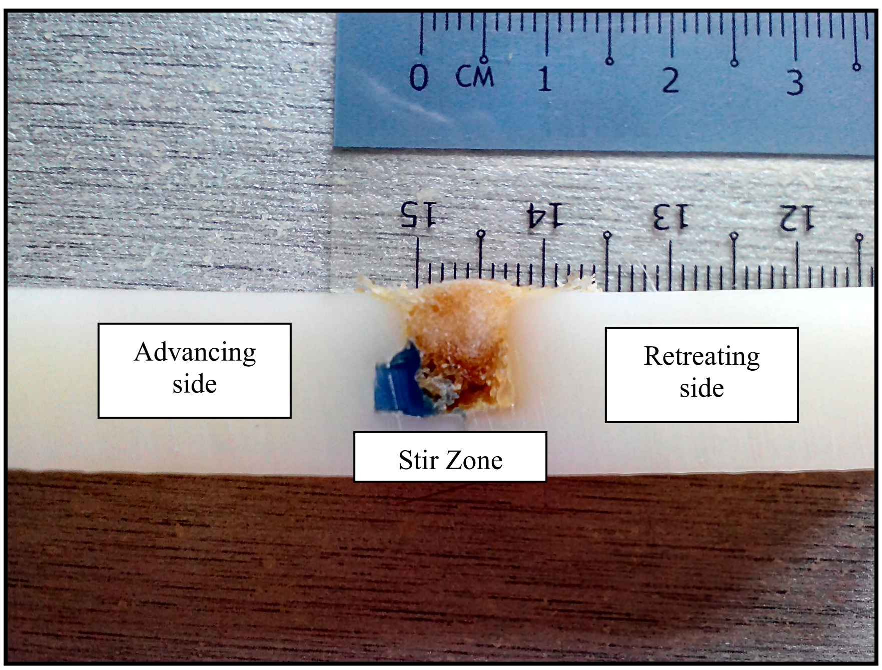


Figure 28 *Cross-section of the butt weld joint at 40 mm/min*

In experiment 4, the result shows nearly the same result as in experiment 3. The distinctive difference is on the colour of the nylon 6 material. Original ivory colour of the nylon 6 material changes to a darker brown colour which indicates burnt effect on to the material. Colloidal formation of nylon 6 is deposited on the reversing side of the joint. Small crystal formation is observed on the upper surface of the stir zone with a rougher formation situated on the early part of the weld length as dwelling time is slightly higher for penetration of the tool on the material. As for the cross sectional appearance, a worm hole with thickness approximately 0.5 mm from the bottom part of the stir zone is produced. The plates were broken of completely as bending stress is applied on them. The crack propagation starts at the bottom part of the butt weld joint as a gap of 0.02mm is located about 0.2mm from the bottom part of the weldment. The table 5 shows the overall data gathered from the four trials obtained.

***Table 6** Observation of Different Feed Rate*

Trial No	Spindle Speed (RPM)	Feed Rate (mm/min)	Weld Conditions
1	300	25	Full length welded without any visible defects. Strong in sustaining bending stress applied.
2	300	30	Welded but having hollow space in stir zone along the entire length of the weld.
3	300	35	Visible burnt marks from the colour change of the nylon 6 Colloidal form of the material is deposited heavily on the reversing side of the weld joint
4	300	40	Cross sectional appearance, a gaping hole with thickness approximately 0.5 mm from the bottom part of the stir zone is produced. Unable to withstand bending stress.

From the findings obtained, critical discussion can be made for further improvement in the effort to study the material flow behaviour of nylon during FSW. First, is on the method of detecting material flow behaviour. The findings revealed that it is possible to detect the flow of the material however it has a number of flaws which can be rectified. The groove with dimensions of (3mm x 5mm x 220mm) must be made with smaller dimensions. As observe at the cross section, although material flow can be seen, the blue colour makes up almost the entire stir zone. This contributes to the difficulty in differentiating the marker with the material's specimen thus observing how the material behaves during FSW.

In addition, the markers which were cut using a laser cutter machine were not cut exactly as the planned dimensions. The markers prepared appeared to be crooked as well as not being in a cuboid shape as desired. This is due to the high temperature of the laser which melts the marker material making it crooked. Another reason was due to the incompetency of the technician in operating the laser cutting machine as the personnel was quite new and didn't have much experience in handling the machine. For future research, special cutting tool is needed to avoid the flaws rose from this research.

Next is the effectiveness the technique used to detect material flow. The markers were place along the groove prepared which covers the welding length. This means that the markers did not fill up the entire length of the groove. As a result, there were less nylon material to be stir during FSW. When the tool penetrated the material and moved along the weld length, the markers were pushed forward which made them fill the hollow area of the groove. In addition, the defects on the markers contributes to the absence of the material which led to lack of nylon material in the stir zone eventually result in the loss of weldment joint strength..

Lastly is regarding the result of the material flow obtained. In experiment 1 and experiment 2, the material moved from the advancing side towards the retreating side and flows back again on the advancing side in a stagnant manner within the stir zone. When compared this findings with the research done by Pannerselvam and Lenin (2013), the material does not behave the same because of the different pin profile utilized in this experiment. The tool rotates in a clockwise direction with a non-threaded cylindrical pin profile with double shoulder. The design of the tool contributes to minimal excessive heat onto the material. The shoulder with smaller diameter provides a smaller surface contact that creates a lesser amount of heat than the larger shoulder but just enough to stir the nylon material. At spindle speed of 300 rpm, the FSW process seems to be the suitable spindle speed for FSW on nylon 6 material. Moreover, the feed rate that suits the nylon material will be at 30 mm/min or less provided that the pin profile used is a non threaded cylindrical profile with double shoulder. The figure below shows a FSW process on nylon plates under the same parameters without the marker.

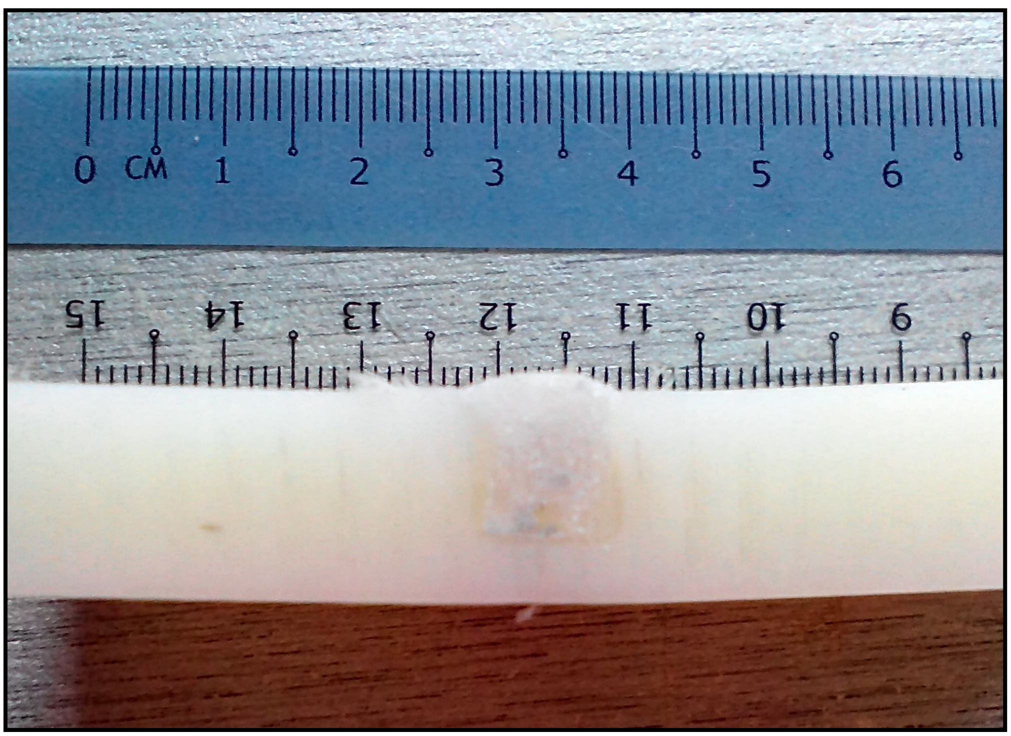


Figure 29 *Cross-section of the butt weld joint at 30 mm/min without markers*

CHAPTER 5: CONCLUSION

Based on the results, it can be concluded that the material flow behaviour of nylon plates during FSW is influenced by the type of pin profile as well as the parameter set for the FSW process. The straight cylindrical pin profile with double shoulder proved to produce a more desirable result as there was no nylon material stuck at the tool profile. It also can be concluded that nylon material flows form the advancing side to the retreating side as shown by the flow of the marker's blue colour.

Furthermore, the second objective for this project was also achieved where assessment on the effect of process parameters in the flow pattern was conducted. In this project, the process parameter that was being manipulated was only the feed rate. Thus at feed rates of 25 mm/min and 30 mm/min, the flow pattern of the material was stirred sufficiently within the weld zone. This makes the weldment stronger and making the nylon plates stick together. Feed rate which is above 30 mm/min result in the change in colour of the nylon material due to excessive heat produced.

CHAPTER 6: RECOMMENDATIONS

There is a need to further expand the potential of this method for improvements. One aspect is in the fabrication method of the marker.The machine used to cut the markers to the intended dimensions must be conducted by a competent technician. Reducing the dimensions of the groove as well as the coloured marker will aid the visibility of the material flow pattern. Moreover,the use of Scanning Electron Microscope (SEM) and Radiography will also ease the visibility of the material flow behaviour pattern. Further experimentation with desired parameters of interest should be explore by other researchers to suggest improvements to the FSW process.

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APPENDICES

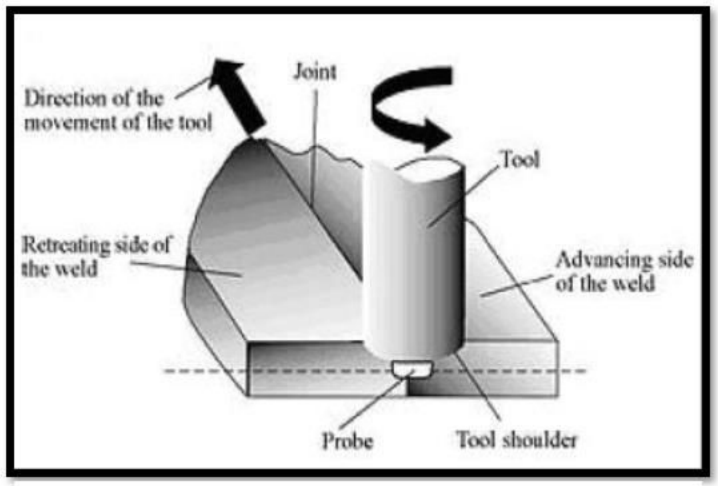

Figure 30 Schematic of FSW Process

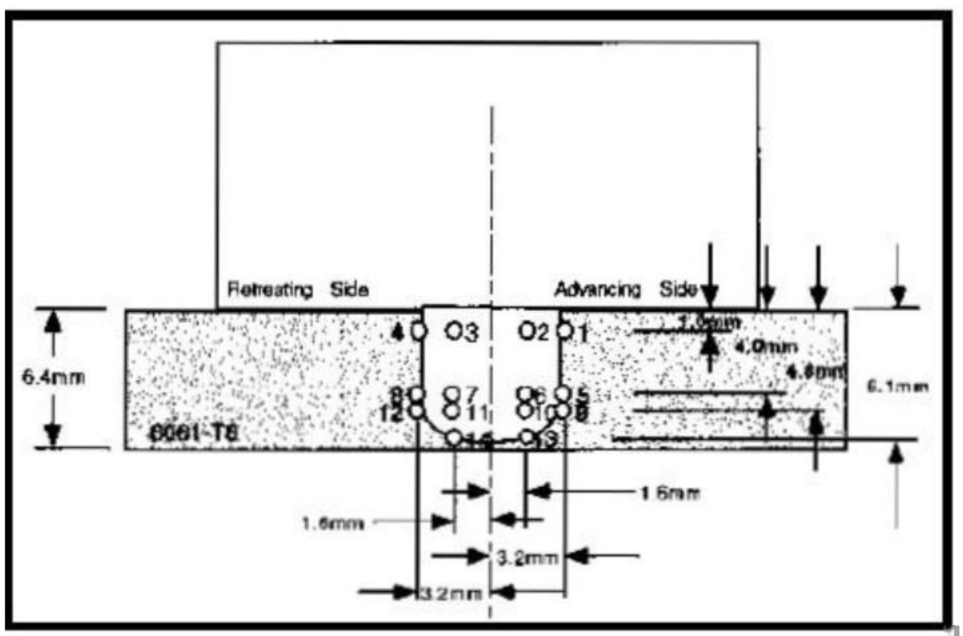

Figure 31 Tracer line positions for 6.4 mm Aluminium 6061-T6 plate. The groove containing the steel shot tracer material was oriented at various positions relative to the welding tool pin and at depths in the work piece plate.

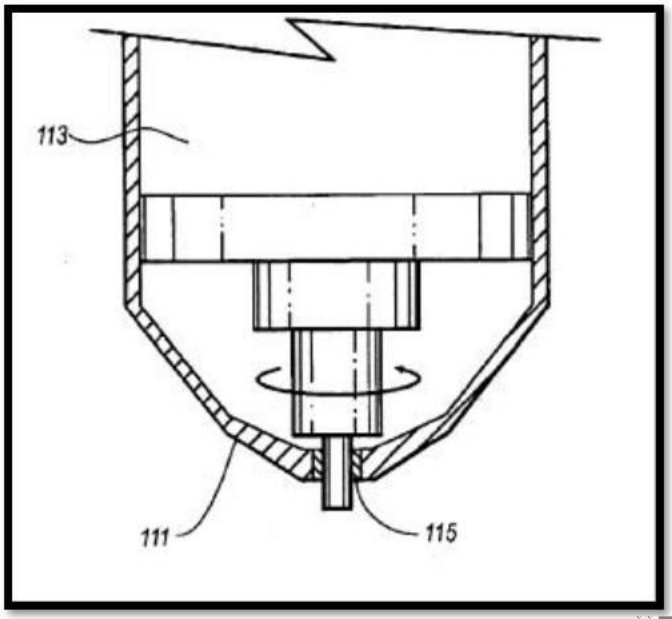

Figure 32 A schematic of a comparative spindle shoulder

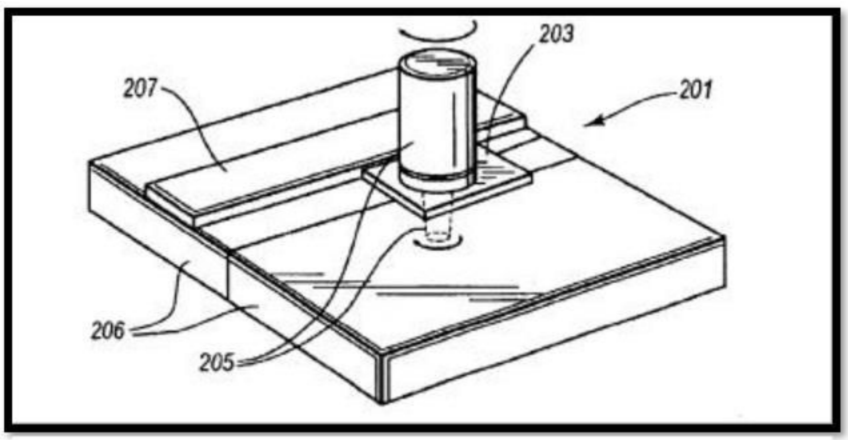

Figure 33 Constrained surface is the form of hot tool shoe

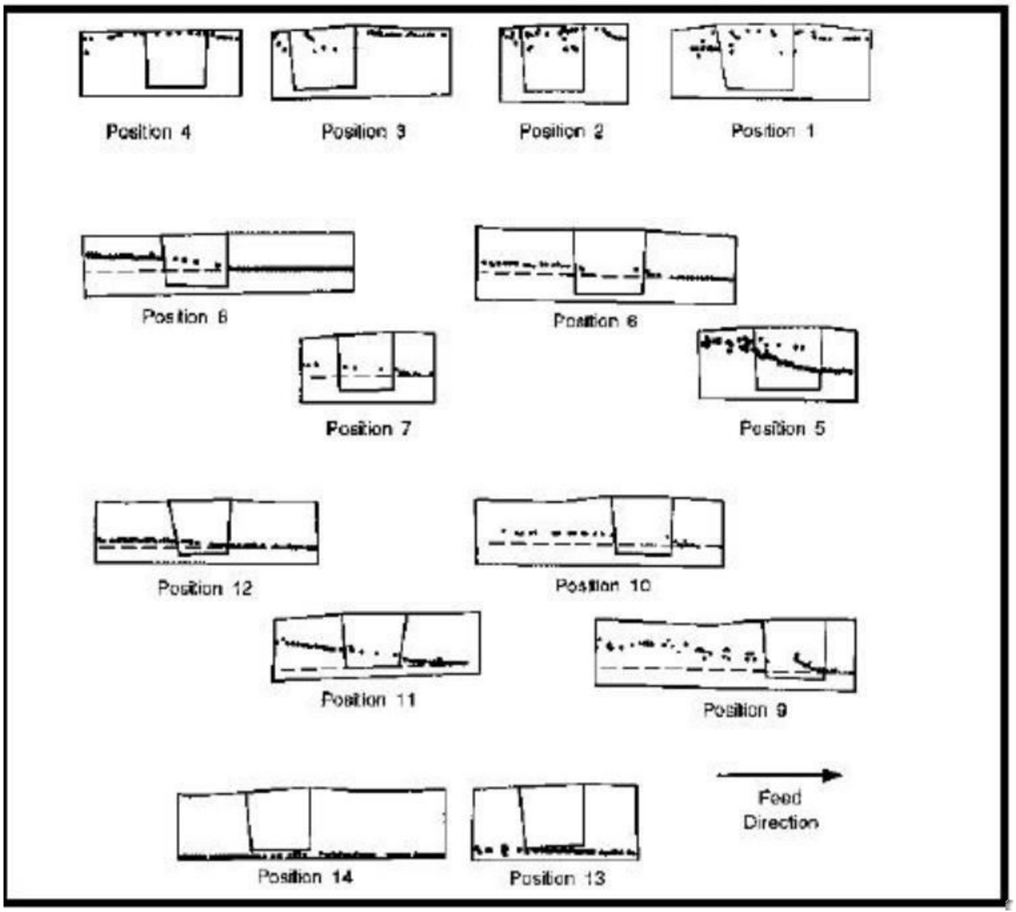

Figure 34 Drawings generated from each of the side view radiographs for the 6061 welds are shown above