Friction Stir Welding of High Density Polyethylene

By

Mohammad Afiq Syazwan Bin Ismail

Dissertation is submitted in partial fulfillment of
The requirement for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

MAY 2011

Universiti Teknologi Petronas
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Friction Stir Welding of High Density Polyethylene

by

Mohammad Afiq Syazwan Bin Ismail

A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

Approved by,

(Dr. Mohamad Zaki Bin Abdullah)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

May 2011

CERTIFICATION OF ORIGINALITY

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

MOHAMMAD AFIQ SYAZWAN

ABSTRACT

In this report, the progress attained in the Friction Stir Welding (FSW) on polymer project is depicted, evaluated, and discussed. FSW is a derivative of friction welding which uses a solid state joining process relying on the conversion of frictional energy into thermal energy to melt the joint. Two rotational speeds of 1300 rpm and 1400 rpm were used. Other parameters were transverse speed of 10 mm/min, dwell time of 40 seconds, plunge depth of 1.8 mm, and plunge rate of 8 mm/min were kept constant throughout the project. The effects of FSW on high density polyethylene (HDPE) were investigated in terms of their tensile and flexural strengths. Due to very limited studies on FSW techniques on polymeric materials, this project focused on HDPE. The project started with the construction of proper FSW equipment such as tooling and clamping device which involved designing and machining. The preliminary experiments were conducted with several rotation speeds and transverse rates while other parameters were held constant. Based on the preliminary results, the transverse rate was kept constant at 10 mm/min in the finalized experiments. Tensile and flexural tests were conducted. While the visual welded specimens showed a promising result, the best tensile strength was 8.9% compared to the original material. Meanwhile, flexural test was failed due to the root defect. The condition and location of the welded part examined using optical microscope.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

Friction Stir Welding (FSW) of polymer such as high density polyethylene (HDPE) can be initiated by introducing heat to the surface and the joint line of the polymeric sample. It is done by a cylindrical shaped tool with a pointed nib rotating and traversing at a certain preset speed. The material of the tool is usually steel or particularly Tool Steel H13.

The FSW method was originated from The Welding Institute (TWI), United Kingdom. It was first proven success in welding metals such as aluminum, steel, magnesium, zinc, and copper in 1991 by Thomas Wayne and his colleague [1]. It was quickly accepted in the domain of metal manufacturing and constant development in research has been carried out in terms of tool design, joint orientation, process parameters and weldable materials. FSW on polymer was later introduced in 1997 and is continually improving ever since [2].

The essence of FSW is it does not alter the mechanical properties of the material being weld. This is because the unique rotating tool only applies heat sufficient enough for the weld piece to soften without reaching melting point. Thus the joint are consolidated as the shoulder of the tool provides forging effect and traps the stirred material to fuse it together [3].

Furthermore, FSW procedure involves few simple steps and almost minimal preparation. The welding process commonly involves the use of CNC or conventional milling machine. Before undergoing welding process, the material to be weld has to be rigidly clamped on a vise or specially design jig. This is to avoid the abutting joint faces to be forced apart by the rotating tool. Then the tool that is mounted to the spindle of milling machine is rotated at a constant speed.

The rotating pin is plunged into the joint of the weld piece until the surface of the material intimately touches the shoulder of the tool. As the tool is rotating, it is left for a certain dwell time to allow the frictional force to generate heat. The tool is then transverse along the weld line with a constant feed rate stirring the softened material while the pressure from the shoulder acts as a forging effect allowing the material to solidify and joining together. The tool is then retracted once the welding finishes.

1.2 PROBLEM STATEMENT

FSW emerges in the joining applications to diminish the problems which arise from other existing methods such like fastening, bonding by using solvent or adhesive, and other welding methods like thermal and electromagnetic particularly. The existing joining processes are collectively involves tardy preparation and expensive machining, tooling and most of them require consumables. Bonding methods like adhesives and solvent involves the use of chemicals that releases toxic fumes and require the use of an extra apparatus and skilled worker. Most of the methods require longer process time and therefore are unproductive [2].

The urge for efficient and productive plastic joining is not only needed in production industry but also during repair and recycling as plastics has becoming the important material for numerous of applications and is highly demanded by consumer [4]. Therefore FSW is the best candidate for the task because of its advantages and it exhibits contradictive attributes comparing to other conventional joining methods. However, very limited efforts have been made to improve FSW for plastics. Therefore, this project is proposed to apply FSW method for plastic or particularly PE.

1.3 OBJECTIVES

The objectives of this project are:

- To determine the suitable parameter for FSW on HDPE.
- To investigate the effects of FSW technique of HDPE on the tensile and flexural strengths.

1.4 SCOPE OF STUDY

This project began with the construction of welding tools and appropriate clamping device for welding operations. The preliminary welding operations were conducted by using rotational speeds ranging from 1000 to 1500 rpm. The feed rates of the tool were tested from 6, 8, and 10 mm/min. The purpose of the preliminary test was to seek parameters that successfully welded HDPE samples. Tensile and flexural tests were conducted according to ASTM D 638 and ASTM D 790, respectively. The characteristics of the welded HDPE were examined using optical microscope.

CHAPTER 2

LITERATURE REVIEW

2.1 FSW AND PLASTIC JOINING

There are several methods of joining plastic that had been used in practice instead of FSW. In developing FSW as amenable joining process for polymeric materials, it is important to compare it against existing processes. Referring to Figure 2.1, the process of joining plastic parts falls into two major categories which are mechanical fastening and joining [5]. The difference between fastening and joining is fastening uses foreign body to mechanically joining two separate parts. It can be made to be permanently closed or re-openable for maintenance purpose but they require external parts and required substantial labor input. Meanwhile the joining secures part without foreign bodies. Bonding uses chemical reaction to create permanent joint.

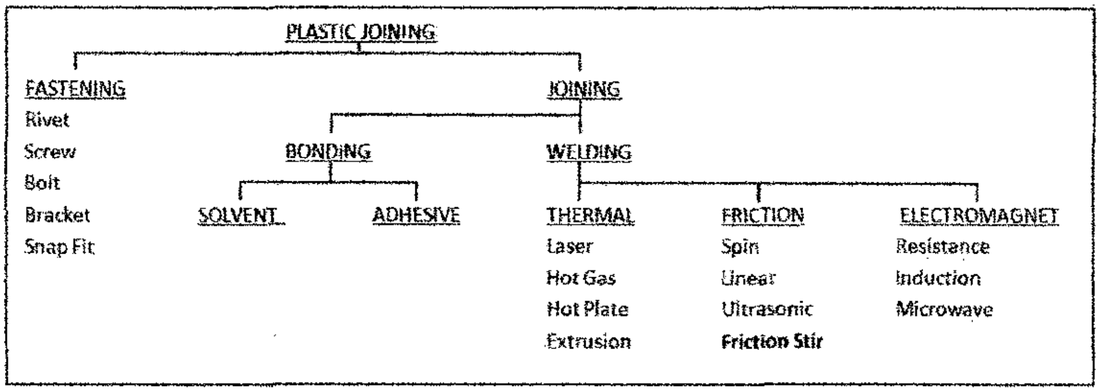


Figure 2.1 Plastic Joining.

All plastic welding techniques requires the melting of small portions of the part of the workpiece. Welding of plastic can be further divided to thermal, friction, and electromagnetic. Friction stir welding is a subcategory of friction welding along with spin, linear, and ultrasonic which share the same welding principle. Among the three of welding subcategory, FSW has been found the most applicable and practical method in joining plastic because of its convenient for pre-welded preparation, low process time, and operating cost, high repeatability, and efficiency [2].

2.2 OVERVIEW OF FRICTION STIR WELDING

Invented and patented by The Welding Institute, a British research and technology organization. The welding process is applicable to aerospace, ship building, aircraft, and automotive industries. The advantages of this welding technique are; the elimination of the welding defects namely crack and porosity often associated with fusion welding processes, reduced distortion, joint edge preparation not needed, can be carried out in all positions, can join conventionally non-fusion weldable alloys and improved mechanical properties of weldable alloys [4-6].

In FSW, a cylindrical-shouldered tool, with a profiled threaded or unthreaded probe (nib or pin) is rotated at a constant speed and fed at a constant transverse rate is plunged into the joint line of two firmly held HDPE sheet or plate. The length of the nib is slightly less than the weld depth required and the tool shoulder should be in intimate contact with the work surface. The nib which is responsible to produce frictional heating on work piece is then moved against it, or vice versa to stir the soften material [7]. The shoe is primarily responsible to trap the material displaced by the nib and holds the weld under pressure as it begins to cool. Additionally, the shoe smoothes any defects in the top surface of the weld [1].

2.3 FRICTION STIR WELDING OF PLASTICS

Since its introduction to plastics in 1997, FSW of polymers is considered new in its realm. Therefore, it is not surprising that limited sources and works had been published. Very few groups have reported performing research into the process as applied to polymers. The leading research groups are working at TWI and Brigham Young University (BYU). An extensive search revealed published results in three areas which are the dynamics of tool design, process parameters, and weldable materials [8].

Among the published literature, the information about the study of the structure of the welded material is unavailable. The study of the effect of the process on the structure of the polymer is also absent from the literature [9].

2.4 FSW TOOL DESIGN

There has not been much written literature or journal regarding on the details of FSW tool geometry. But generally FSW tools are necessarily cylindrical that contributes to the dynamics of the rotation. Commonly it has threaded or tapered or simply a cylindrical shaped nib or pin in the middle of a shoulder at the tip of the tool. The integrated geometry of the nib of the tool are designed and used depending on the material of the weld or joint position while this project uses only simple cylindrical shaped nib.

The desirable length of the nib is typically shorter than the thickness of the material being weld while the diameter is approximately equal to the thickness of the weld plates. The tolerable diameter of the shoulder may be three times the diameter of the nib [8]. The material of the tool that is being used for the project is Tool Steel H13 which is fabricated using lathe machine and undergone heat treatment afterwards.

2.4.1 Heating Shoe

Meanwhile, a researcher from Brigham Young University (BYU) has proposed a different method in tool design to produce a good weld by mounting an "add-on" equipment to the tool called a "shoe" as shown in Figure 2.2. The invention of the device begins due to the formation of the void on the surface of the weld line. The formation of the void occurred when the outer material cools much quicker than the inner, resulting a formation of a hard shell. As the inner layers then cool, the material contracts and pulls away from the shell. Large voids are formed which detract greatly from the mechanical performance of the welded joint [10].

The shoe traps the displaced material and promotes a uniform cooling rate throughout the weld volume by allowing pressure to be maintained for a longer time as the weld cools. Because more cooling and solidification of the weld occur under pressure, material shrinkage is more uniform, and void formation is reduced. It can be heated if additional energy is needed for proper fusion of the joint.

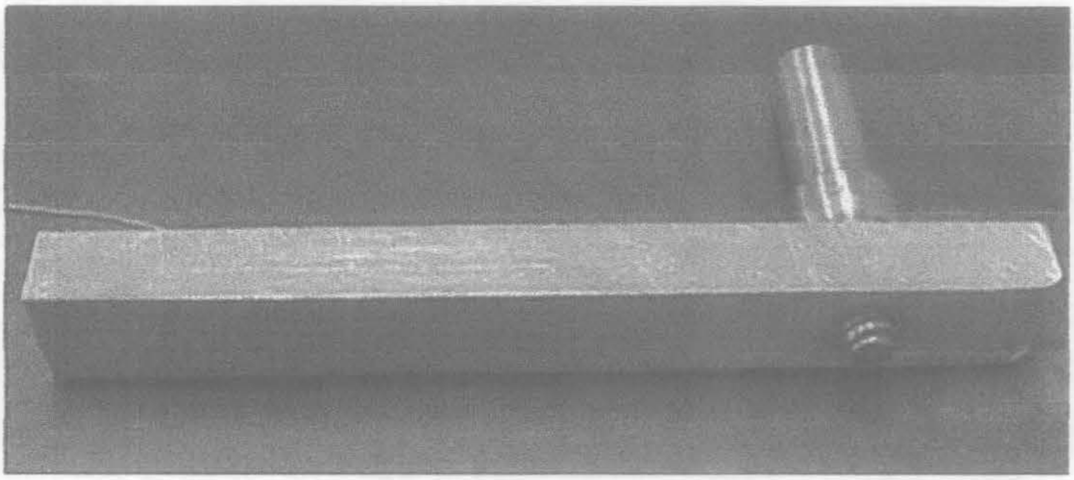


Figure 2.2 Heating shoe.

From the above reference, it is clear that the tool design affected the weld joint. However, regular tooling design is used for this project and further corrective measure or adjustment will be taken after the preliminary stage of experiment [10].

2.4.2 Double Pass Technique

A study from Kocaeli University, Turkey by Armagan Arici and Tamer Sinmaz has been able to eliminate the common weakness exhibited by regular FSW process on polymer. The regular FSW only perform a single tool pass on the surface of the joint line thus leaving the bottom part of the joint unwelded. The bottom area that was not welded is defined as root defect which is the weakest part of the weld region commonly responsible for all tensile and bending failures [8].

The research team proposed that in order to eliminate the root defect, the work piece has to be welded using double pass technique. In the first pass, the tool welded approximately half of the material and then they flip the sample for the second pass of the tool. With this technique they reported that no root defect appeared after the second pass and were able to retain up to 97% tensile strength of welded joint relative to the unwelded parent material [8].

2.5 ADVANTAGES AND DISADVANTAGES OF USING FSW

In general, FSW is claimed to produce stronger, lighter and more efficient welds than other joining process, with the ability to join materials previously thought to be unweldable, or no recommended for fusion welding. Specific advantages claimed for the process include [11]:

- The absence of melting resulting in less weld contamination.
- Cost efficient - no consumables.
- Minimal edge preparation involved.
- Very controllable process with high productivity.
- High integrity welds with low shrinkage and little porosity.
- Relatively simple process, with low running costs.
- Fine-grained microstructure in the weld region, leading to improved mechanical properties.
- Low distortion and residual stress levels, compared to conventional arc welding processes.
- Environmentally friendly – relatively quiet process, and releases no toxic fumes and spatter.
- No gas shielding required.
- Able to join wrought to cast product.
- Repeatable, resulting in less structural conservatism and possible over-design.

The current limitations of the FSW process are quoted as:

- Welding speeds slower comparing to some fusion welding process.
- Workpiece require rigid clamping.
- Backing bar required.
- Keyhole at the end of each weld.

2.6 SAMPLE MATERIAL

High density polyethylene or HDPE is a thermoplastic polymer made by the chemical industry and used in a wide variety of applications such as containers, dispensing bottles, wash bottles, tubing, plastic bags for computer components, and various molded laboratory equipment. HDPE is weldable or machinable, possess good chemical resistance, has high impact strength at low temperature, and can be process by any conventional method [12].

Table 2.1 Typical HDPE properties.

Maximum Temperature (°C)	120
Minimum Temperature (°C)	-100
Melting Point, T_M (°C)	135
Density (g/cm^3)	> 0.941
Hardness	SD65

2.7 INJECTION MOLDING

Since the workpiece of the weld need to be produced, it is important to know the process and parameters involved in injection molding. Injection molding process was chosen to produce the HDPE specimen because the workpiece will be welded in the dumbell shape. Welding the workpiece in this manner is better rather than welding it on a HDPE plate and cut it out into test specimen shape later on because the welding strengt could be affected in the cutting process. Injection molding process is a manufacturing process of forming a material part by heating the molding material until it can flow and injecting it into a mold [13]. In this case, the mold shape that was used is a dog bone shape according to ASTM D 638 standard.

Injection molding begins by feeding the pellet or granules into heated cylinder and the melt was forced into mold by rotating screw system of an extruder. As the pressure builds up at the mold entrance, the rotating screw began to move backwards under pressure and when sufficient polymer has built-up, the screw rotation will stop. Then, the screw was pushed forward by hydraulic cylinder, forcing the molten polymer into the mold cavity. After the polymer was solidified, the mold opened and ejector pins removed the molded part.

2.7.1 Parameters of Injection Molding Process

The injection molding process was operated via several parameters which were depending to the material that is going to be produced. Process control of injection molding involves the melt temperature, holding pressure, holding time, and injection pressure.

Melt temperature refers to the temperature of the cylinder of the machine which will control the melting of the material. The melt temperature was set based on the materials' melting point. Holding pressure is the pressure used for regulating and closing the mold. Holding time is the amount of time that the injection screw maintains pressure against the plastic after it has been injected into the mold. The force applied by the rotation screw to the melt material in the mold is called injection pressure.

The material that will be used for injection molding was pure low density polyethylene (HDPE) which has a melting point of 135^{0}C.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

The work starts with literature search on FSW and the material to be used for welding in this project. Then it proceeds with welding process after the suitable parameters for welding, tool material and geometry, and work piece material are determined. Figure 3.1 shows the project workflow of the whole project. After

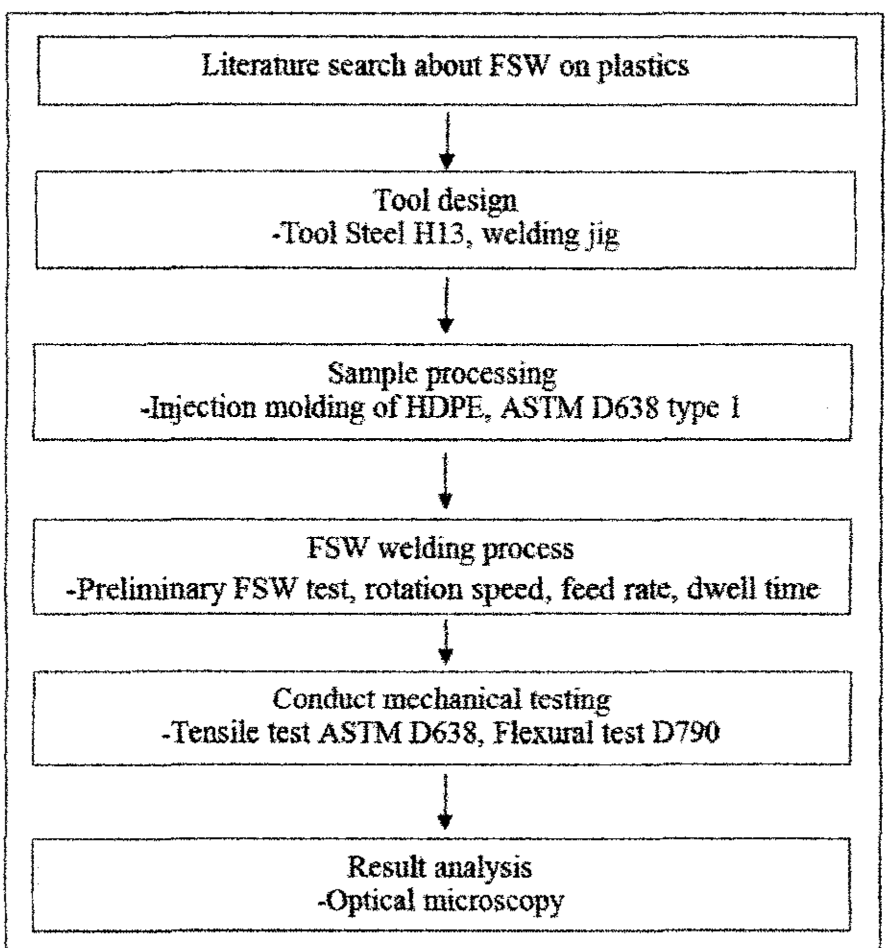


Figure 3.1 Project work flow.

undergoing the welding process, the welded sample was taken to be tested with Universal Testing Machine to determine the ultimate tensile strength of the welded sample relative to the base material. After that, the weld region will be analyzed visually using optical microscopy. This chapter will discuss the procedure throughout FYP 1 and FYP 2. The Gantt chart of FYP 1 and FYP 2 are presented in Tables 3.1 Table 3.2.

Table 3.1 Gantt chart of FYP 1.

No	Details	Week														
		1	2	3	4	5	6	MID SEMESTER BREAK	7	8	9	10	11	12	13	14
1	Selection of project topic															
2	Preliminary research work/ literature search															
3	Submission of preliminary report															
4	Project Work: investigation of proper tooling material & geometry															
5	Project Work:Familiarize with apparatus,machine,and material involved															
6	Submission of Progress report															
7	Seminar															
8	Project work: fabrication of the work piece material (PE)															
9	Project work: Preliminary experiments															
10	Submission of interim report final draft															
11	Oral presentation															

Table 3.2 Gantt chart of FYP 2.

No	Activities	Week																
		1	2	3	4	5	6	7	MID SEMESTER BREAK	8	9	10	11	12	13	14	15
1	Project work continues: Fabrication of Tool & Heat Treatment																
2	Perform Preliminary Welding Experiment																
3	Perform Welding Experiment																
4	Submission of Progress Report																
5	Tensile and Flexural Test																
6	Pre-EDX																
7	Submission of Dissertation(soft Bound)																
8	Submission of Technical Paper																
9	Oral Presentation																
10	Submission of Dissertation(Hard Bound)																

3.1.1 Tool & Weld Equipment

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. The depth of the pin or nib of the tool was slightly less than the depth of the welded material, which was 1.7 mm. The total length of the tool was about 71.7 mm. The diameters of the nib and shoulder were 4.0 mm and 10.0 mm, respectively (refer APPENDIX B). Tool Steel H13 was selected as FSW tool and was fabricated using CNC lathe machine. The tool used for FSW is displayed in Figure 3.2.

FSW tool should be sufficiently strong to avoid fracture to the small nib at welding temperature. Furthermore it should have good oxidation resistance and low thermal conductivity in order to minimize heat loss and thermal damage. To achieve this, the tool was heated after fabrication process which will be discussed in the next section.

A jig was included to hold the workpiec. The jig or clamping device offered a vertical holding forces which averted the abutting joint of the material from opening a gap while the rotation and transverse movement of the tool exerting horizontal force to the joint. Figure 3.3 below shows an example of a FSW jig.

Figure 3.2 FSW tool.

A pair of jig was designed particularly for this project where one was used to clamp tensile specimen and the other was for clamping flexural specimen. The jig was made from a 100 mm x 100 mm x 10 mm aluminum plate where a 2 mm slot is milled on the plate surface to fit the welded specimen. And then the specimen was held by two piece of aluminum plate using 4 pieces of 8 mm bolt.

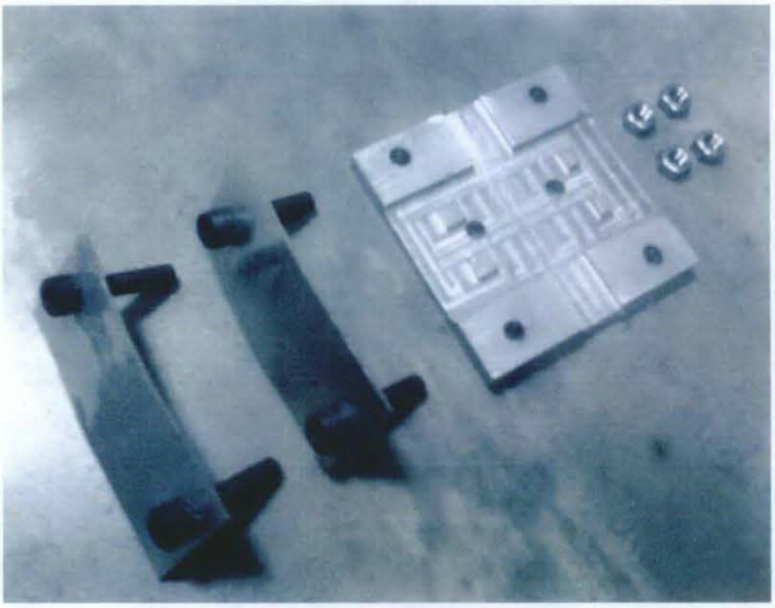


Figure 3.3 FSW jig.

3.1.2 Heat Treatment

Heat treatment process is also included in tool design section as the tool steel will undergo heat treatment process to further hardened it and increase its wear resistance. The heat treatment is necessary because Tool Steel H13 is normally delivered in the soft annealed condition. The purpose is to make the material easy to machine with cutting tools and to give it a microstructure suitable for hardening. The microstructure consists of a soft matrix in which carbides are embedded. Carbides are compounds of carbon that has very high hardness. Higher carbide content means higher resistance to wear [14].

In soft annealed tool steel, most of the alloying elements are bound up with carbon in carbides. Additionally, cobalt and nickel do not form carbides but instead dissolved in the matrix. When the steel is heated for hardening, the basic idea is to dissolve the carbides to such a degree that the matrix acquires an alloying content that gives the hardening effect without becoming coarse grained and brittle [15]. The temperature vs. time graph and heat treatment process is shown in Figure 3.4.

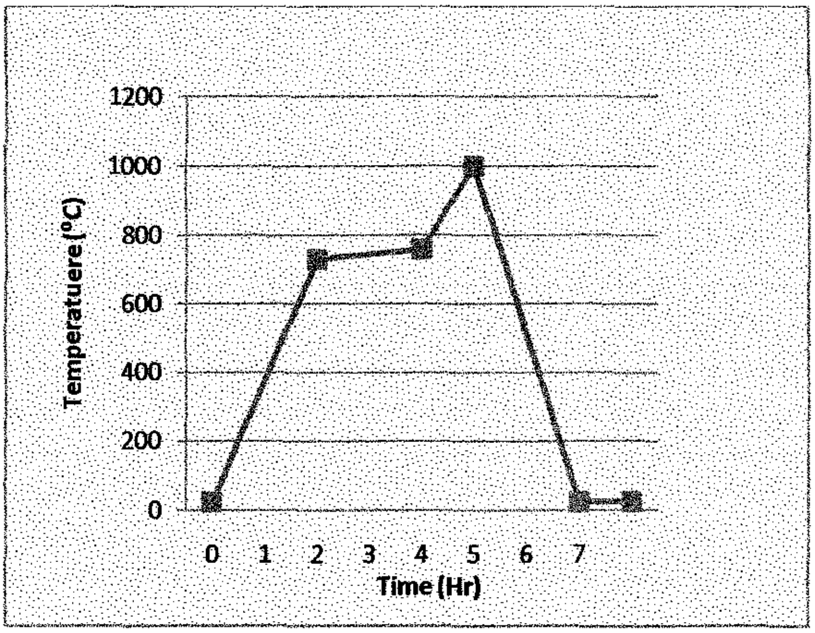


Figure 3.4 Temperature vs Time graph for heat treatment.

The heat treatment of the tool was carried out in the furnace and there were some changes to the color of the tool due to the oxidation process during heat treatment. Initially, the tool was inserted into the furnace and preheated for 2 hours to raise the temperature from 25°C (room temperature) to 724°C. As the tool is heated above the critical temperature, 724°C, it underwent a phase change, recrystallizing as austenite. The tool continued to be heated slowly to the hardening temperature, 724°C to 760°C for another 2 hours. Then the temperature was increased to 1000°C for 1 hour to ensure complete conversion to austenite. At this point the steel was no longer magnetic, and its color was cherry-red (refer APPENDIX A).

Then the austenitic steel was cooled (quenched) back to room temperature for 2 hours. Then a new crystal structure, martensite, was formed. Martensite is characterized by an angular needle-like structure and it has a very high hardness.

While martensitic steel is extremely hard, it is also extremely brittle. Internal stresses remain in the tool from the sudden quenching may facilitate breakage of the tool. Heating relieves these stresses and causes partial decomposition of the martensite into ferrite and cementite. The amount of this partial phase change is controlled by the temperature. The heated steel is not as hard as pure martensite, but is much tougher [16].

3.1.3 Sample Processing

The initial attempt of the project was to conduct a FSW welding on Low Density Polyethylene (LDPE). However, LPDE piece was failed to be welded due to its loose structure of molecular chain, HDPE was selected as a substitute sample to LDPE. In this project, 30 HDPE dogbone samples were produced using injection molding method at temperatures in the range of 200°C to 240°C. Some of the samples were used in tensile test using Universal Testing Machine and the other portions were used as welding work piece for FSW.

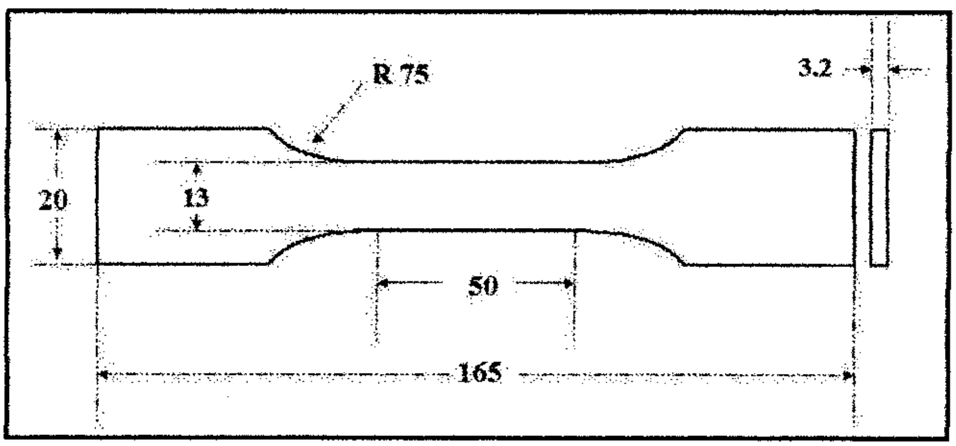


Figure 3.5 ASTM D638 Type I tensile specimen.

The preparation of HDPE tensile specimen was governed by ASTM D638 according to Type 1 tensile specimen dimension as shown in Figure 3.5. The raw material used was HDPE by Titan Chemicals, product code Titanvene™ HD6070UA which nominal density was 0.958 g/cm^3 and melting point of 132°C (refer Appendix C).

3.1.4 Preliminary Experiment

During preliminary experiment, multiple set of parameters were tested to find the suitable parameters that gives the best effects on the weld joint. As mentioned in previous chapter, the scope of study of this project is to study the effect of FSW parameter which is rotational speed on the weld quality. Therefore, the variable is rotational speed while feed rate are held constant. The feed rate of the tool will be varied in the preliminary stage to adjust to the weld outcome, but later on was set to constant in final welding process.

In the end of preliminary experiment, weld results were obtained and the suitable parameters for FSW works on HDPE were determined. The weld process was carried out with series of tests using rotational speed of 1000, 1200, 1300, 1400, and 1500 rpm. The feed rates of 6, 8, and 10 mm/min were tested. Other parameters set to be constant were plunge rate of 8 mm/min, plunge depth of 1.8 mm and dwell time of 40 seconds. Plunge rate is the rate of the tool is plunged from the touching point between pin and weld surface.

3.1.5 Welding Process

In this stage, the welding process will be carried out using the parameters that were determined in previous preliminary experiment. The product which is the welded specimen of HDPE will be used in tensile testing to obtain the ultimate tensile strength of the weld joint. The FSW process will be performed using Bridgeport CNC Milling Machine shown in Figure 3.6.

Figure 3.6 Bridgeport CNC milling machine.

The FSW process will be carried out on a HDPE sample in butt joint position. Referring to Figure 3.7 the material will be clamped in between a sacrificial plate which is of the same material as the work piece or the tensile specimen. A sacrificial plate is a "dummy" sample with material and size similar to the HDPE specimen that provides an extra space for the tool to transverse. The sacrificial plate and the weld specimen were inserted tightly in the slot of the jig and will be held down by another pair of aluminum plate. After the jig is place on the table of milling machine, the tool pin was brought close to joint line to make sure it is parallel to the tool path.

After the setup is finished, the tool is then rotated at speed of 1300 rpm for the first test and 1400 rpm for the second test. As the tip of the pin touches the surface of the tensile specimen, the tool is plunged at rate of 8 mm/min in between the joint line. After the pin reaches a depth of 1.8 mm in the work piece, it is left for 40 seconds of dwell time. The setting of plunge rate and dwell time of the tool is to ensure that the tool can generate enough heat in the polymer. After the dwell time is passed, the welding commences at a transverse speed or feed rate of 10 mm/min. Note that feed rate, plunge rate and depth, dwell time, and tool size are constant throughout the test whilst the only manipulated variable in this project is the rotation speed.

At the end of the weld line, the tool is retracted which usually leaves a hole marked by the pin of the tool which the FSW pioneers called "the keyhole" [17]. After the weld is finished, the welded samples were taken to the next stage of this project which is tensile test.

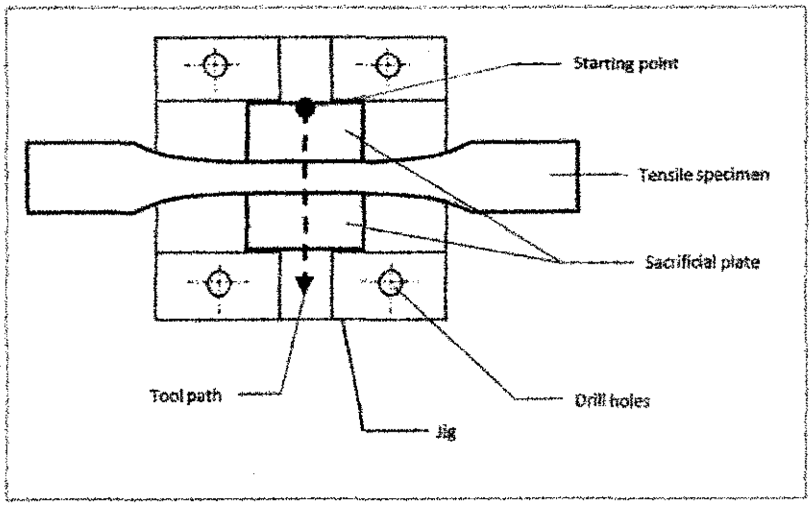


Figure 3.7 FSW weld layout.

3.1.6 Tensile Test & Flexural Test

The tensile test is the most common test to determine such mechanical property of a material such as strength. For the study in this project, the tensile strength and flexural test is the properties that will be consider. Tensile strength is defined as the stress at the maximum on the stress-strain curve in MPa or psi. Flexural strength is the measure of a bending strengt of a material.

To perform this test, a LLOYD Instrument LR5K, 5kN load Universal Testing Machine (UTM) will be used. The standard test method for the tensile strength was according to ASTM standard D 638. At least 5 specimens were prepared for each sample to be tested. Therefore a sum of 10 specimens was prepared to satisfy the testing of FSW with rotation speed 1300 rpm and 1400 rpm. Before the test specimen was mounted to the UTM, the width and thickness of specimens was measured at the center and within 5 mm of each end of gage length. When mounting the test specimen to the jig, the tip of the gripper was set 7 mm away from the gripping section of the test specimen. After the grippers are tight, the test can now be run until the specimen reaches the breaking point. The results of tensile and flexural tests were collected and discussed in the next section.

3.1.7 Optical Microscopy

After the mechanical tests were carried out, the specimens were then examined using optical microscopy. The optical microscopy was used to observe fracture locations of the weld or any signs of void or cracks in the weld region.

CHAPTER 4

RESULT & DISCUSSION

4.1 FRICTION STIR WELDING OF HDPE

This section will discuss about the testing that have been conducted and how the data will be analyzed. Since the initial FSW test on LDPE has proven to be unsuccessful, HDPE has been chosen as substitute because it has higher density compared to LDPE. The reason that LDPE is unweldable using FSW and Tool Steel H13 is because of the material structure and physical properties itself. Comparing to HDPE, LDPE possesses a molecular structure that is less compact and is much softer than HDPE.

Several trials were conducted to determine the suitable parameters to produce a successful welding. The parameters that were used in the preliminary test and their results were summarized in Table 4.1. Rotation speeds and feed rate are varied in the preliminary test while other variable are held constant.

Table 4.1 FSW preliminary test result.

Test num.	Rotational Speed (rpm)	Feed Rate (mm/min)	Remarks
1	1000	8	Weld unsuccessful
2	1000	10	Weld unsuccessful
3	1200	6	Weld unsuccessful
4	1200	8	Semi joining
5	1200	10	Semi joining
6	1300	8	Semi joining
7	1300	10	Weld success
8	1400	10	Weld success
9	1500	6	Weld unsuccessful
10	1500	10	Weld unsuccessful

From the remarks, weld unsuccessful denotes that the welding was not successful and the joining of the material does not occur. Instead of fusing the material together, the rotational friction gives the drilling effect in which it leaves a lot of residue or dust caused from material deposition by the pin. This parameter only produces a trail of gutter line instead of weld line as shown in Figure 4.1. Meanwhile semi joining means that the weld is successful and the weld result shows that the material is plasticized and accumulated behind the pin trail.

However the weld is not strong and easily breaks due to insufficient heat contributed by the rotation or the feed rate of the tool. This is because polymer like HDPE possesses a loose and large molecular chain in contrast to metals which atoms are positioned in orderly and repeated pattern [18]. Hence the frictional heating generated merely by the rotating tool was not uniform. Seth Strand reported in his paper that by using external heating element, he was able to eliminate the voids and improve the mixing in the weld region. The heating element which called "shoe" is a solid cuboid with a built-in heater and a hole drilled for the pin [10].

Figure 4.1 Unsucessful welding sample.

The weld success remarks that the material is successfully joined and it exhibits good material fusion on the weld line. The test number 7 and 8 are then used in the final welding process because of their fine weld products as shown in Figure 4.2. The HDPE sample exhibits a fairly fine joint finishing after the weld. Although tensile test result proves quite unsatisfactory, there are other improvising measures and technique to be implemented in the future study to increase the strength of the joining. The weak joining of the weld produced in this project is caused by insufficient heating that is hard to be attained. From the Figure 4.2, notice how the stirred HDPE left a "ripple-like" form caused by the stirred material deposited by the tool pin. At the edge of weld line where the tool is retracted, there was a "key hole".

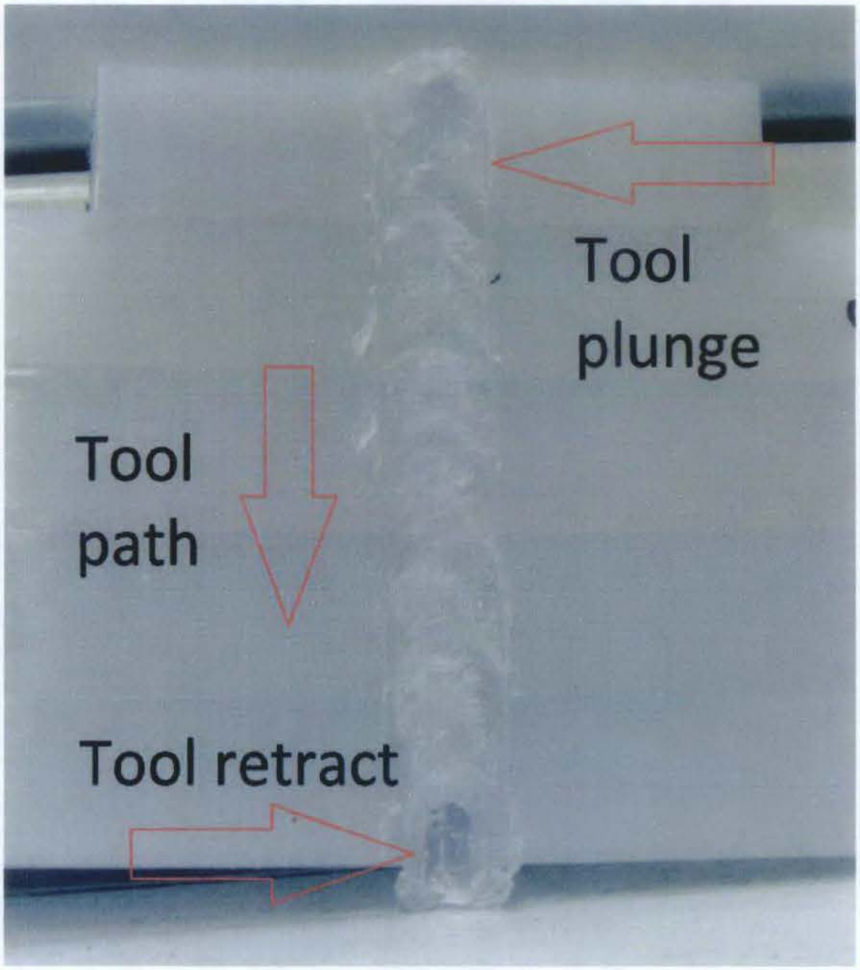


Figure 4.2 A welded HDPE piece.

4.2 TENSILE TEST & FLEXURAL TEST

The test started with pure HDPE samples to obtain its original tensile strength value, and then the test was repeated with other two sets of test specimen. Tensile strength data were then obtained and tabulated in the Table 4.2

From the result, we can observe the distinction in tensile strength value between the two sets of parameter. The welded samples were fractured without showing a yield necking. Although the tensile value of the welded sample was very low compared to the original HDPE, the welded samples showed visually successful in welding

HDPE samples. There is still room for improvement to be taken into consideration to increase the strength of the joint. The reason that the value of the tensile strength of the welded sample was low because of the existence of root defect and the welded sample was already prone to break before being pulled in UTM because there was a gap underneath the weld pool that was not joined during FSW.

Table 4.2 Tensile strength result.

Sample type/num.	Tensile Strength (MPa)		
	Unwelded Original HDPE SPECIMEN	Specimen welded with 1300 rpm	Specimen welded with 1400 rpm
1.	26.8	1.3	1.4
2.	26.9	1.1	2.1
3.	27.5	0.6	3.3
4.	27.2	0.8	2.7
5.	27.8	1.1	2.3
Average	27.2	1.0	2.4
Standard Deviation	0.4	0.3	1.0

The result indicates that the specimens that were welded with rotation speed of 1400 rpm are better compared to the specimens welded with 1300 rpm rotation speed. Tensile values of each parameter are 3.7% and 8.9% respectively compared to the original HDPE specimen. The data from Table 4.2 were used to create an ultimate tensile strength versus sample type graph as shown in Figure 4.3.

The flexural test conducted on welded HDPE sample was failed to produce any results because of the root defect. The root defect and the pressure from the tool plunge causing the flexural sample to bend after the welding is finished. All welded flexural sample exhibit similar error when the flexural test was carried out. Therefore the test could not be run and the result was invalid to be evaluated and discussed.

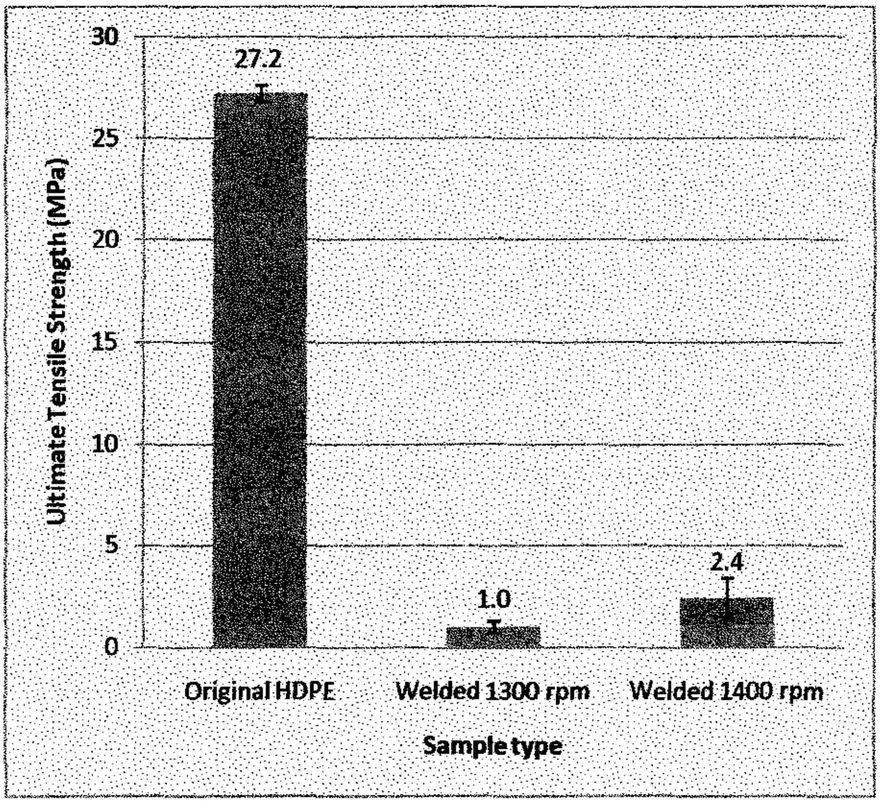


Figure 4.3 Bar chart and error bar of tensile strength result.

4.3 OPTICAL MICROSCOPY

Figure 4.4 shows the region of which a HDPE was photographed. The fractured welded specimen was then viewed and photographed using an optical microscope to observe the fracture of the weld. Figures 4.5 and 4.6 showed the pictures of a microscopic view of a weld and the fracture that was taken at 5x magnification. The sample shown was welded with 1400 rpm rotational speed.

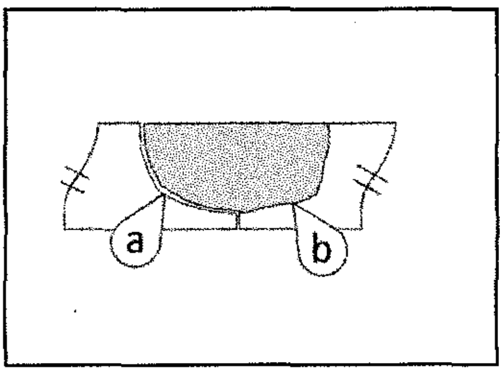


Figure 4.4 Region of where FSW sample is photographed.

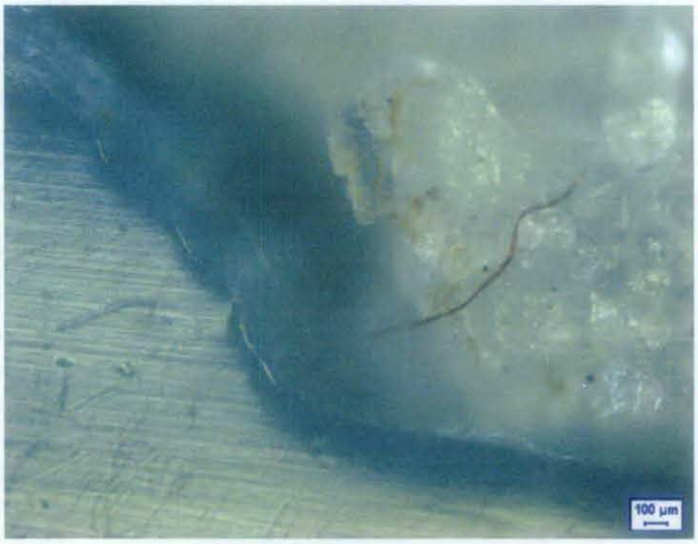


Figure 4.5 Region (a) which indicate the type of fracture.

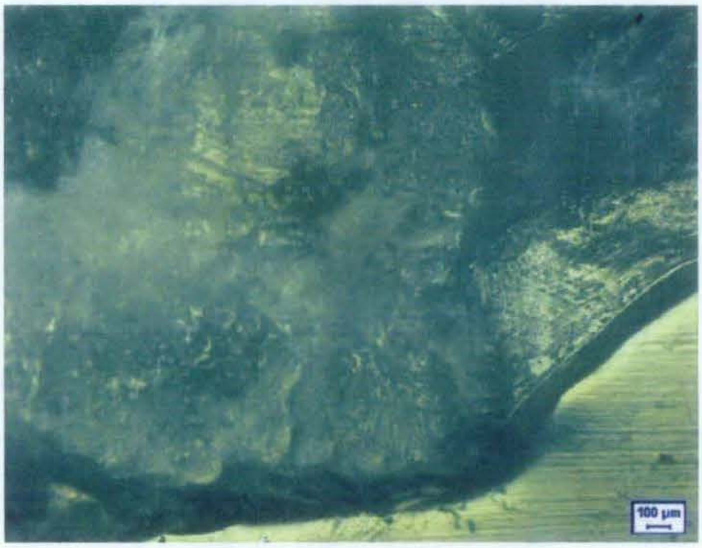


Figure 4.6 Region (b) which shows the structure of weld pool.

From the optical microscopic figure, we can see that the crack initiated from the gap at the base of the material and through either side of the weld. Figure 4.6 shows that there is no void or crack formation in the weld, however the fracture prone to occur because of the gap underneath the weld which has high stress concentration.

CHAPTER 5

CONCLUSION

5.1 CONCLUSION

The following conclusions can be drawn from this study:

- FSW on HDPE was proven to be successfully feasible using existing tool and equipment at UTP.
- Rotation speed of 1400 rpm and feed rate of 10 mm/min showed promising results of FSW on HDPE. Visually, the specimens were welded.
- Very low tensile strength was achieved. Th best result was 8.9 % compared to the original HDPE specimen.

5.2 RECOMMENDATIONS

Based on the observations and tensile strength results, the following recommendations are proposed:

Research on external heating elements for FSW on polymer material should be explored. With the utilization of the external heating element, the forging rate of the stirred material can be extended, allowing the welding to achieve uniform cooling. The external heating element was found to be capable to eliminate cracks and voids of the welding as reported by Seth R. Strand [10].

Furthermore, in order to rectify the drawbacks of the tensile strength of the welded polymer obtained in this project and to eliminate the root defect. Double passing method should be performed in order to eliminate the gap which is the weak point where the stress is concentrating at that region. It is recommended to perform the weld at the top and the bottom of the joint line as reported by Armagan Arici and

Tamer Sinmaz. They managed to obtain the tensile strength of 97% compared to the original MDPE specimen [8].

Tooling geometry and material should be further investigated to improve welding quality. Pin shape such as tapered/non tapered or threaded/non threaded should be included in the studies. It was believed that the pressure applied to the tool by the shoulder also played an important role in controlling the stirred material. Furthermore, the effect of tool tilt angle should also be taken into account as well [8].

REFERENCE

1. Kallee, S.W. 2006, *Friction Stir Welding at TWI*, The Welding Institute (TWI).
2. Seth Strand, 2003, *Joining Plastics-Can Friction Stir Welding Complete?*, Brigham Young University.
3. Carter, B. Lawless, K. Dr. Arthur, N. Carolyn, R. Michael, S. Dr. Judy, S. 2009, "A Decade of Friction Stir Welding R&D at NASA's Marshall Space Flight Center And a Glance into the Future", NASA.
4. Thomas, W.M. Nicholas, E.D. Needham, J.C. Murch, M.G. Temple-Smith, P. Dawes, C.J. 1991, "Friction-stir butt welding", *Journal of The Welding Institute*, **13(4):**123-143 .
5. Stokes and Vijay K. Oct 1989,"Joining methods for plastics and plastics composites: an overview", *Polymer Engineering and Science*, Society of Plastics Engineers, Inc., **29(19):** 1313.
6. Boz, M.and Kurt, A. 2004, "The influence of stirrer geometry on bonding and mechanical properties in friction stir welding process", *Material Design* **25:** 343.
7. Nicholas, E.D. 1998, "Developments in the friction-stir welding of metals". *ICAA-6: 6th International Conference on Aluminum Alloys*. Toyohashi, Japan.
8. Armagan, A. and Tamer, S. 2005, "Effect of Double Passes of The Tool on Friction Stir Welding of Polyethylene", *Journal of Material Science* **40:** 3313-3316.
9. Nelson, T.W. 2000. "Joining of thermoplastics with friction stir welding" *2nd International Symposium on Friction Stir Welding*, Gothenburg, Sweden
10. Seth R. Strand, April 2004, *Effects Of Friction Stir Welding On Polymer Microstructure*, Master of Science Thesis, Brigham Young University.
11. Harris, D. & Norman, A.F. 2003, *Properties of Friction Stir Welded Joint: A Review of Literature*, Progress Report Presented at the 6th PSG Meeting, EUROSTIR.
12. Roger D. Corneliussen, 2002 <http://www.maropolymeronline.com/Properties/HDPE%20Prop.asp>.
13. S. Kamaruddin, Zahid A.Khan and K.S. Wan, "Optimization of the Injection Molding Parameter Using the Taguchi Method," *Journal of Mechanical Engineering* **54**, 79-93.

14. Qamar, S.Z. Sheikh, A.K. Arif, A.F.M. Perves, T. Siddiqui, R.A. , 2007 "Heat treatment of Hot Work Die Steel", *Achieves of Material Science and Engineering*, **28(8):** 503-508.

15. Spencer, M., 2007 "Heat Treatment of the Tool Steel", Material Safety Data Sheet, 6th edition,UDDEHOLM.

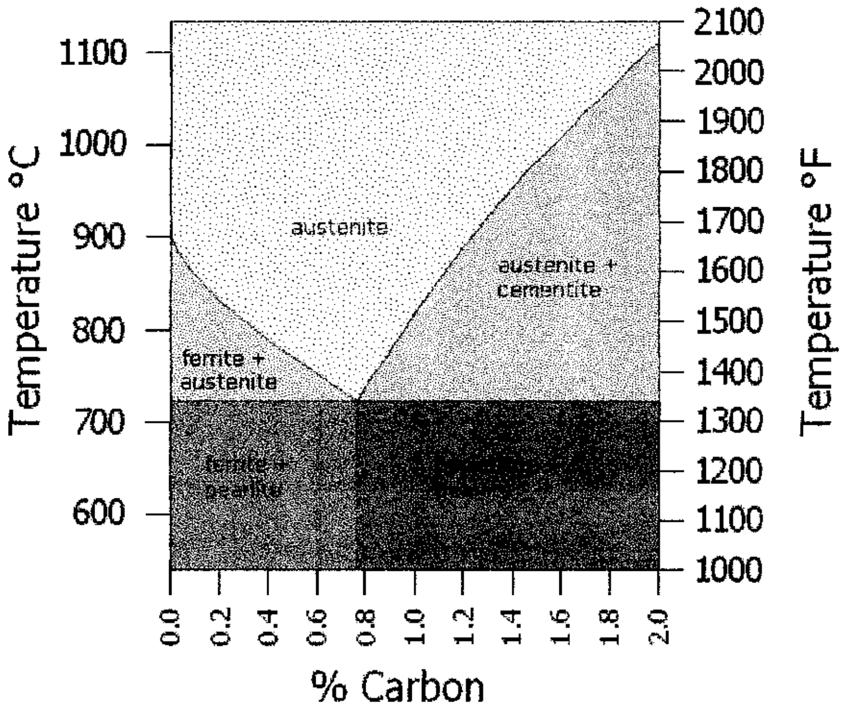
16. Peter L Berglund, Sept 6, 2010 <http://www.threeplanes.net/toolsteel.html>.

17. John Jones, May 1, 2011 <http://www.sti.nasa.gov/tto/Spinoff2008/ip_4.html>.

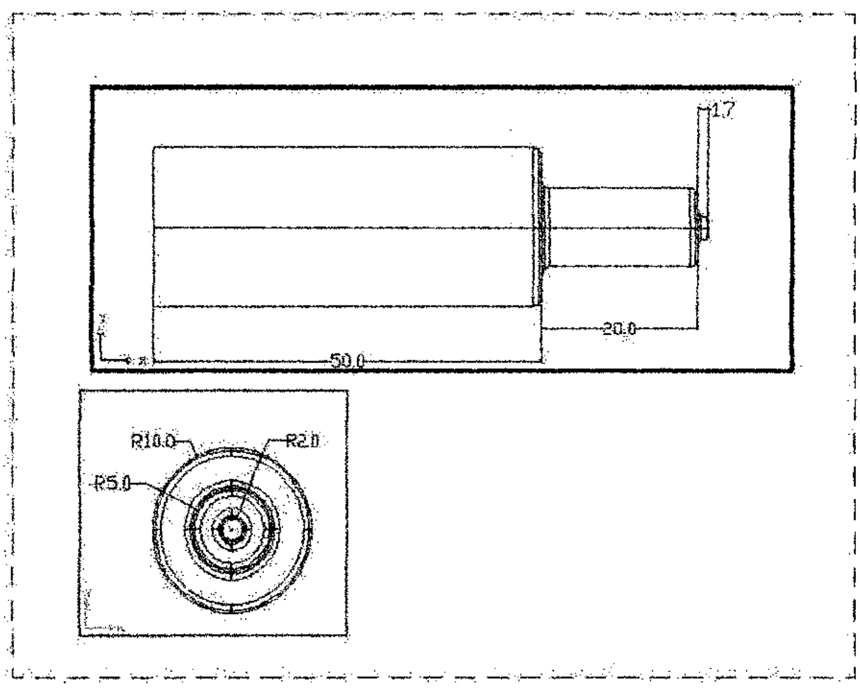
18. Callister, W.D. 2007, *Material Science and Engineering: An Introduction*, Iowa, John Wiley & Sons.

APPENDICES

APPENDIX A: Simplified Fe-C Phase Diagram (Steel Portion)



APPENDIX B: FSW tool dimensions



APPENDIX C: HDPE product data sheet

TITAN CHEMICALS

PT. TITAN Petrokimia Nusantara

Product Data Sheet

Jl. Raya Merak Km.116
Cilegon 42436, Banten
Indonesia
Phone +62 254 571333
Fax +62 254 571290
Website : www.pttitan.com
E-mail : tsc@titangroup.com

Titanvene™ HD6070UA

General Injection Moulding Applications

Titanvene™ **HD6070UA** is a high density polyethylene copolymer with a narrow molecular weight distribution protected by a UV stabilizer for outdoor exposure. Titanvene™ **HD6070UA** is suitable for a wide range of injection moulding applications. Titanvene™ **HD6070UA** is characterised by its easy processing, high rigidity/good impact resistance and high warpage resistance.

Applications
Titanvene™ **HD6070UA** is designed for:
- Crates, pails and containers.
- Pallets, structural foam and seats.

Recommended Processing Conditions (1)
Titanvene™ **HD6070UA** can be easily processed on normal polyethylene injection moulding machines at temperatures in the range of 200°C to 240°C.

Food Contact Compliance
Titanvene™ **HD6070UA** can be used in food contact applications. Please contact your nearest PT. TITAN Petrokimia Nusantara representative for more detail of food contact compliance statements for the specific grade.

General Properties	Value (2)	Unit	Test Method
Melt Flow Rate (190°C/2.16 kg)	7.5	g/10 min	ISO 1133 Condition 4
Nominal Density	958	kg/m^3	ISO 1183 Method D
Vicat Softening Point	127	°C	ISO 306
Melting Point	132	°C	ISO 3146 Method C

Mechanical Properties (3)	*Value* (2)	*Unit*	*Test Method*
Tensile Stress at Yield	27	MPa	ISO/R 527 Type 2 Speed C
Elongation at Break	1500	%	ISO/R 527 Type 2 Speed C
Charpy Impact Strength	6	kJ/m^2	ISO 179 Type 1 Notch A
Flexural Modulus	1500	MPa	ISO 178
ESCR Condition B, F_{50} (4)	7	Hours	ASTM D1693

(1) The optimum processing conditions can be different from one machine to the others, depend on the mould and part design.
(2) The values shown are typical values obtained by averaging a number of tests. Small divergences from the quoted figures may occur.
(3) Measured on compression molded plaques.
(4) Environment Stress Cracking Resistance 10% Igepal : CO-630

" World's 1st Halal Certified Resins - preserve integrity, wholesomeness & hygiene "