Investigation of Friction Stir Welding Tool Wear on Different Hardening Method

by

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

JANUARY 2015

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the

Mechanical Engineering Programme

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In partial fulfilment of the requirement for the

BACHELOR OF ENGINEERING (Hons)

(MECHANICAL)

Approved by,

____

(Dr. Mokhtar Awang)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

January 2015

CERTIFICATION OF ORIGINALITY

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

MUHAMMAD AMRI BAHRI BIN SUNIF

ABSTRACT

The use of non-heat treated and non-hardened tool steel on normal Friction Stir Welding (FSW) application will result in severe deterioration and wear of the tool steel itself for short period of time. Therefore, the main purpose of carrying out this project is to reduce the wear of the tool by investigating the effect of hardening methods on the Friction Stir Welding (FSW) tool wear. The hardening method considered in this project are heat treatment and gas nitriding. Once the hardening process are applied to the tool steel, the wear resistance performance of the tool steel are evaluated with respect to the hardening method applied. This project is basically divided into three main parts. The first part is the welding tool fabrication, the second part is carrying out the hardening process, and the third part is performing FSW on the Al-6061 plates. The first part of the project which is the fabrication process involves the process of designing the welding tools and machining them. In the second part of the project, the fabricated tool steel will undergone several hardening process which includes the heat treatment and gas nitriding process. The third part of the project involves the FSW performed on the Al-6061 plates after the tool has been hardened. Hardness testing and wear measurement are carried out after that in order to determine and evaluate the hardness and wear of the tool. At the end of the experiment, the results obtained are analyzed in order to determine the effectiveness and feasibility of the hardening methods applied in reducing the FSW tool wear. Tool steel that is heat treated and nitrided shows the best wear resistance performance and hardness while the untreated/raw tool steel shows the worst. Meanwhile, the nitrided only tool steel shows better wear resistance performance and hardness than the heat treated only tool steel. Gas nitriding of H13 tool steel at high temperature by using nitrogen gas only is applicable and practical from this study.

ACKNOWLEDGEMENT

The author of this dissertation would like to take this opportunity to express his utmost appreciation and gratitude to every single person who directly or indirectly involved in assisting the author throughout the journey of completing this project. Without their help, surely this project would not be able to be completed smoothly and successfully. First and foremost, the author would like to thank the project's and also the author's supervisor, Dr. Mokhtar Awang for all his precious guidance, advice, and assistance given throughout this Final Year Project journey. Without him, there is no doubt that this project could not be completed within the given timeframe. The author also would like to express his sincere gratitude and appreciation to all the graduate assistants involved, Mr. Sattar, Mr. Adeel, and Mr. Hassan and the technicians involved, Mr. Jani, Mr. Adam, Mr. Shairul, Mr. Danial, and Mr. Saiful for giving their precious time to help and assist the author's project works and lab works. Their help means a lot to the author because without their help, this project surely cannot be completed. Last but not least, the author's thankfulness goes to his family and friends for their endless moral support throughout this challenging journey.

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ABBREVIATIONS AND NOMENCLATURES

FSW – Friction Stir Welding

Metal Matrix Composites – MMC

Tungsten Carbide – WC

Chemical Vapor Deposition - CVD

CHAPTER 1

INTRODUCTION

1. INTRODUCTION

1.1. Background of Study

Friction Stir Welding (FSW) is relatively new and innovative joining technique which has a great potential to weld similar or dissimilar materials that can be considered difficult to weld by conventional fusion welding process [1]. In FSW, a rotating tool is used and pushed along the joint line of the two materials. Frictional heat will then be generated from the rotation of the tool against the material surfaces thus ease the plastic deformation of that particular material. The softened materials will flow around the tool and form a solid-state weld behind the tool due to the consolidation of the stirred materials [2].

Friction Stir Welding also is one of the welding processes that is widely used in many industrial applications. Some of the industrial applications include ship building and offshore, aerospace, automotive, robotics and even personal computers [3, 4]. The reason is mainly because of the outstanding advantages and benefits [5, 6] that it offers which include:

- Provides opportunities for new solutions to old joining problems.
- It is a ‘green’ process due to its low energy input and lack of fumes, gases and etc. that results from the process thus makes friction stir welding friendly to the environment.
- It has no gas shielding for welding aluminium.
- The products of the welding process have excellent mechanical properties in fatigue, tensile and bend tests.

Due to its extensive use in various industrial applications, the need for better quality tool steel that possesses high hardness and wear resistance performance become higher to reduce tool wear, prolong tool service life and also enable FSW of harder materials. One of the way to produce harder and less wear tool steel is by applying hardening methods to the tool steel rather than just simply changing the tool steel material. Therefore, this research will look into several hardening methods that can be applied to as-received tool steel in order to serve the purpose of this project which is to strengthen the tool steel and evaluate the wear resistance performance of the hardened tool after that. The strength of the hardened tool steel will be tested by performing FSW on Al-6061 plates.

1.2. Problem Statement

Non-heat treated, non-hardened and non-coated tool steel exhibits high abrasive wear from even a normal FSW application i.e. FSW of aluminium plates due to its poor hardness and wear resistance performance. Based from previous studies and application, hardening methods such as heat treatment and nitriding proves to be useful in increasing the hardness and wear resistance performance of the tool steel. However, the application and studies are mostly on tool steel that is used in die extrusion application. The studies and research on how those hardening methods can affects the hardness and wear resistance performance of FSW tool steel are very rare or maybe none although the results are expected to be more or less the same as the one in die extrusion application.

By strengthening the FSW tool steel, in this case by applying several hardening methods to the tool steel, it can not only minimize the tool wear but also increasing the productivity of the tool steel at factory, improving the tool life, and thus reduce the replacement cost of the tool steel in a long run. Another problem faced in this project is the shortages of study and information regarding the use of gas nitriding on FSW tool steel. Hence, this project is proposed in order to overcome the problem mentioned earlier.

1.3. Objective

The objectives of this project are:

- To investigate the hardness of FSW tool steel by using different hardening methods.
- To investigate the wear of FSW tool steel by using different hardening methods.

1.4. Scope of study

This study mainly focuses on the hardening methods applied to the tool steel which are the heat treatment and gas nitriding process and also how each of the hardening methods can affect the wear resistance performance of the tool itself. Next, the study on the wear resistance performance of the hardened tool steel after FSW of Al-6061 plates are needed in order to determine the effectiveness, feasibility and performance of the tool in welding the Al-6061 plates. Apart from that, the study on the hardness of the hardened tool steel is carried out in order to determine which hardening methods results in greater tool steel hardness. The feasibility and effectiveness of gas nitriding on FSW tool steel is also studied in this project.

CHAPTER 2

LITERATURE REVIEW

2. LITERATURE REVIEW

2.1. Variation of Wear with Process Parameters

The wear of the tool steel depends on various factors. Such factors include the rotation speed of the tool, the traverse speed of the tool and etc. A study was done by Fernandez and Murr [7] from the University of Texas at El Paso regarding the characterization of tool wear in the friction-stir welding of cast aluminum 359+20% SiC MMC. During the friction stir welding process, the conventional threaded steel pin tool shows a significant wear at high rotation speeds and slow weld traverse speeds as shown in Figure 2.1.1 [7]. However, when the tool rotation speed is reduced and the weld traverse speed is increased, the tool wear declines initially due to the threads fill with work piece material [7].

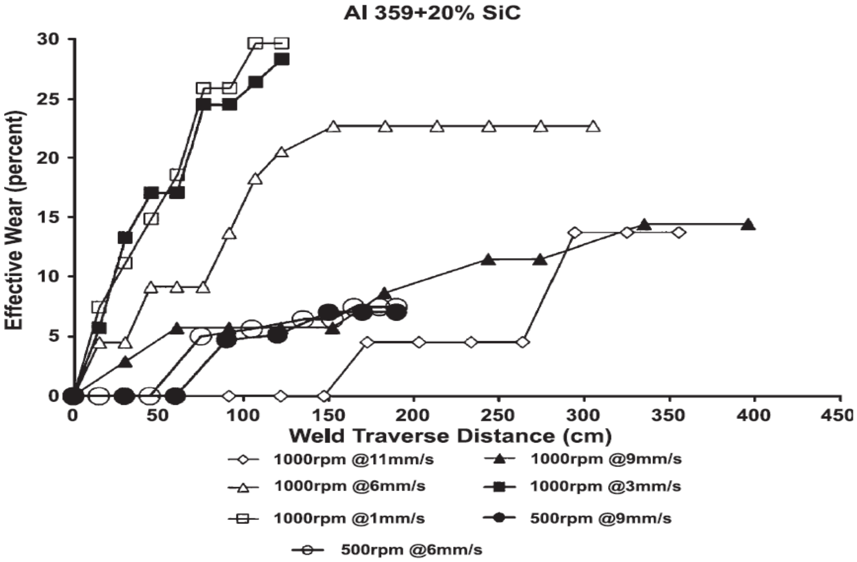

Figure 2.1.1 Wear for Al 359/SiC/20p for a range of parameters [7].

2.2. Combating Wear in Friction Stir Welding of Metal Matrix Composites (MMC)

Combating wear during FSW of Metal Matrix Composites can be done in a lot of ways. One of the methods is by varying the process parameters as mentioned in the section 2.1 above. Another method is by altering the work piece material [8, 9, 10] but for this project, the focus is on the tool steel itself. Since the wear mechanism in FSW of MMCs is abrasive, as confirmed by Prater [8] in her study, a potentially more robust means in combating wear potentially dependent in the use of harder tool materials that has a hardness value greater than that of the reinforcement. Weinert in his tool wear research emphasizes the importance of material properties of the tool relative to the reinforcement by declaring it to be a determining factor in the abrasive wear process [11].

2.3. Tool Materials

As discussed in section 2.2 above, in order to combat abrasive wear during FSW process, we need to use tool material that is harder than that of the reinforcement. Many researches and experiments have been done to strengthen the tool material. In a study conducted by Lee et al., they use coating as a mean to strengthen the tool material [9]. In their study, H13 tool steel was used coated with a B_4C coating in order to join Al 6092/SiC/17.5p. However, the results show no increased in wear resistance. The reason is due to the delamination of the B_4C coating from the h13 substrate after being welded for a short distance. When the coating has come off the substrate, the coarse joint surface characteristic of decohesion between matrix and reinforcing particles reappears [8].

Another option in the selection of the tool material is by using Tungsten Carbide (WC). The hardness value of WC is more closely aligned with that of the ceramic reinforcement but still the reinforcement is harder than the tool. WC is commonly alloyed with cobalt in order to improve its ductility and reduce the chances of tool failure. WC/Co tool used in FSW of MMCs is produced with two varieties, one with micrograin and the other with submicrograin cobalt binders as there is evidence that the grain size of the cobalt binder phase affects wear resistance [11]. Nevertheless, harder tool materials are still required in FSW of metal composites reinforced with SiC or B_4C [11, 12] as WC/Co tools still exhibit substantial wear.

Prater [13], in her study utilizes diamond, the hardest known material, as a coating material for the tool. The problem in using diamond as a coating material is in the selection of the substrates. In Prater's study, molybdenum is used as substrates due to its ability to withstand extreme temperature during the coating process through Chemical Vapor Deposition (CVD). However, molybdenum is too brittle to use for FSW. Steel can be used as a substrate for diamond coating if there is an intermediate layer being deposited first such as chromium nitride, CrN [8, 14]. However, the problem with multiple coatings is that it increases the chances of delamination due to the weaker bond between the coatings of CrN and diamond compared to the bond between steel and CrN [8, 14]. Because of that, commercial alternatives were explored in which WC/Co tools is used as a substrate for diamond coating process.

Another study had been conducted by Prater et al. [14] to compare the evaluation of wear resistance of various tool materials in FSW of MMCs. The tool materials used includes O1 steel, micrograin WC, submicrograin WC, and WC coated with diamond as mentioned earlier. The FSW process involves the welding of Al 359 MMC with either 20 or 30% SiC reinforcement. The wear resistance performances of all the chosen tool materials are illustrated in Figure 2.3.1.

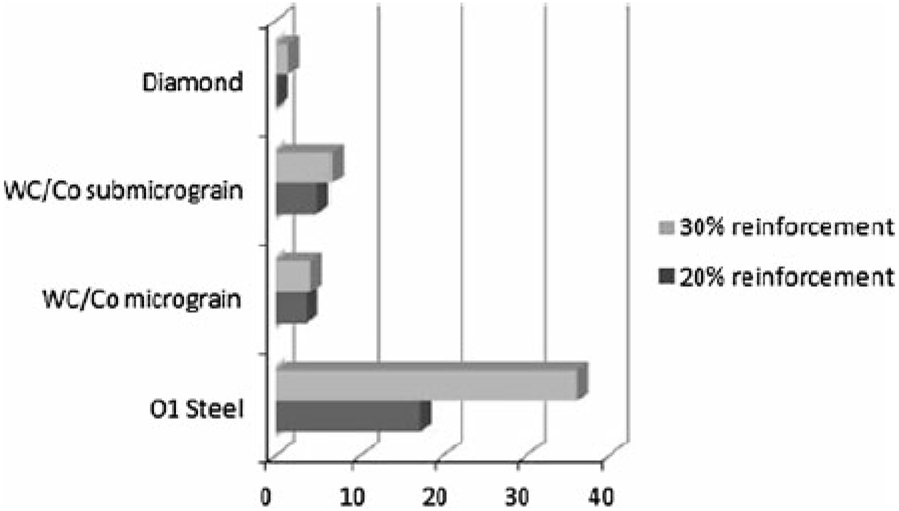

Figure 2.3.1 Plot of % wear vs. tool material [8, 14].

Based from the graphs, the conventional O1 tool steel experienced the highest wear values and least wear values are demonstrated by WC tool coated with diamond. Although WC/Co and WC/Co coated with diamond shows superior wear resistance performance compared to the O1 steel, both the materials shows susceptibility to fracture. In addition, the welded distances completed by the diamond coated WC/Co tool are quiet short but it shows a significant improvement in tool life compared to the diamond coated tools studied by Prater [13]. If we were to compare the wear resistance performance between WC/Co tools with micrograin and submicrograin, the one with micrograin experienced less wear compared to the one with submicrograin. This is due to the finer grain size of the submicrograin which causes the grains to be more easily stripped from the tool by reinforcing particles (SiC) than the coarser micrograin during machining process [14]. Therefore, this makes the tool to be more susceptible to abrasion.

CHAPTER 3

METHODOLOGY

3. METHODOLOGY

3.1. Project Methodology

Project methodology is very crucial in every project as it outlines the important element that needs to be done step by step thus ensures the quality of the project outcome and also the smoothness of the project work process. The process flow of the methodology is illustrated in Figure 3.1.1.

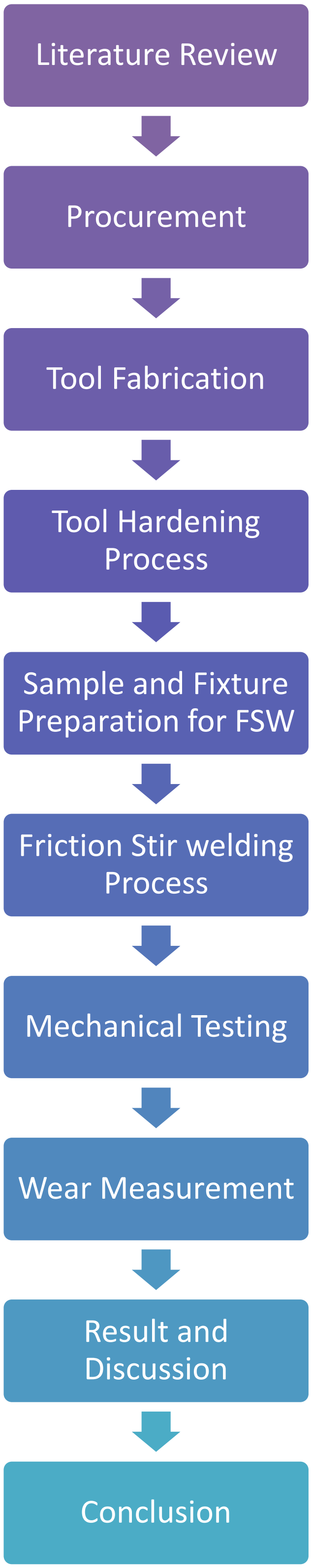

Figure 3.1.1 Methodology Process Flow

3.1.1. Tool fabrication

H13 tool steel was selected as the welding tool material due to its high hardenability, excellent wear resistance, easy to be machined and can be heat treated and nitrided to improve its hardness [15]. The dimensions of the raw H13 tool steel material purchased is 30mm in diameter and 85mm in length. The quantity of the raw material purchased was 4. Figure 3.1.2 below shows the picture of raw material H13 tool steel for welding tool fabrication.

Figure 3.1.2 Raw material of H13 tool steel.

After the procurement process, welding tool fabrication will be carried out which consists of designing and machining the tool. The schematic illustration of FSW tool design is attached in **Appendix 5**.

The dimensions and design of the welding tools is determined through consultation with the laboratory technician and supervisor. The shoulder diameter of the welding tool is set to be 24mm where the diameter of the tool tip is set to be 8mm. Meanwhile, the total length of the welding tool is set to be 85mm in order to ease the length adjustment of the tool when the tool is clamped to the milling machine. The length of the tool tip must be at least 80% of that the plate thickness in order to ensure optimum mixing of the aluminium at the welded zone. Since the thickness of the plate is 10mm, the length of the tool tip will be 8mm. The size of the fixture which is used to support the aluminium plates during FSW process will determine the dimensions of the Al-6061 plates.

Once the designing process of the tool is done, the next process is the machining process. For the machining process, CNC Lathe Bridgeport model ROMI Power Path-15 is used to fabricate and transform the raw materials H13 tool steel into proper welding tool steel according to the design made earlier. The parameters for the machining process such as the spindle speed, tool change and workpiece is set by the experienced lab technician and they are the one who will also write and edit the coding in the CNC machine. The product which is the fabricated welding tool from the machining process is shown in Figure 3.1.3.

Figure 3.1.3 The fabricated welding tool after machining process.

3.1.2. Heat Treatment Process

After the machining process, heat treatment is carried out on 2 out of 4 tool steels fabricated in order to harden the surface of the welding tool. The heat treatment process is done by using CARBOLITE Heat Treatment Furnace. The purpose of tool surface hardening is none other than to increase the performance of the welding tools itself during FSW process. Basically, there are four main stages involved in the heat treatment process [16]. At the first stage, the tool will be initially preheated to raise the temperature of the tool from room temperature to 650^{o}C in 90 minutes and hold for 15 minutes. At second stage, the tool will be constantly preheated to increase the temperature of the tool from 650^{o}C to 850^{o}C in 30 minutes and hold for 15 minutes. At third stage, the tool temperature is increased from 850^{o}C to 1020^{o}C in 30 minutes and hold for 30 minutes. Then, at the last stage, water quenching is carried out in order to decrease the temperature of the tool drastically from 1020^{o}C to room temperature. Immediately after quenching, the tools undergo tempering process which is a reheating process in which the tools are heated at 565^{o}C in the furnace for 2 hours and air quenched after that to room temperature. The stages are illustrated for clear view in Figure 3.1.4.

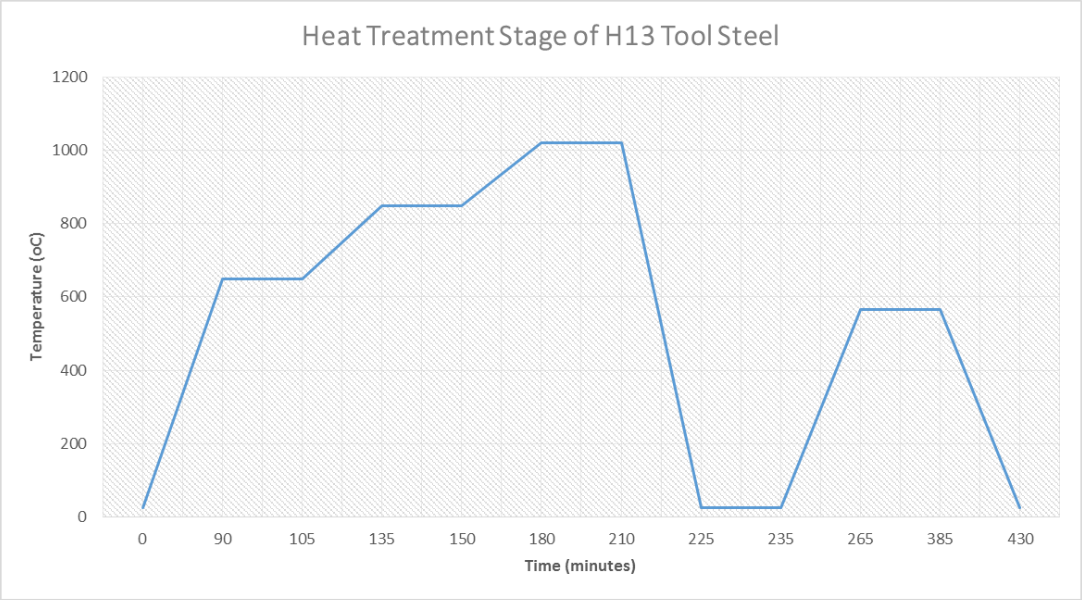

Figure 3.1.4 Heat treatment stage of H13 tool steel [16]

At the first and second stage of heat treatment process, preheating cycle is carried out. Preheating cycle is important as it helps in relieving the stresses, restructuring the grain structure of the H13 tool steel and reducing the possibility of mechanical fatigue initiation or cracking due to thermal shock after machining process [17]. At the 3rd stage, the welding tool is heated to austenizing temperature which is at 1020^{o}C. The reason is to dissolve carbides into the austenite matrix up until the point to develop the effect of hardening by transforming ferrite into austenite [18]. At the last stage, the welding tool is water-quenched immediately from 1020^{o}C to room temperature by using water as a cooling medium. The reason is to transform the austenite phase into martensite phase as the structure of martensite could improve the strength as well as hardness of the welding tool. Water is used as a cooling medium because it gives the fastest cooling rate compared to oil and air [17]. Tempering process is required immediately after quenching for stress releasing and also for retained austenite transformation [19]. The result of the heat treated tool is shown in Figure 3.1.5.

Figure 3.1.5 Heat treated H13 welding tool steel

3.1.3. Gas Nitriding Process

After the heat treatment process, 2 out of 4 tools, one with heat treated and the other one without heat treated will undergo gas nitriding process. The purpose of conducting gas nitriding process is to further increase the hardness and also the wear resistance performance of the tool after heat treatment process. One of the tool is gas nitrided only without any heat treatment done in order to experiment and investigate how much hardness that it can give by being gas nitrided alone and also its resistance to wear. In gas nitriding process, the parameter and the techniques used affects the surface hardness of the tool. The most important parameter that needs to be paid attention to is temperature. Apart from temperature, time is also considered as one of the important nitriding parameter as the longer the nitriding time, the thicker the nitrided layer.

Gas nitriding process involves the diffusion of atomic nitrogen, from dissociating ammonia gas, into the steel surface in the temperature range between 450°C to 500°C [20]. In summary, the nitriding of the steel can be visualized as bringing nitrogen gas into contact with the surface of the tool under extremely high pressure which becomes possible by using ammonia gas mixed with nitrogen gas or hydrogen gas [20]. For this project, the flow of nitriding process is shown in Figure 3.1.6.

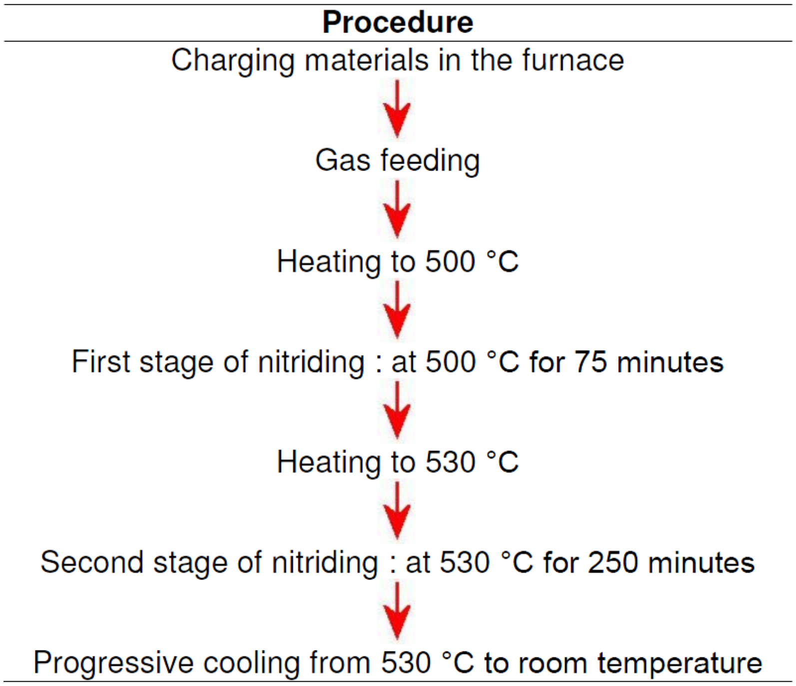

Figure 3.1.6 Flow of nitriding process for H13 tool steel [20]

However, due to some technical problem with the ammonia gas regulator at the time, ammonia gas cannot be used for the nitriding process. Therefore, the nitriding process is done by using alternative way in which the tool steel is heated to 1100°C and nitrided for 4 hours using nitrogen gas only. High temperature nitriding does not require ammonia gas for the nitrogen to be able to diffuse onto the tool's surface. The result of the gas nitrided tool steel is shown in Figure 3.1.7.

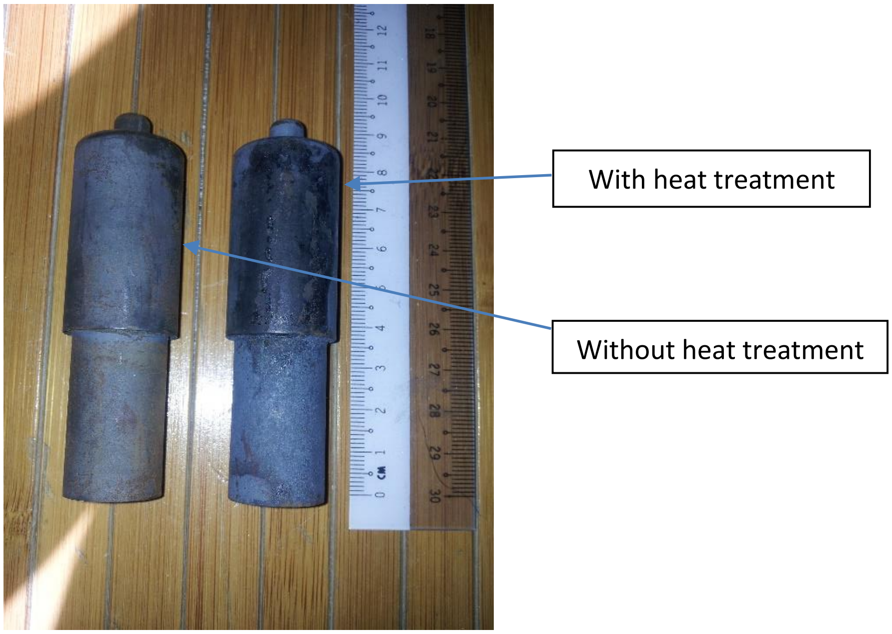

Figure 3.1.7 Gas nitrided H13 tool steel with and without heat treatment

3.1.4. Sample and Fixture Preparation for FSW

Once the hardening process of the welding tool is completed, design fixtures for Al-6061 plates will take place which requires consultation from in-charged technician for more detail information. After that, FSW of Al-6061 will be conducted by using the FSW machine and the fabricated tool.

3.1.5. Friction Stir Welding Process

The parameters for the welding process i.e. tool rotational speed and tool travel speed are decided by supervisor with agreement from the technician in-charged. Each tool steel is welded on Al-6061 plates for a weld distance of 1000mm.

3.1.6. Mechanical Testing

Mechanical testing done in this project is hardness test only. It can be conducted before or after FSW in order to determine the hardness of the hardened tool steels.

i. Hardness Test

During the hardness test, the hardness of the tool is determined at five different positions in order to analyze the ability of the materials to resist plastic deformation. The average hardness value will be calculated after that. The test is carried out by referring to ASTM E18-11 Standard Test Methods for Rockwell Hardness of Metallic Materials.

3.1.7. Wear Measurement

Wear measurement is carried out in this project to predict the wear resistance performance and to investigate the wear mechanism of the tool [21]. The wear resistance performance of the tool can be evaluated through the amount of loss in mass and volume of the tool. Some of the wear test methods that can be implemented are scratch hardness test and Taber test by referring to ASTM 1044 in which it is used to measure the low-stress abrasive wear resistance of materials and coatings [22]. For this project, wear is measured by just calculating the weight loss for each tool steel after FSW.

3.2. Project Key Milestone

Table 3.2.1: Key milestones of the project

No	**Activities**	**Date**
1	Selection of materials for welding tools and workpiece	**4 July 2014**
2	Completion of welding tool fabrication	**15 August 2014**
3	Completion of sample preparation for FSW	**20 February 2015**
4	Completion of testing for mechanical properties and tool wear resistance performance	**20 March 2015**

3.3. Project Gantt Chart

Table 3.3.1: Project Gantt Chart

No.	Project Activities	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1	Literature review	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
2	Procurement and materials selection			🟥	🟥	🟥	🟥	🟥🟦																					
3	Designing of the welding tools							🟥	🟥	🟥																			
4	Machining of the tools									🟥	🟥	🟥																	
5	Heat treatment on the tools for surface hardening											🟥	🟥	🟥🟦															
6	Constructing fixture thin plates													🟥	🟥	🟥													
7	Coating process of the tool steel															🟥	🟥	🟥											
8	Sample Preparation																🟥	🟥	🟥	🟥	🟥🟦								
9	Mechanical testing																			🟥	🟥	🟥	🟥	🟥	🟥🟦				
10	Analyzing data and report writing																							🟥	🟥	🟥	🟥	🟥	🟥

🟦 **Key Milestones of Project Work**

CHAPTER 4

RESULTS AND DISCUSSION

4. RESULTS AND DISCUSSION

4.1. Hardness Test

Once all the heat treatment and gas nitriding process of the tool steel is completed, hardness test is conducted to determine the hardness value for all the 4 tool steels with respect to its surface hardening process. The test is carried out by the technicians in-charged with reference to ASTM E18-11 Standard Test Methods for Rockwell Hardness of Metallic Materials. For H13 tool steel, the Rockwell hardness scales used is scale C. The results for the hardness value of the tool steels are tabulated and illustrated in the Table 4.1.1 and Figure 4.1.1 respectively.

Table 4.1.1 Hardness value data in Rockwell C scale

Tool Steel	Tool condition	Hardness Testing Trials (HRC)					Average Hardness Value (HRC)
		1	2	3	4	5	
1	Untreated/Raw	8.3	11.0	8.6	8.0	9.1	9.0
2	Heat treated only	38.4	46.0	41.3	39.0	32.1	39.4
3	Nitrided only	41.5	42.4	39.3	42.1	46.9	42.4
4	Heat treated and nitrided	53.3	51.6	56.8	54.2	54.1	54.0

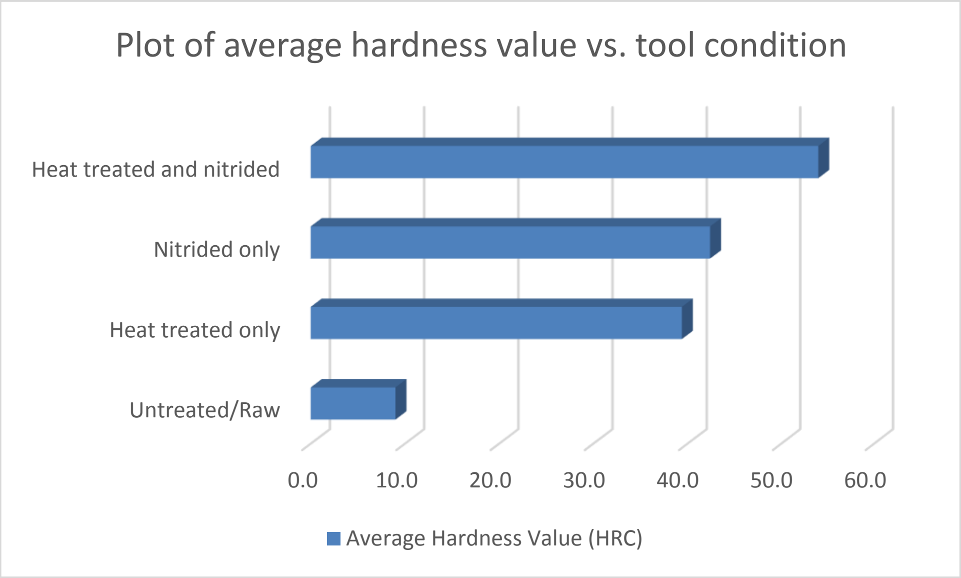

Figure 4.1.1 Plot of average hardness value against tool condition

Based from the hardness results obtained above, tool steel that yields the highest hardness value is the one that is being heat treated and nitrided which gives the average hardness value of 54 HRC. Meanwhile, tool steel that yields the lowest hardness value is obviously the untreated/raw one which gives the average hardness value of 9.0 HRC. The average hardness value for the untreated/raw tool steel is made as the baseline value for comparison purposes with the other three tool steels. Theoretically, the tool steel that is heat treated and nitrided should give the highest average hardness value because the surface of the tool is harden with two processes compared to those that undergoes single process only as proved by the experimental results obtained above. The experimental hardness value for untreated/raw tool steel and heat treated and nitrided tool steel in this project meets the theoretical expectation. However, the theoretical expectation hardness value for tool steel that is heat treated only and nitrided only remains unknown.

In this study, tool steel that is heat treated only shows increase in average hardness value compared to the average hardness value of the untreated/raw tool steel but still the value is less than those that undergoes nitriding process. The nitrided only tool steel shows higher average hardness value compared to the one that is heat treated only. This shows that coating the tool steel with atomic nitrogen is better than just changing the atomic structure phase of the tool steel in obtaining greater hardness. Even better if both processes are done accordingly for a single tool steel.

4.2. Wear Measurement and Evaluation

In this project, the tool wear is measured by calculating the weight loss of the tool steels after performing FSW on Al-6061 plates. The weight of the tool steel is measured before conducting FSW by using precision balance with 3 decimal points in unit gram (g). The weight of the tool is measured again after performing FSW by using the same balance. The parameter for FSW is set to be 1100rpm spindle speed and 40mm/min tool travel speed in order to generate enough heat to plasticize the material and reduce the likelihood of tool failure. The weld distance for each tool is set to be 1000mm. The resulting weight loss and percent wear for each tool steel is tabulated and illustrated in Table 4.2.1 and Figure 4.2.1 respectively below. The percent wear is calculated by using Equation 1 below where m_i denotes the initial mass of the tool steel and Δm is the change in mass of the tool.

$$\frac{\Delta m}{m_i} x100\% \qquad \text{(Eq) 1}$$

Table 4.2.1 Weight loss and percent wear of the tool steels

Tool Steel	Tool condition	Weight (g)			Percent Wear (%)
		Before	After	Loss	
1	Untreated/Raw	238.150	237.244	0.91	0.38
2	Nitrided only	236.951	236.481	0.47	0.19
3	Heat treated and nitrided	231.355	231.086	0.27	0.12

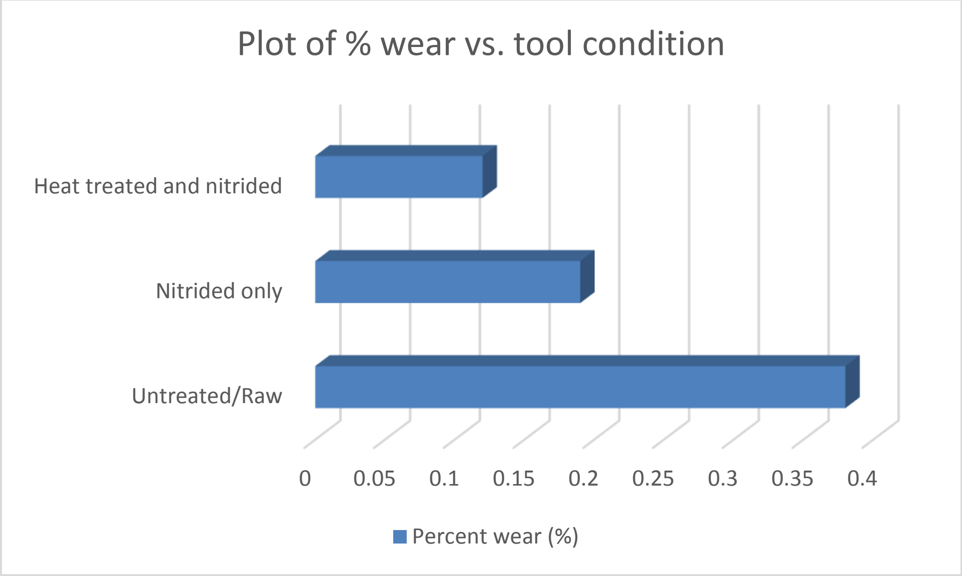

Figure 4.2.1 Plot of % wear against tool condition

Based from the results obtained above, tool steel that is heat treated and nitrided shows the lowest weight loss and percent wear while the one that is untreated/raw shows the highest weight loss and percent wear as expected. Both the nitrided tool steels shows significant improvement in tool wear in which the wear experienced by the nitrided only tool steel is approximately two times less than that observed for the untreated/raw tool steel under the same condition. However, applying heat treatment before nitriding on the tool steel proves better wear resistance performance. If we compare the hardness results obtained before and percent wear results obtained, both results are actually inversely related. The relationship between hardness and tool wear are in such a way that it is inversely proportional with one another which means the greater the tool steel hardness, the smaller the tool wear exhibits by the tool steel as proved in this project. The relationship is as predicted by Rabinowicz's classical theory [23] in which the wear resistance increases with hardness ratio. The relationship between tool steel hardness and percent wear is represented in Figure 4.2.2 for clear view.

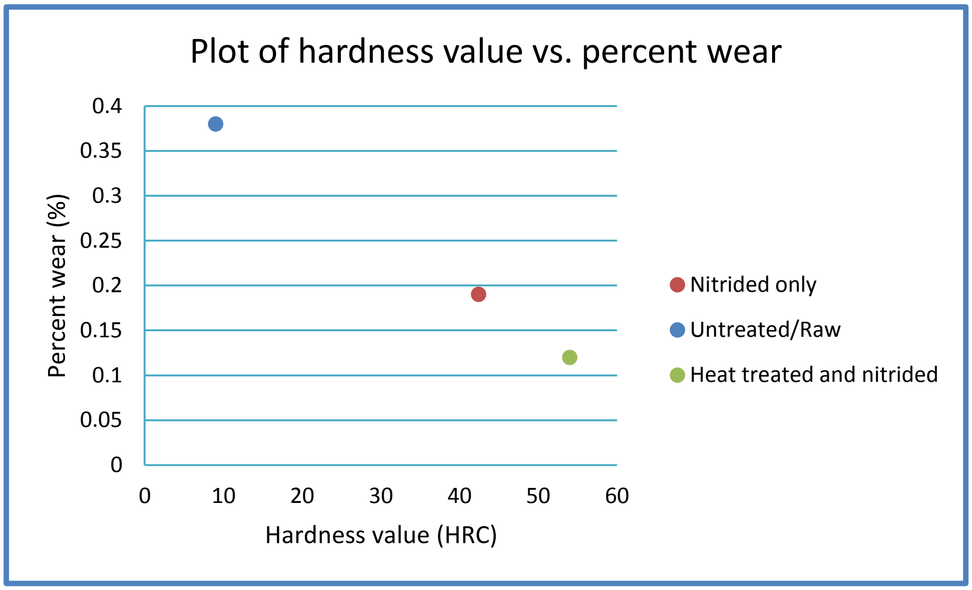

Figure 4.2.2 Plot of hardness value against percent wear

CHAPTER 5

CONCLUSION AND RECOMMENDATION

In order to increase tool service life and quality of the tool, tool wear must be reduced. One of the way to do that is by strengthening the tool through surface hardening methods but the effectiveness and feasibility of the methods in reducing FSW tool wear remains unclear. In this project, tool wear is investigated with respect to the hardening methods applied to the tool steel and the outcome of the study can be concluded as follows:

1) Gas nitriding of H13 tool steel can also be done at high temperature instead of low temperature by using nitrogen gas only as the hardness results for nitrided tool steels shows significant and satisfactory increase in hardness value compared to the untreated/raw tool steel.
2) FSW of the hardened tool steels on Al-6061 plates are completed successfully without any visible tool fracture or cracking.
3) As expected, the heat treated and nitrided tool steels yields the highest hardness value while the untreated/raw tool steel yields the lowest hardness value.
4) The nitrided only tool steel yields better hardness value compared to the heat treated only tool steel due to the hard thin nitrogen coating on the tool's surface.

Some recommendations for future work that can be done are:

1) Modifying the grinding machine by removing the ring plate that holds the sand paper but still ensure that the sand paper remain intact on the rotating disk so that the oxide layer on the shoulder and the pin of the tool steel can be grinded at the edge of the disk to obtain better hardness value.
2) Applying other hardening methods to the tool steel such as carburizing to see its effect to the tool wear.
3) Carry out microstructure analysis on the surface of the tool to examine and study the nitride layer and atomic structure phase of the steel.

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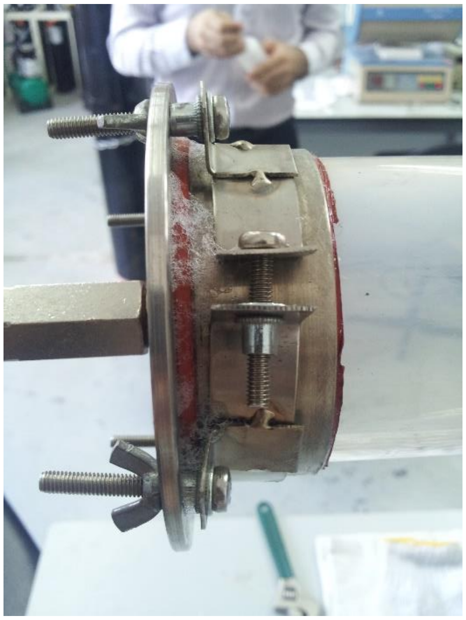
APPENDICES

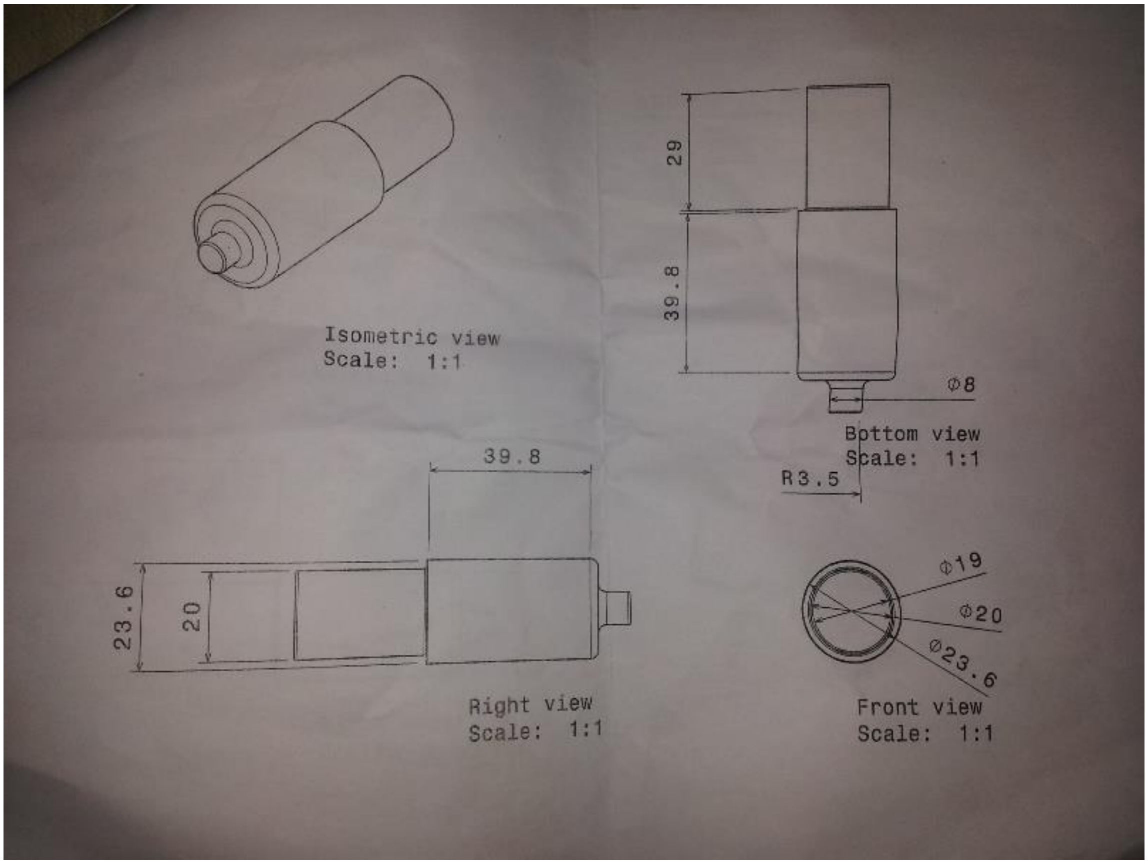
Appendix 1: CNC Lathe Bridgeport model Power Path-15

Appendix 2: CARBOLITE Heat Treatment Furnace

Appendix 3: Equipment setup before conducting gas nitriding process



Appendix 4: Gas leakage testing by applying bubble foam at the closure of the glass tube



Appendix 5: Schematic FSW tool design