# EFFECT OF HEAT TREATMENT ON FATIGUE LIFE

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**JUDUL: EFFECT OF HEAT TREATMENT ON FATIGUE LIFE**

**SESI PENGAJIAN: 2011/2012**

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I certify that the project entitled *"Effect of Heat Treatment on Fatigue Life"* is written by *Zulqarnain bin Fuad.* I have examined the final copy of this project and in our opinion; it is fully adequate in terms of scope and quality for the award of the degree of Bachelor of Engineering. I herewith recommend that it be accepted in partial fulfilment of the requirements for the degree of Bachelor of Mechanical Engineering.

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# EFFECT OF HEAT TREATMENT ON FATIGUE LIFE

ZULQARNAIN BIN FUAD

Thesis submitted in fulfilment of the requirements
for the award of the degree of
Bachelor of Mechanical Engineering

Faculty of Mechanical Engineering
UNIVERSITI MALAYSIA PAHANG

JUNE 2012

## SUPERVISOR'S DECLARATION

I hereby declare that I have checked this project and in my opinion, this project is adequate in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

Signature
Name of Supervisor: NASRUL AZUAN BIN ALANG
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Date: 22 JUNE 2012

## STUDENT'S DECLARATION

I hereby declare that the work in this project is my own except for quotations and summaries which have been duly acknowledged. The project has not been accepted for any degree and is not concurrently submitted for award of other degree.

Signature

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ID Number: MA08036

Date: 22 JUNE 2012

**IN THE NAME OF ALLAH,**

**THE MOST BENEFICENT, THE MOST MERCIFUL**

*A special dedication of This Grateful Feeling to My*

*Beloved parents, En. Fuad bin Alwi and Pn. Badariah binti Mat Som for giving me full of moral and financial support. It is very meaningful to me in order to finish up my degree's study. Not forgetting also to all my loving brothers and sisters. Last but not least to all my colleagues and my lovely friends.*

*Thanks for all the support, wishes and love.*

## ACKNOWLEDGEMENTS

I am greatly indebted to ALLAH SWT on His blessing for making this project successful. I would like to express my sincere gratitude to my supervisor Mr. Nasrul Azuan bin Alang for his brilliant ideas, invaluable guidance, continuous encouragement and constant support in making this project possible. I appreciate their consistent support from the first day I start this project to these concluding moments.

My sincere thanks go to all my colleagues under the same supervision for sharing the ideas and information, advice and guidance throughout this project. My sincere thanks also go to all members of the staff of the Mechanical Engineering Department, UMP, especially to Aziha bin Abdul Aziz, Khairidz Azuwar bin Safie', Mohd Fazli bin Ismail and Mohd Tarmizy bin Che Kar who helped me in many ways and made my stay at UMP pleasant and unforgettable.

I acknowledge my sincere indebtedness and gratitude to my parents and for their love, dream and sacrifice throughout my life. I acknowledge the sincerity of my brother and sister who consistently encouraged me to work hard for this project.

## ABSTRACT

The main purpose of this project is to determine the effect of various heat treatment processes on fatigue life of mild steel specimen. The study of fatigue life and effect of heat treatment is very important in order to increase the hardness of the material and its life before failure. The influence of heat treatment process to the specimen has been investigated. Total eighteen specimens have been machined where six were oil quenched, six were tempered and another six remained as received. The rotational bending fatigue test was conducted on all prepared specimens at room temperature with stress ratio of -1. From the fatigue test, the results show that tempered specimens has highest fatigue life compared to other two conditions. After the fatigue test have been done, the fracture surface of failed specimens were analysed to ensure that the specimens were failed due to fatigue. Based on the analysis, the mild steel specimens failed due to fatigue with transgranular manners. It was observed that there are three distinct region on specimen's fracture surface which are crack initiation, crack propagation and rapid fracture region.

# ABSTRAK

Tujuan utama projek ini adalah untuk menentukan kesan pelbagai proses rawatan haba ke atas hayat lesu specimen rendah karbon. Kajian ke atas hayat lesu dan kesan rawatan haba amat penting untuk menambah kekerasan bahan dan hayatnya sebelum ia lesu. Pengaruh rawatan haba yang telah dilakukan ke atas bahan telah disiasat. Lapan belas bahan telah di mesin di mana enam telah dilindapkejutkan di dalam minyak, enam telah di tempa di udara persekitaran dan enam tidak dikenakan apa-apa rawatan haba. Ujian hayat lesu terhadap putaran telah dijalankan ke atas semua bahan pada suhu bilik dengan nisbah tekanan bernilai -1. Daripada ujian hayat lesu, keputusan menunjukkan bahawa bahan yang ditempa mempunyai jangka hayat lesu yang tinggi berbanding bahan di dalam keadaan lain. Selepas ujian hayat lesu telah dijalankan ke atas setiap bahan, permukaan bahan yang telah patah telah di analisis untuk menentukan bahawa bahan itu telah patah disebabkan oleh hayat lesu. Berdasarkan analisis, bahan rendah karbon yang telah diuji telah gagal mengikut cara 'transgranular'. Ia telah diperhatikan bahawa permukaan itu terbahagi kepada tiga bahagian iaitu permulaan keretakan, perambatan keretakan dan kawasan kepesatan kepatahan.

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| | |
|---|---|
| $N$ | Spindle speed |
| $CS$ | Cutting Speed |
| $d$ | Diameter of raw material |
| $f$ | Feed |
| $v_f$ | Feed rate |
| $d_0$ | Initial diameter |
| $d_f$ | Final diameter |
| $T$ | Temperature |
| $t$ | Time |
| $R$ | Stress ratio |
| $l$ | Length |
| $S_{ut}$ | Minimum tensile strength |
| $S_{yield}$ | Yield strength |
| $S_e'$ | Endurance limit |
| $K_f$ | Fatigue stress-concentration factor |
| $q$ | Notch sensitivity |
| $K_t$ | Stress-concentration factor |
| $r$ | Notch radius |
| $M$ | Moment |
| $y$ | Radius of back part of specimen |
| $I$ | Inertia |
| $\sigma$ | Stress |

| | |
|---|---|
| $N$ | Number of cycles to failure |
| $F$ | Load |

## LIST OF ABBREVIATIONS

| | |
|---|---|
| S-N | Stress-Cycles |
| BCC | Body Centered Crystal |
| FCC | Face Centered Cubic |
| AISI | American Iron and Steel Institute |
| VHN | Vickers Hardness Number |

# CHAPTER 1

# INTRODUCTION

## 1.1 PROJECT BACKGROUND

Fatigue is a progressive and localized structural damage when the material is subjected to cyclic loading whereas the fatigue life is the number of cycles that will cause failure at a certain stress level. In this project, the effect of heat treatment on the fatigue life of low carbon steel will be investigated. For this purpose, the specimens with various heat treatments will be prepared and tested in tension-compression rotational bending fatigue test. The rotational bending fatigue experiment was carried out at room temperature, applying a fully reversed cyclic load with constant frequency and mean stress using a cantilever rotating-bending fatigue machine. Morphological study was carried out to observe the microstructure of the heat treated specimen. Fracture surface of specimens will be analysed using optical microscope.

## 1.2 OBJECTIVES

For this project, several objectives have been developed to be achieved:

1) To study the effect of various heat treatment on fatigue life of carbon steel.
2) To investigate the microstructure of carbon steel after being heat treated by various type of heat treatment.

## 1.3 PROBLEM STATEMENT

Fatigue is an engineering problem where it happens when a material is subjected to cyclic load. Low carbon steel is steel that has low carbon composition which is less than 0.25%. It is inherently easier to cold-form due to their soft and ductile nature. It is cheap and easy to get thus it is widely used in engineering structure. For example, in making pipes, chains, wire nail and some other machine part. But, it is often failed due to fatigue. So, in order to reduce the fatigue failure of low carbon steel, heat treating method such as quenching and tempering was used. Heat treatment is another way to reinforce steel and is the best way to increase the strength of the material. Thus, the fatigue failure problem will be decreasing.

## 1.4 SCOPE OF PROJECT

This project concentrated on how the various heat treatment methods affect the carbon steel fatigue life and its microstructure. The scope of this project includes the preparation of material where the carbon steel was taken from laboratory and then machined to desired dimension. After preparation of 18 specimens, the heat treatment processes take over. Two heat treatment processes were conducted, which are quenching and tempering. After heat treatment processes have been done, the microstructure and hardness of the specimen were investigated. Then, the specimens were subjected rotational bending fatigue test. Surface fracture of the failed specimen was analysed to make sure the specimen failed due to fatigue.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 INTRODUCTION

This chapter discusses the literatures that are related to fatigue life on material such as low carbon steel. This chapter will review on the material that are used, the S-N curve, the processes that are used for specimens preparation, the heat treatment processes and the fatigue test on the specimen.

## 2.2 THE METALLURGY OF STEEL

When a small amount of carbon is added to iron, thus steel is obtained. So, all steel have some carbon and iron in its mechanical properties and a little bit of alloying elements since the influence of carbon on mechanical properties of iron is much larger than other alloying elements. It also can be said that steel is a crystalline alloy of iron, carbon and several other elements. These alloys vary both in the way they are made and in the amount of the materials added to the iron.

### 2.2.1 Plain Carbon Steel

Carbon steel is one of the most used steel. The properties of carbon steel depend on the amount of carbon that contains in the steel. Most of the carbon steel has a carbon content of less than 1%. Carbon steel is also used in many products that are commonly used such as structural beams, car bodies, kitchen appliances, and cans. There are three types of carbon steel that are low carbon steel, medium carbon steel and high carbon steel and each one of them differs in the amount of carbon that it contains. So, plain carbon steel is a type of steel that contains the maximum carbon content of 1.5% along with small percentages of silica, sulphur, phosphorus and manganese.

Low carbon steel or mild steel is a carbon steel that contains carbon up to 0.25% and responds to heat treatment as improvement in the ductility of the steel is concerned but has no effect on its strength properties.

Medium carbon steel is a carbon steel that contains carbon ranging from 0.25% to 0.7% and it improves in the machinability by heat treatment. This steel is especially adaptable for machining or forging where surface hardness is desirable

High carbon steel is plain carbon steel that contains carbon ranging from 0.7% to 1.05% and it is especially classed as high carbon steel. It is very hard in heat treatment and it will withstand high shear and wear and will be subjected to little deformation. There are also other properties of plain carbon steel that needs to be considered as shown in Table 2.1.

**Table 2.1:** Properties of low carbon steel

| **Material** | **Density ($\times 10^3 kgm^{-3}$)** | **Thermal conductivity ($Jm^{-1}K^{-1}s^{-1}$)** | **Thermal expansion ($\times 10^{-6}K^{-1}$)** | **Young's modulus ($GNm^{-2}$)** | **Tensile strength ($MNm^{-2}$)** | **% elongation** |
|---|---|---|---|---|---|---|
| **0.2% C Steel** | 7.86 | 50 | 11.7 | 210 | 350 | 30 |
| **0.4% C Steel** | 7.85 | 48 | 11.3 | 210 | 600 | 20 |
| **0.8% C Steel** | 7.84 | 46 | 10.8 | 210 | 800 | 8 |

Source: Raghavan (2001)

The atomic diameter of carbon is less than the interstices between iron atoms and so the carbon goes into solid solution of iron. As carbon dissolves in the gabs between the atoms, it distorts the original crystal lattice of iron. This change of crystal lattice of interferes with the external applied strain to the crystal lattice by mechanically blocking the dislocation of crystal lattices and the steel is now having higher mechanical strength. The more carbon added to the solid solution of iron, the more distortion it will made to the crystal lattice and thus the mechanical strength is increasing. Thus the high carbon steel has more carbon in the mechanical properties and low carbon steel has small amount of carbon in its mechanical properties. But by adding the carbon into iron, there are other properties that are influenced by the carbon that is the ductility which is the ability of iron to undergo plastic deformation. Thus, the more carbon added to the iron, the strength is increasing but the ductility is reduced. Adding carbon is not the only way to increase the strength of steel. More carbon amount means that when in welding process, it will cause trouble because of the strength. Figure 2.1 shows diagram of temperature versus weight % of carbon of carbon steel.

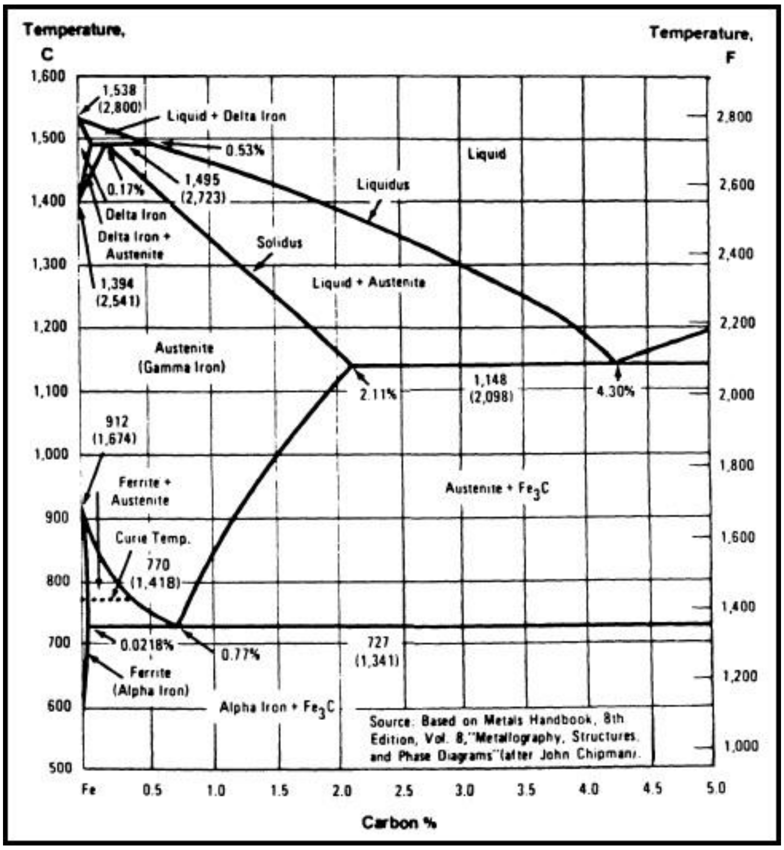


**Figure 2.1:** Temperature versus weight % of carbon of carbon steel

Source: Meier (2004)

Ferrite (α) is virtually pure iron with body centered cubic crystal structure (BCC). It is stable at all temperatures up to 9100°C. The carbon solubility in ferrite depends on the temperature where the maximum carbon amount is 0.02% at 723°C. Cementite is an Iron Carbide ($Fe_3C$), a compound iron containing 6.67% of carbon by weight. It is commonly used as a tool in lathe machine for machining the material. Pearlite is a fine mixture of ferrite and cementite arranged in lamellar form. It is stable at all temperatures below 723°C. Austenite (γ) is a face centered cubic structure (FCC). It is stable at temperatures above 723°C depending on the carbon content. It can dissolve up to 2% of carbon.

The maximum solubility of carbon in the form of $Fe_3C$ in iron is 6.67%. If the addition is above the limit, it will result in formation of free carbon or graphite in iron. At 6.67% of carbon, iron transforms completely into cementite of $Fe_3C$ that is Iron Carbide. Generally, carbon content in structural steels is in the range of 0.12-0.25%. Up to 2% of carbon, we will get a structure of ferrite + pearlite or pearlite + cementite depending on the whether the carbon content is less than 0.8% or beyond 0.8%. Beyond 2% carbon in iron a brittle cast iron is formed.

Furthermore, the hardness, brittleness and ductility are very important properties as they determine mainly the way these different carbon content steels are used. Considering the microstructure of slowly cooled steel for example mild steel with 0.2% carbon. Such steel consists of about 75% of proeutectoid ferrite that forms above the eutectoid temperature and about 25% of pearlite with pearlite and ferrite being microstructure components of steel. When the carbon content in steel is increased, the amount of pearlite increases until we get the fully pearlitic structure of a composition of 0.8% carbon. Beyond 0.8%, high carbon steel contain proeutectoid cementite n addition to pearlite.

But in slowly cooled carbon steels, the overall hardness and ductility of the steel are determined by the relative proportions of soft, ductile ferrite and the hard, brittle cementite. The cementite content increases with increasing carbon content, resulting in an increase of hardness and the decrease of ductility, as we go from low to high carbon steels.

There are also some limitations if carbon steels that are it there can't be strengthening beyond 100000 psi without significant loss in toughness (impact resistance) and ductility. Then, the large sections cannot be made with martensite structure throughout, and thus are not deep hardenable. Rapid quench rates are necessary for full hardening in medium-carbon leads to shape distortion and cracking of heat treated steels.

The characteristic of plain-carbon steels is that it has poor impact resistance at low temperatures. It also has a poor corrosion resistance for engineering problems. That means that it is easily corroded when the corroding element exists and it also oxidise readily at elevated temperature. Figure 2.2 shows three types of plain carbon steel microstructure.

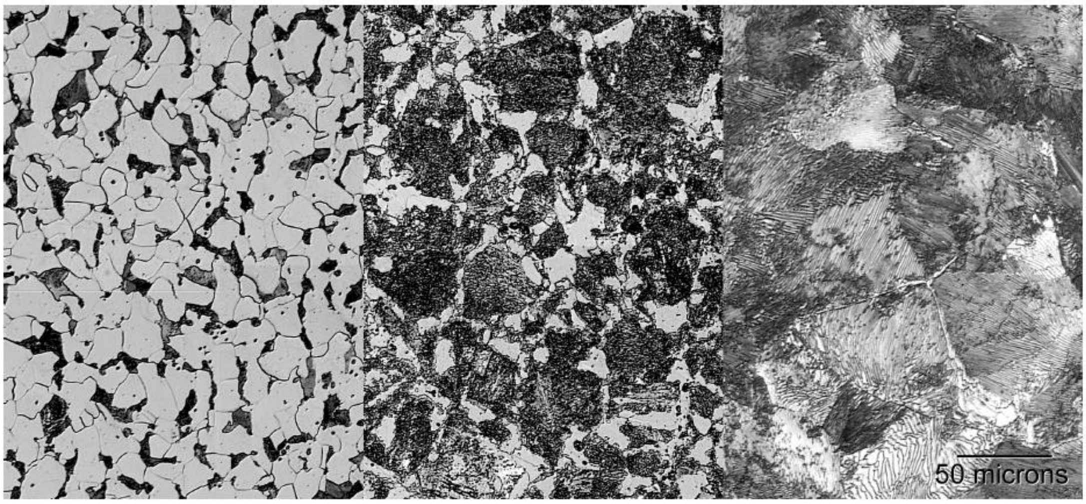


**Figure 2.2:** Three plain carbon steels, from left to right: 1018, 1045 and 1095. Increasing the carbon content (from 0.18% to 0.95%) causes the amount of ferrite (light) to decrease and the amount of pearlite (dark, lamellar) to increase.

Source: Meier (2004)

## 2.3 HEAT TREATMENT PROCESS

Heat treatment is a process of transformation of phases in the microstructures and properties of steel during heating and cooling to change the microstructure in a solid state. In heat treatment processes, the processing is most often entirely thermal and modifies only the structure of material. Thermomechanical treatments which modify components shape and structure and thermochemical treatments which modify surface chemistry and structure are also important processing approaches which fall into the domain of heat treatment.

Heat treatment is often associated with increasing the strength of material, but it can also be used to alter certain manufacturability objectives such as improve machining, improve formability, restore ductility after a cold working operation. Thus it is a very enabling manufacturing process that can not only help other manufacturing process, but can also improve product performance by increasing strength or other desirable characteristics. There are three main objectives that steels needed to be heat treated that are softening, hardening, and material modification.

### 2.3.1 Quenching

Quenching is a heat treatment process of rapid cooling of a workpiece to obtain certain material properties. This process is most commonly used to harden steel by introducing martensite, in which case the steel must be rapidly cooled through its eutectoid point, the temperature at which austenite becomes unstable. The common quenching medium: air, water and oil. Quenched material has relatively good proportion between yield strength and toughness due to fine dispersion of ferrite-cementite mixture. Yield strength of ferrite-cemetite mixture are higher if the grain size of previous austenite is finer. The grain size refinement of steel can be done by repeated alpha and gamma phase transformations. If the cyclic heat treatment were done to the material, a stronger and tougher microstructure will be gained.

Oil is used when a slower cooling rate is desired. Since oil has a very high boiling point, the transition from start of Martensite formation to the finish is slow and this reduces the likelihood of cracking. Oil quenching results in fumes, spills, and sometimes a fire hazard.

Quenching can also be done by plunging the hot steel in water. The water adjacent to the hot steel vaporizes, and there is no direct contact of the water with the steel. This slows down cooling until the bubbles break and allow water contact with the hot steel. As the water contacts and boils, a great amount of heat is removed from the steel. With good agitation, bubbles can be prevented from sticking to the steel, and thereby prevent soft spots. Figure 2.3 shows the microstructure of quenched low carbon steel. From the figure, martensite that is needle-like is introduced after quenching process.

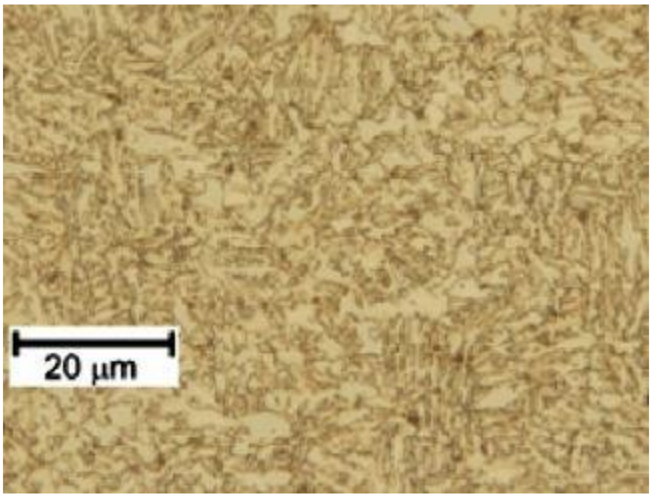


**Figure 2.3:** Microstructure of quenched low carbon steel

Source: Hilditch et al. (2011)

### 2.3.2 Tempering

Tempering is a process done subsequent to quench hardening. Quench-hardened parts are often too brittle. This brittleness is caused by a predominance of Martensite. This brittleness is removed by tempering. Tempering results in a desired combination of hardness, ductility, toughness, strength, and structural stability. Tempering is not to be confused with tempers on rolled stock-these tempers are an indication of the degree of cold work performed. The mechanism of tempering depends on the steel and the tempering temperature. The prevalent Martensite is a somewhat unstable structure. When heated, the Carbon atoms diffuse from Martensite to form a carbide precipitate and the concurrent formation of Ferrite and Cementite, which is the stable form. Tempering is done immediately after quench hardening. When the steel cools to about 40 ºC (104 ºF) after quenching, it is ready to be tempered. The part is reheated to a temperature of 150 to 400 ºC (302 to 752 ºF). In this region a softer and tougher structure Troostite is formed. Alternatively, the steel can be heated to a temperature of 400 to 700 ºC (752 to 1292 ºF) that results in a softer structure known as Sorbite. This has less strength than Troostite but more ductility and toughness. Figure 2.4 shows the microstructure of tempered low carbon steel.

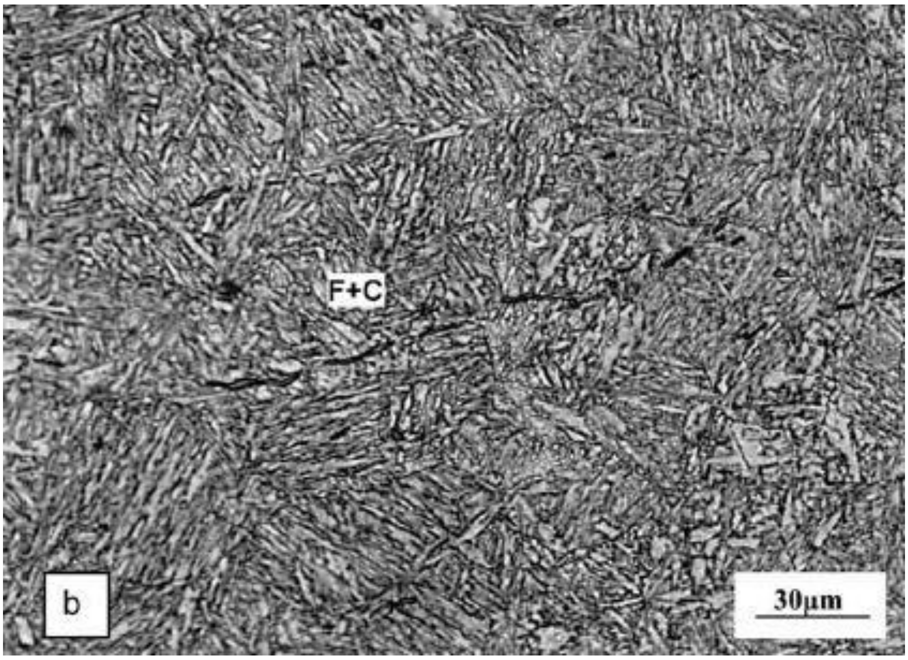


**Figure 2.4:** The microstructure of tempered low carbon steel

Source: Sankaran et al. (2003)

## 2.4 FATIGUE

The term fatigue is often used to a progressive and localized structural damage when the material is subjected to cyclic loading. The term progressive means that the crack will grow depending on the number of cycle the load is subjected to the material. Meanwhile localized means that it first starts at one point and then the crack will grow further. Fatigue is a failure in engineering materials characterized by the stress levels where the material might have relatively low stress levels compared to its yielding stress. The other factor that contributes in fatigue is the number of cycles where it is a high number of repetitions of load to the material. The other factor is the stress concentration, the notch sensitivity, surface conditions, type of loadings, the size of materials and the temperature. Fatigue life is the number of cycles that will cause failure at a certain stress level of the material. Fatigue limit is a characteristic of the material and its geometry. If a material is loaded below its fatigue limit, the material will not fail regardless the number of cycles it is subjected to. Fatigue strength is the strength at which the failure occurs for a given number of cycles.

### 2.4.1 Fatigue Failure Incidents

Fatigue is studied because of accidents that happened around the world and some people were trying to overcome it. First is the incident of train crash at France where abount 55 people were killed in that incident. Due to further investigation, it is due to broken locomotive axle. Then, Rankine investigated it further and highlighted that stress concentration and mechanism of crack growth due to repeated loading is important. He and his colleagues suggested a crack growth through repeated loading and were ignored and the incidents of train crash due to broke locomotive axle is increasing. Other incident that related to fatigue failure happened also in de Havilland Comet passenger jet where the jet broke up in mid air and crashed within a few months after the broke. The failure is due to metal fatigue caused by the repeated pressurization and de-pressurization of the aircraft cabin. Another fact is that the supports around the window were riveted, not bonded as the original specifications for the aircraft has called for. So, fatigue failure study has been developed because of these incidents that has robbed many lives of people and it is an important studies because it can overcome many problems that related to fatigue around the world. Figure 2.5 shows fatigue failure occurred in engineering field.


**Figure 2.5:** Fatigue failure of a lateral link

Source: Kang (2008)

### 2.4.2 Fatigue Study History

Fatigue analysis as we know it today has come a long way. In 1837, Wilhelm Albert has published the first article on fatigue, establishing a correlation between applied loads and durability. Two years later, in 1839, Jean-Victor Poncelet, designer of cast iron axles for mill wheels, officially used the term "fatigue" for the first time in a book on mechanics. The summarized work of August Wohler in 1870 heps improve testing procedures of axles and thereby increased axle life. He then developed his own rotating-bending fatigue test and also introduces the fatigue life concept. Wohler also initiated the development of design strategies for fatigue and has identified the importance of cyclic and mean stresses. By the end of 19$^{th}$ century, Gerber and Godmann investigated the influence of mean stress and proposed simplified theories. In 1886, Johann Bauschinger wrote the first paper on cyclic stress-strain hysteresis behaviour behaviour of materials (named later after himself; Bauschinger effect). Based on those theories and procedures, engineers implemented fatigue test analysis in product development processes and were able to predict product life better than ever before. Despite these developments, fatigue test analysis remained a niche methodology, carried out only by experts for many years to come. Figure 2.6 shows the first fatigue test machine designed by August Woehler.

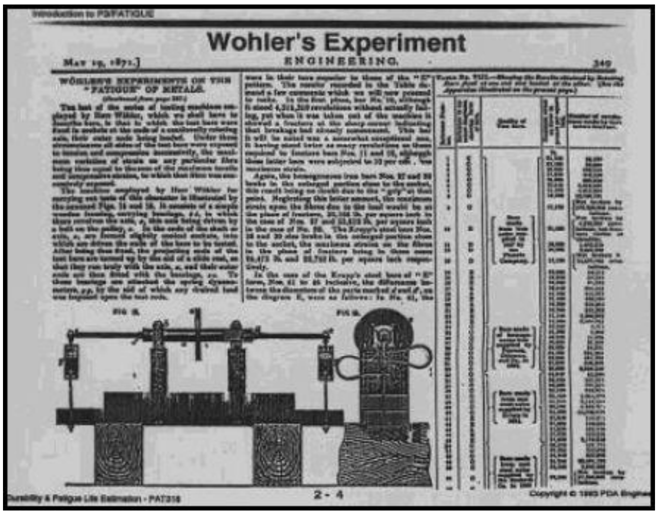


**Figure 2.6:** August Wohler’s fatigue test machine in 1870

Source: Vervoort (2012)

### 2.4.3 Fatigue Test

There are many types of loads that are to be applied for the fatigue test such as rotating-bending, cantilever bend, axial push and pull and also torsion. Fatigue test experiment was done to determine the fatigue life of a material where the material will be attached to the machine and load will be applied to the material to see on which cycle that the material fails. The parameters that needed to be considered for rotating bending fatigue test are its length, its diameter and notch radius. Fatigue strength is determined by applying different levels of cyclic stresses to individual test specimens and measuring the number of cycles to failure. Then, the data taken are the stress value and the number of cycle that the material fails. The data are plotted in the form of stress number versus the number of cycles or it is called (S-N curve). For material such as low carbon steel, it exhibits a flattening off at a particular stress level at (a) which is referred to as fatigue limit. Roughly, the fatigue limit is usually about 40% of the tensile strength. In principle, the component was designed so that the applied stress does not exceed this level or the components will fail. The main factor is that when the stress concentration is high, it will leads to initiation of the crack although the components has been designed to handle the stress below the safe limit. Most material, however, exhibits a continually falling curve (b) and the usual indicator of fatigue strength is to quote that the stress below which failure will not expected in less than a given number of cycles is referred to as endurance limit. Figure 2.7 shows S-N curve for low carbon steel and aluminium.

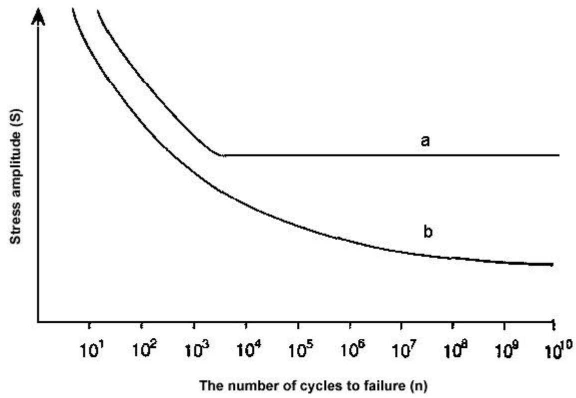


**Figure 2.7:** S-N curve for low carbon steel (a) and aluminium (b)

Source: Boyer (1986)

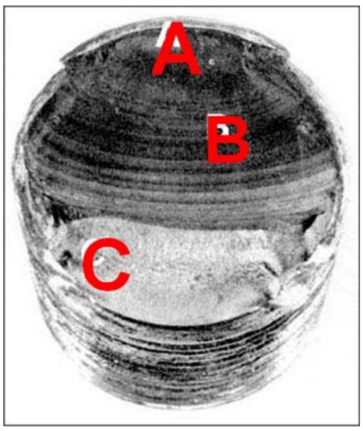


**Figure 2.8:** Fracture surface, from above to bottom: crack initiation (A), crack propagation (B), sudden failure (C)

Source: Budynas (2008)

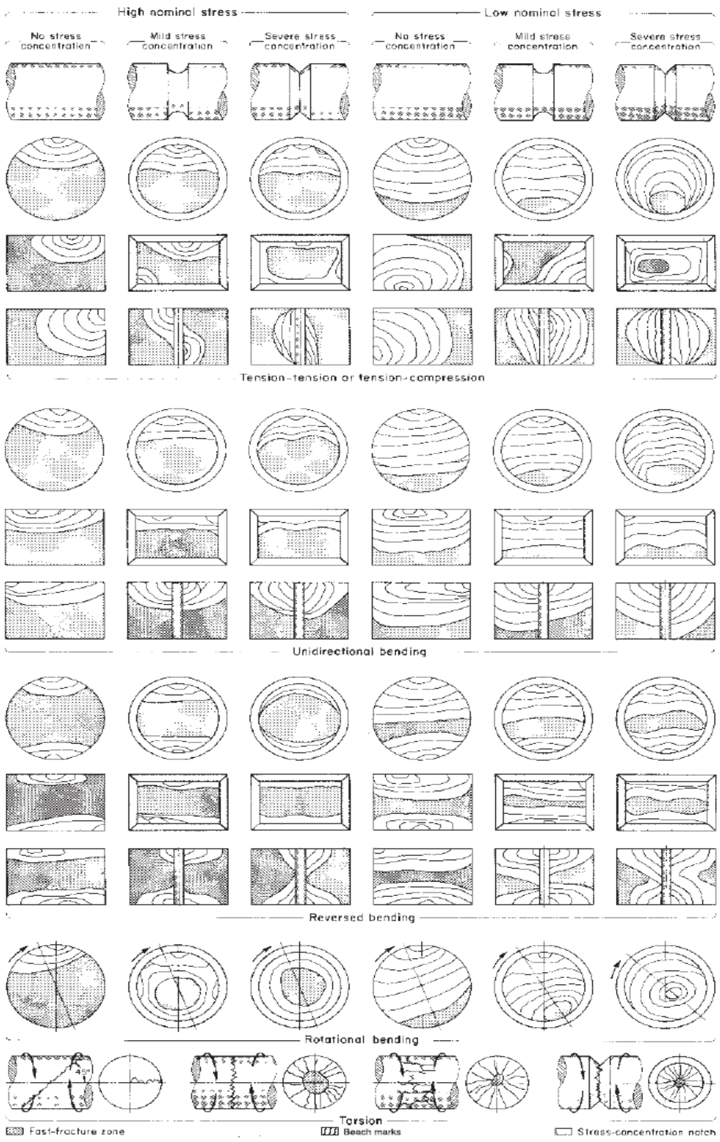


**Figure 2.9:** Type of surface fracture

Source: Budynas (2008)

Figure 2.8 shows three region in fatigue failure such as crack initiation, crack propagation and rapid fracture or sudden failure region. Figure 2.9 shows type of surface fracture depending on the stress used. There have been many researches that have been done to study the effect of fatigue. In one study of fatigue, contact fatigue has been studied and experimented. Contact fatigue often happens in gear. It can increase the sound emitted from the gearbox and also subsequent to gear tooth failure due to the reduced load carrying ability of the tooth and by the damages acting as initiation points for fatigue cracks as shown in Figure 2.10.

**Figure 2.10:** Extensive contact fatigue damage in gear

Source: Widwark (1998)

From the gear box experiment, there is some evidence that material structure plays a role in fatigue life in materials. In carburised steel was compared to a through-hardening bearing steel alloy with same surface hardness and roughness in roller to roller testing. This study showed that the carburised steel displayed the longest fatigue lives and that the induction-hardened steel and through-hardened steel had approximately the same fatigue contact life.

From this research, the idea of heat treating the material before fatigue testing is applied to quenching and tempering method to low carbon steel to see the microstructure of the low carbon steel after it fails to the number of cycle with specific load.

### 2.4.4 Fracture

The fracture happens because of the material failure after subjected to cyclic loadings. There are two types of failure that are intergranular fracture and transgranular fracture. Intergranular fracture is fracture that follows the grains of the material as shown in Figure 2.11. If the material has multiple lattice organizations, when one lattice ends and another begins, the fracture changes direction to follow the new grain. This results in a fairly jagged looking fracture with bumpy edges. Transgranular fracture is fracture that follows the edges of lattices in a granular material, ignoring the grains in the individual lattices as shown in Figure 2.12. This results in a fairly smooth looking fracture with less sharp edges than one that follows the changing grains. With heat treatment methods, the microstructure of a material will change whether the grains become larger or smaller depending on the type of heat treatment done.

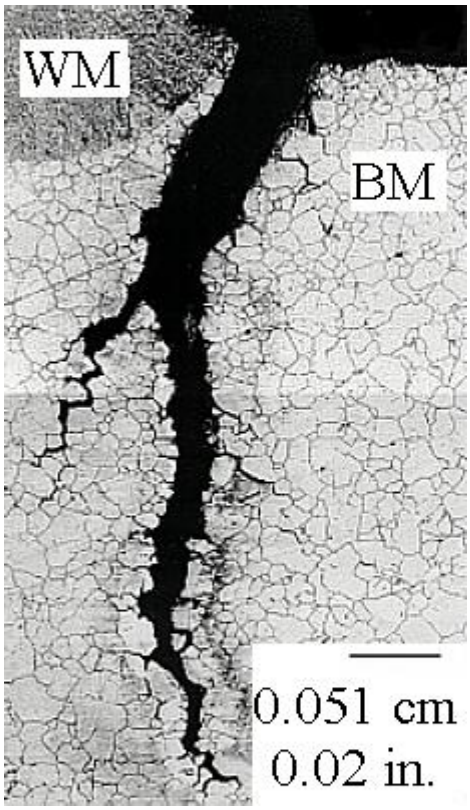


**Figure 2.11:** Intergranular fracture

Source: Bartlett (2012)

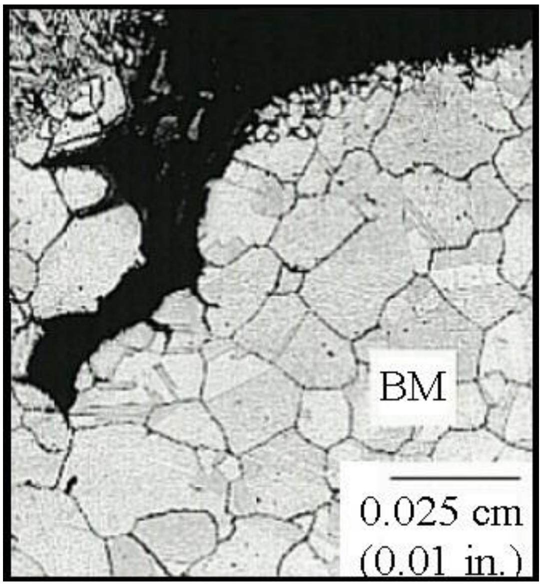


**Figure 2.12:** Transgranular fracture

Source: Bartlett (2012)

# CHAPTER 3

# METHODOLOGY

## 3.1 INTRODUCTION

In order for the project to success, a flow of method was used. The project starts by creating flow chart and Gantt chart. Flow chart acts as a guide for this project to be successfully carried out accordingly following the steps proposed. The gantt chart helps as a guide for the project to be finished within its timeframe. The most important part of this project is the rotational bending fatigue test where the S-N curve was determined. Precise steps were done in order to achieve the expected results. The flow chart of project was shown in Figure 3.1.

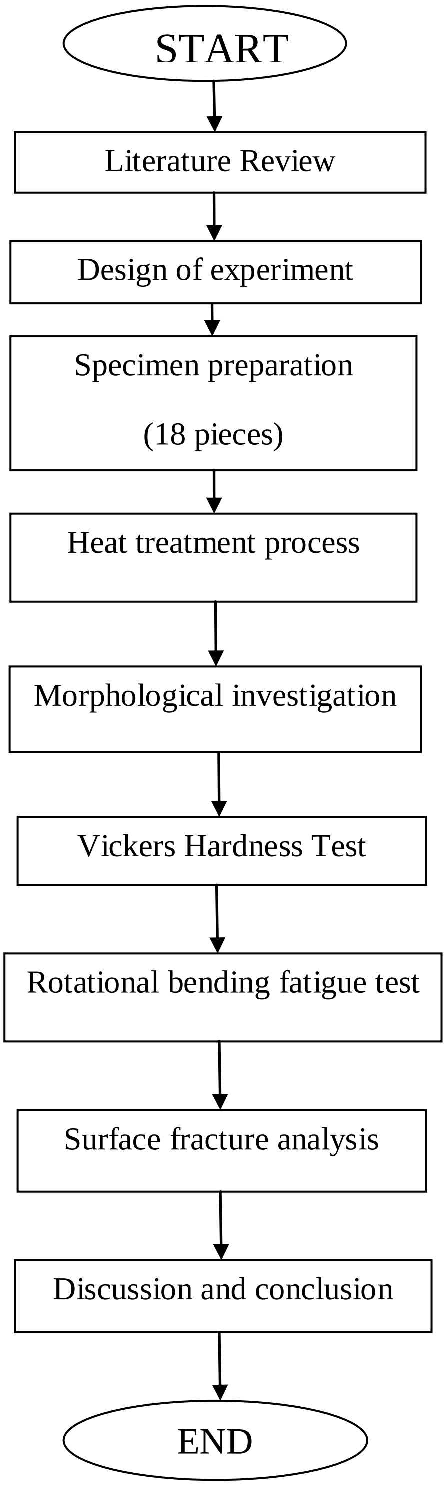


**Figure 3.1:** Project flow chart

## 3.2 DESIGN OF EXPERIMENT

To study the effect of heat treatment on fatigue life of low carbon steel, the important thing that needed to be done is the design of experiment. The first thing that needed to do is selecting the material and determine the number of specimens needed for the experiment. For the first step, raw low carbon steel material was machined according to the dimensions needed. Two heat treatment processes were carried out to the specimens. To see whether the heat treatment process was a success, the microstructure of the specimens was investigated using optical microscope. The hardness of the specimens was investigated using Vickers hardness test method. The most important step of this project was rotational bending fatigue test to determine the S-N curve of low carbon steel AISI 1025. Next, the fracture surface of the failed specimens were analysed under optical microscope to see the type of fracture.

### 3.2.1 Specimens Preparation

After the design of experiment process end, the specimens preparation were done. The material that was tested is AISI 1025 low carbon steel. A total of 18 pieces of raw material was prepared and machined according to the dimension needed. The length of the raw material is 150 mm with the diameter of 20 mm as shown in Figure 3.4.

#### 3.2.1.1 Material

The material chosen for this experiment is mild steel where the carbon content of this material is only 0.24% and suitable for low carbon steel specification. It was provided by the shape of cylindrical bar that has the length of 150 mm and 20 mm of diameter. It has typical properties of steel that are high strength, high ductility and easy for machining process. Figure 3.2 shows the design of specimen drawn using SOLIDWORKS.

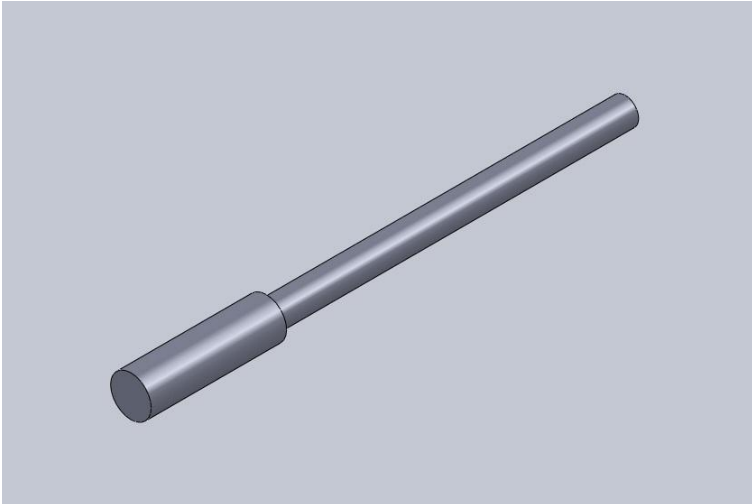

**Figure 3.2:** Specimen drawn by SOLIDWORKS

#### 3.2.1.2 Machining

Turning process using lathe machine was done to reduce the diameter of the specimens. Parameters such as feed rate, the feed, the spindle speed and the depth of cut needs to be calculated before starting the process to produce a good finishing. The type of lathe machine used is ERL-1340LATHE (ERL series) that was developed by SHUN CHUAN MACHINERY IND.CO., LTD as shown in Figure 3.3. The tool used was carbide with radius of 0.2 mm. The cutting speed of low carbon steel by using high speed tool is shown in Table 3.1.

**Table 3.1:** Cutting speed selection

| **Material** | **Cutting speed (mm/min)** |
|---|---|
| Mild steel | 100-200 |

Then the spindle speed is calculated by Equation 3.1:

***Sample of calculation:***

$$N = \frac{CS \times 1000}{\pi d} \tag{3.1}$$

Where:

$N$ = spindle speed (rpm)

$CS$ = Cutting speed (mm/min)

$d$ = diameter of raw material (mm)

From Table 3.1, taking cutting speed ranging from 100 to 200 and substitute into Equation 3.1

$$N = \frac{100 \times 1000}{\pi (20)}$$
$$= 1591.549431 \text{ rpm}$$

**Table 3.2**: Feed selection based on type of material

| **Material** | **Feed, *f* (mm/rev)** |
|---|---|
| Mild steel | 0.13 |
| Brass | 0.1 |
| Aluminium | 0.25 |

The feed rate is calculated using Equation 3.2:

$$v_f = f \times N \tag{3.2}$$

Where:

$f$ = feed (mm/rev)

$N$ = spindle speed (rpm)

Substitute $N$ = 1591.549431 rpm into Equation 3.2 and taking the value of feed = 0.13 mm.rev

$$v_f = 0.13 \times 1591.549431$$
$$= 206.901 \text{ mm/min}$$

$$d = \frac{d_0 - d_f}{2} \tag{3.3}$$

Where:

$d_0$ = Initial diameter (mm)

$d_f$ = Final diameter (mm)

Substitute $d_0$ with 20mm and $d_f$ with 12 mm

$$d = \frac{20 - 12}{2}$$

$$= 4 \text{ mm}$$

The procedures that were done are firstly, the lathe machine was switched on and the safety was ensured so that the process will run smoothly. Then, the specific parameters that were determined in the calculation were set up to the machine so that the finishing will be smooth.

After machine checking, the raw material was attached to the spindle and was checked whether it is centralised so that there are no nipples at the end of the process. Then, to make sure the specimen is not vibrating during machining process, a drill hole was made to the both end of the specimen using centre drill with diameter of 2.0 mm and 5 mm length. After that, live centre was attached to the drilled hole and make sure it rotates along with the specimen as a support to make sure the specimen does not vibrate during the process. Then, the machine was switched on using 1600 rpm of spindle speed and 0.2 mm of diameter was slowly fed to the material as shown in Figure 3.5. Figure 3.6 shows the half completed specimen with the diameter of 12 mm.

After the machining process has been done, the specimen was measured using vernier caliper to make sure whether it is machined according to the specific design.

Then, the steps were repeated for other 17 pieces. Figure 3.7 shows the completed specimen.


**Figure 3.3:** Conventional lathe machine, ERL-1340LATHE (ERL series)

**Figure 3.4:** Raw material

**Figure 3.5:** Turning process

**Figure 3.6:** Specimen (12 mm)

**Figure 3.7:** Completed specimen

### 3.2.2 Heat Treatment

Heat treatment is one of the methods used to improve the strength of steel. Heat treatment was done to change the microstructure of the specimen. For this experiment, two heat treatment processes were conducted that was oil quenching and tempering. The brand of the furnace that was used is Nabertherm from German that can heat up from 30°C to 3000°C. The parameters that need to be considered in this process are the temperature and holding time. Table 3.3 and 3.4 show the parameters for oil quenching and tempering processes. Figure 3.8 and 3.9 show the diagram for both heat treatment processes.

**Table 3.3:** Parameters for oil quench process

| **Parameters** | **Value** |
|---|---|
| Temperature (°C) | 870 |
| Holding time (minutes) | 30 |
| Period in oil bath (seconds) | 30 |

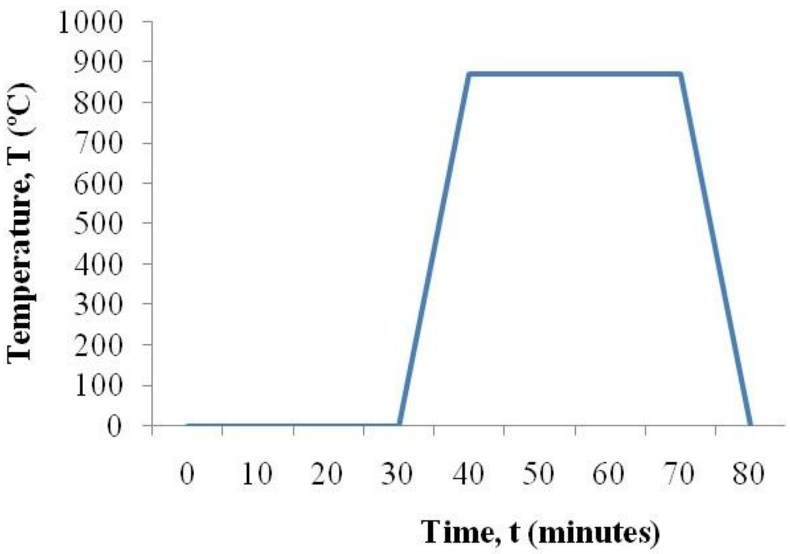


**Figure 3.8:** Diagram for quenching process

**Table 3.4:** Parameters for tempering process

| Parameters | Value |
|---|---|
| Temperature (°C) | 450 |
| Holding time (minutes) | 60 |

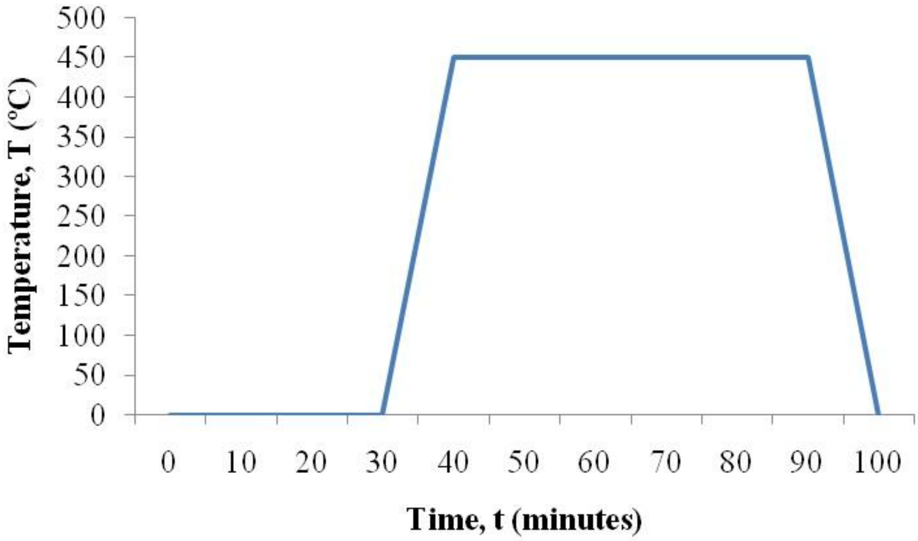


**Figure 3.9:** Diagram for tempering process

The procedures that were done in this process are firstly, the furnace was heated up until it reaches the austenite temperature of 870°C and the waiting time for the temperature of the furnace to rise is 30 minutes from the room temperature. After the furnace has reached the specific temperature, the specimen was put in the furnace and was held in the furnace for 30 minutes. Then, it was taken out and was directly quenched in oil bath as shown in Figure 3.11 and 3.12 for 30 seconds. After that, the steps that were done before were repeated for the next 11 specimens. Figure 3.13 shows the appearance of the oil quenched specimen.

After quenching process for all 12 specimens have been done, six specimens were selected to do further heat treatment called tempering. The furnace was reheated until it reaches the temperature of 450°C. After the furnace has reached the specific temperature, the specimen was put in the furnace and was held for one hour. The specimen was taken out and let it cooled in room temperature. Steps for tempering process were repeated for next five specimens. Figure 3.14 shows the tempered specimen.


**Figure 3.10:** Nabertherm furnace


**Figure 3.11:** Oil bath

**Figure 3.12:** Oil bath (inside)

**Figure 3.13:** Oil quenched specimen

**Figure 3.14:** Tempered specimen

### 3.2.3 Fatigue Test

Fatigue is a localised, progressive and permanent structural damage when a material is subjected to cyclic loading. For this test, the important parameter that needed to be determined is the number of cycle to failure. This test was conducted using a fatigue testing machine that manufactured by Gunt Hamburg company from German as shown in Figure 3.15. From this experiment, S-N curve for low carbon steel with different type of heat treatment processes is to be determined.

The procedures that were done for the fatigue test is that fatigue testing machine was first connected to power supply. The protective hood was removed to put the specimen in. The load gauge was relieved to 0 N using the hand wheel by rotating it using counter-clockwise direction. The specimen was inserted into the machine, and the chuck was tightened so that the specimen will not move during rotation. Then, the protective hood was placed back and all of the knobs were locked. Before starting, the cycle value was reset to zero. The start button was pressed and let the specimen rotate with load of 0 N for a few seconds. The load was set to the desired load by rotating it following clockwise direction. Wait until the specimen failed, and the reading of cycle was taken.

There are things that needed to be considered before doing this experiment. Firstly, EMERGENCY OFF is pulled out and is functioning well. Secondly, the machine was switched on using the master switch. Third, the counter display must be zero and was reset using RST button. Fourth, motor was started up using motor controlling switch. Fifth, make sure the spindle running smoothly. Sixth, make sure the counter is counting correctly. Table 3.5 shows the fatigue test parameters to be used.

**Table 3.5:** Fatigue test parameters

| Parameters | Value |
|---|---|
| Frequency (Hz) | 50 |
| Temperature (°C) | 20-25 (room temperature) |
| Load (N) | 60-170 |
| Stress ratio, R | -1 |

**Figure 3.15:** Fatigue testing machine

### 3.2.4 Mounting Process

After one specimen of each heat treatment process has been failed, a sample with approximately 1 cm of height was cut from the specimens using vertical grinding machine. The cold mounting method was used to mount the sample. The purpose of mounting the sample is to ease the grinding and polishing processes. The mixture of the resin polymer in the form of powder and resin monomer in the form of liquid is 2:1. It takes about 10 minutes for the mixture of acrylics resin to be cured in the pressure vessel at 2 kPa. Figure 3.16 shows the mounted sample.

**Figure 3.16:** Mounted specimens

### 3.2.5 Grinding

The purpose of grinding process was to remove the excess material from the surface to make the sample smoother. The samples were ground by using the roll grinder as shown in Figure 3.17. The specimens were ground using four different grit of sand paper. Initially, sand paper with a grit of #240 was used followed by #320, #400 and #600. The position of sample for grinding process is important to make sure the surface does not scratch. Firstly, arrows were being drawn at the bottom of the mounted samples. The direction for grinding process is always downward. For sand paper with grit of #240, the position of the samples according to the arrow is upward. For the sand paper with the grit of #320, the samples were rotated 90° clockwise and grounded downward. The process continued for #400 and #600.


**Figure 3.17:** Grinding machine, from left to right: sand paper #240, #320, #400 and #600

### 3.2.6 Polishing

Polishing is the process of creating a smooth and shiny surface by rubbing it or using a chemical action, leaving a surface with a significant reflection. When an unpolished surface is magnified thousands of times, it usually looks like mountains and valleys. The process of polishing with abrasives starts with coarse ones and graduates to fine ones. There are three stages for polishing according to the roughness of the polisher that are 6 μm, 3 μm and 0.5 μm. The time for polishing is about 3 minutes for each roughness and can be set from the machine. The speed of the machine is 250 rpm. Figure 3.18 shows the polishing machine that was used.

**Figure 3.18:** Polishing machine

### 3.2.7 Etching

The specimens have undergone the etching process using nitric acid with 0.2% concentration for about two seconds. The function of etching is to make sure the surface of the specimens reacts with photosensitive chemical. Proper technique and attire was used during etching the specimens, washing the specimens using distilled water and the disposal of the etchant. It is where the chemical reacts with the surface along the grain boundary and the grain size will be clearly seen.

### 3.2.8 Vickers Hardness Test

Vickers test is often easier to use than other hardness tests since the required calculations are independent of the size of the indenter, and the indenter can be used for all materials irrespective of hardness. The Vickers hardness test parameters were shown in Table 3.6. The method used for this test is taking five points at the radius of 6 mm. The distance between the points is 1 mm. Then, Vickers hardness number for each sample were taken and analysed. Figure 3.19 shows the Vickers hardness tester machine.

**Table 3.6:** Vickers hardness test parameters

| Parameters | Value |
|---|---|
| Load | 500gf |
| Dwell time | 10 seconds |
| Magnification | 40× |
| Light intensity | 32 |

**Figure 3.19:** Vickers hardness test machine

## 3.3 MORPHOLOGICAL STUDY

The optical microscope, often referred to as the "light microscope", is a type of microscope which uses visible light and a system of lenses to magnify images of small samples. Figure 3.20 shows the optical microscope. The optical microscope magnifies an image by sending a beam of light through the object. In order for any specimen to be observed, the sample was grounded using sandpaper of different grit sizes. Then the sample was polished into a mirror-like image and was etched with a 0.2% concentration nitric acid. The methods were carefully handled so that the microstructure can be seen. The optical microscope was connected the computer which the Progress CapturePro 2.5 software was installed. For this project, three magnifications were used and the lens needs to be carefully adjusted in order to get a clearer view of the microstructure. The scale that used for this project is 1:100 µm.

**Figure 3.20:** Optical microscope

# CHAPTER 4

# RESULTS & DISCUSSION

## 4.1 INTRODUCTION

The analysis process is the process to gather the result from any simulation process, theoretical equation or experiment process. The analysis method that was used in this project is the experiment of the mild steel that has been heat treated by various heat treatment processes. Then, the specimens were subjected to rotational bending force from fatigue test. In this project, the rotating bending fatigue testing has been conducted to define the number of cycle to failure in a certain range of applied stress. The purpose of this experiment is to study on how the various heat treatment processes affected the fatigue life of a material. Based on the studies, it was shown that the further heat treatment will resulted in higher fatigue life compared to the material that has not undergone heat treatment processes. Figure 4.1 shows the specimen's physical appearance.

**Figure 4.1:** Specimen’s appearance, from left to right: Specimen with no heat treatment, oil quenched specimen and tempered specimen

## 4.2 MATERIAL COMPOSITION

The material composition for the specimens has been analyzed using spectrometer machine. The main purpose of this analysis is to define the percentage of carbon and iron type of material used in the present study. The percentage of the chemical composition for this material is shown in Table 4.1. This analysis is also important to define the temperature that can be used for the heat treatment processes. The carbon percentage for the material used in this experiment is 0.24%. Based on the composition is AISI 1025.

**Table 4.1:** Chemical composition of the specimen

| Chemical composition | Reading | | | |
|---|---|---|---|---|
| | **1** | **2** | **3** | **Average (%)** |
| Iron (Fe) | 98.2 | 98.2 | 98.2 | 98.2 |
| Carbon (C) | 0.253 | 0.235 | 0.231 | 0.240 |
| Manganese(Mn) | 0.448 | 0.462 | 0.447 | 0.453 |
| Sulphur (S) | 0.0084 | 0.0088 | 0.0090 | 0.0087 |
| Silicone (Si) | 0.0711 | 0.0632 | 0.0616 | 0.0653 |
| Chromium (Cr) | 0.132 | 0.135 | 0.136 | 0.134 |
| Molybdenum(Mo) | 0.0226 | 0.0237 | 0.0290 | 0.0251 |
| Nickel (Ni) | 0.111 | 0.109 | 0.111 | 0.110 |
| Stannum (Sn) | 0.0119 | 0.0121 | 0.0130 | 0.0123 |

## 4.3 MORPHOLOGICAL INVESTIGATION

In order to determine whether the heat treatment processes done is success or not, morphological investigation has been done. It was done by using optical microscope to investigate the microstructure of the specimen. For specimens with no heat treatment, the microstructure is ferrite and pearlite. After oil quenching has been done, martensite was introduced thus harden the steel. Then, further treatment called tempering has been done and the microstructure becomes cementite. The scale used on the optical microscope for investigating the microstructure is 1:100 μm.

### 4.3.1 Mild Steel With No Heat Treatment

The type of microstructure for the specimen with no heat treatment is ferrite and pearlite. The picture was captured using three magnification that are 10×, 20× and 50×. The light colored grain is called ferrite and the dark one is called pearlite as shown in Figure 4.2. Figure 4.3 and Figure 4.4 show the microstructure under 20× and 50× respectively taken at the same field of view.

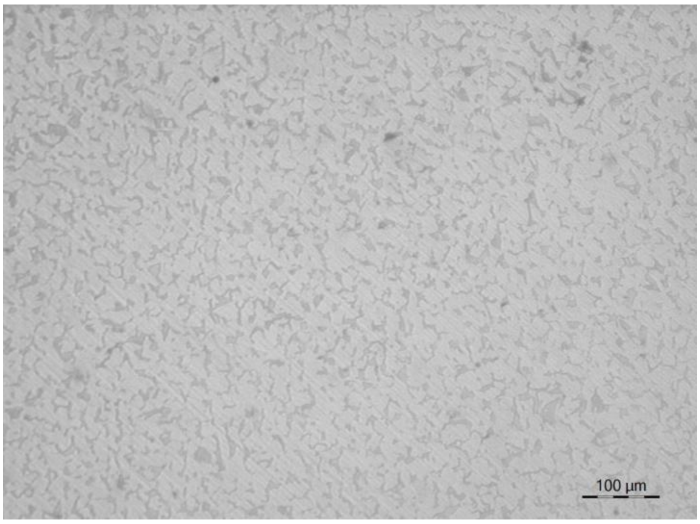


**Figure 4.2:** Microstructure under 10× magnification

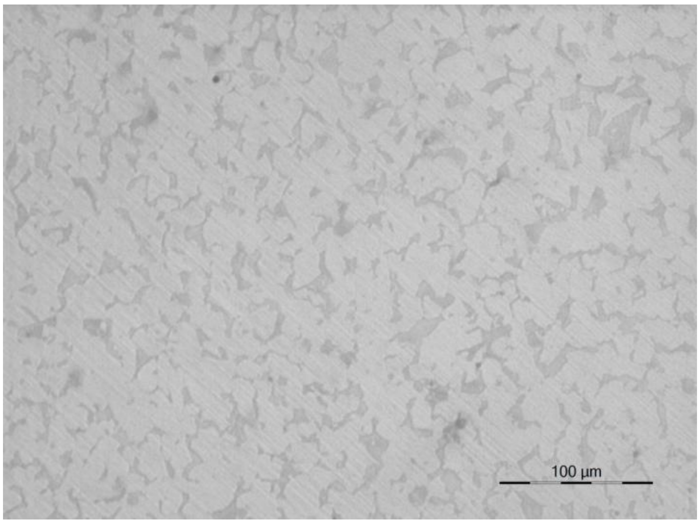


**Figure 4.3:** Microstructure under 20× magnification

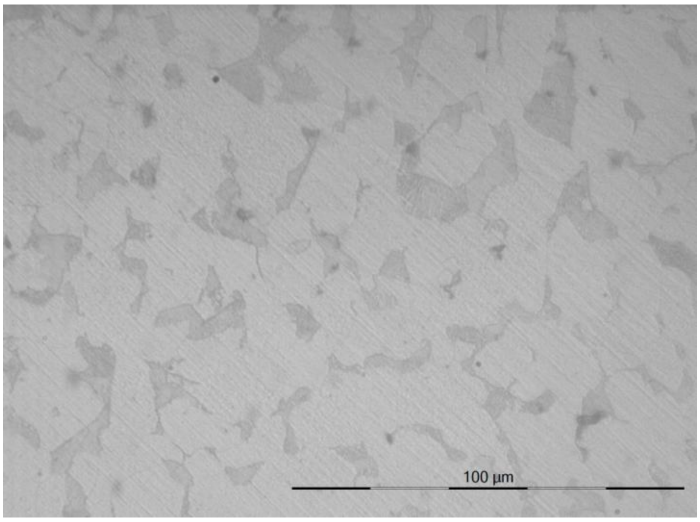


**Figure 4.4:** Microstructure under 50× magnification

### 4.3.2 Oil Quenched Mild Steel

When quenching process has been done, the microstructure becomes martensite where the ferrite is reduced thus the martensite (black) is increasing and the material becomes harder. Martensite in plain-carbon steels is a metastable phase consisting of a supersaturated interstitial solid solution of carbon in body-centered cubic iron of body-centered tetragonal iron. The microstructure of martensites in plain-carbon steel depends on the carbon content of the steel. If the steel contains less then about 0.6% C, the martensite consists of domains of laths of different but limited orientations through a whole domain. Figure 4.5, 4.6 and 4.7 show the microstructure under magnification of 10×, 20× and 50× respectively taken at the same field of view.

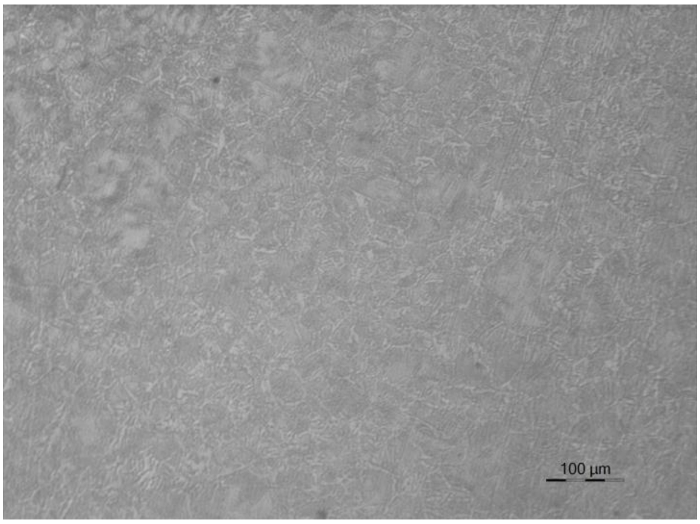


**Figure 4.5:** Microstructure under 10× magnification

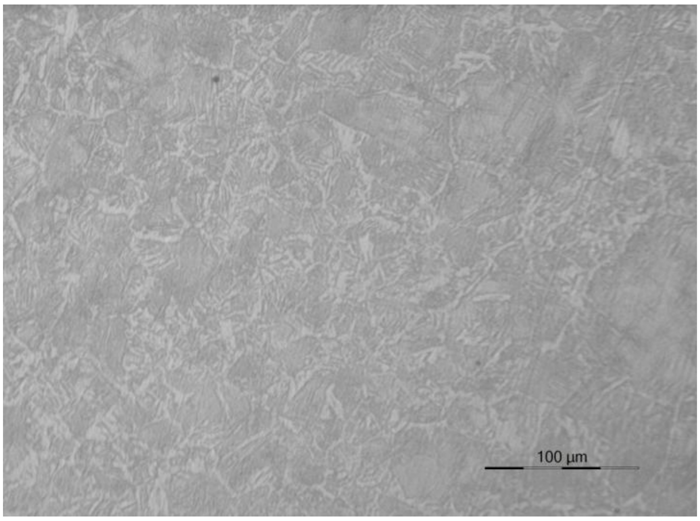


**Figure 4.6:** Microstructure under 20× magnification

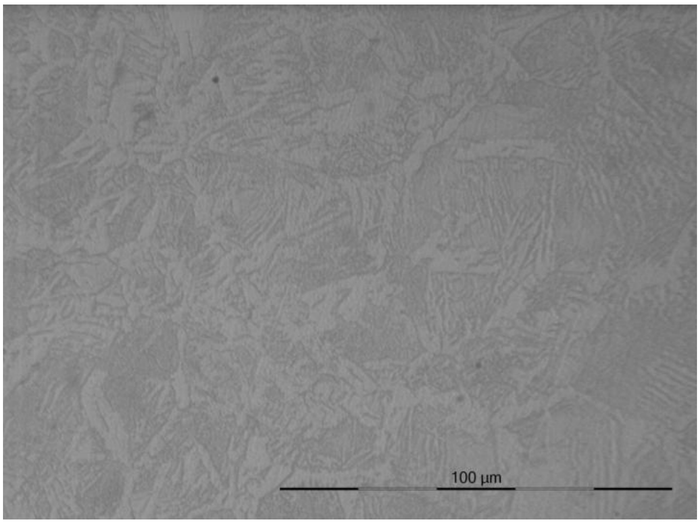


**Figure 4.7:** Microstructure under 50× magnification

### 4.3.3 Tempered Mild Steel

A process done subsequent to quenching is tempering. Tempering is further heat treatment to increase the hardness of the specimen by removing the brittleness formed during quenching process. The temperature to reheat the specimen is under eutectoid temperature and it is also to soften the martensite formed during rapid cooling process that is quenching by transforming it to a structure of iron carbide particles in a matrix of ferrite.

Martensite is a metastable structure and decomposes upon reheating. In lath martensites of low-carbon plan-carbon steels there is a high dislocation density, and these dislocations provide lower-energy sites for carbon atoms than their regular interstitial positions. Htun (2008) stated that in tempered process, ferrite and epsilon carbide are formed at 400°C and 450°C, and spheroid cementite are formed and grown above 450°C. Epsilon carbide are formed when tempered. The carbide that forms when martensitic steels are tempered from 200 - 700°C is cementite, $Fe_3C$. Figure 4.8, 4.9 and 4.10 show the microstructure under magnification of 10×, 20× and 50× respectively taken at the same field of view.

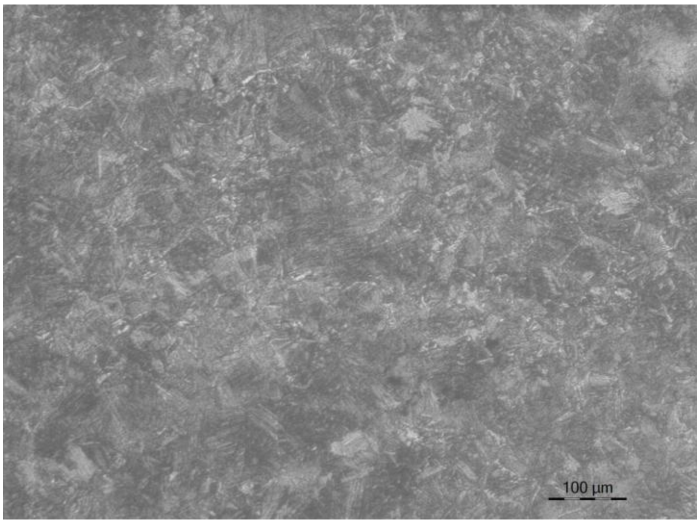


**Figure 4.8:** Microstructure under 10× magnification

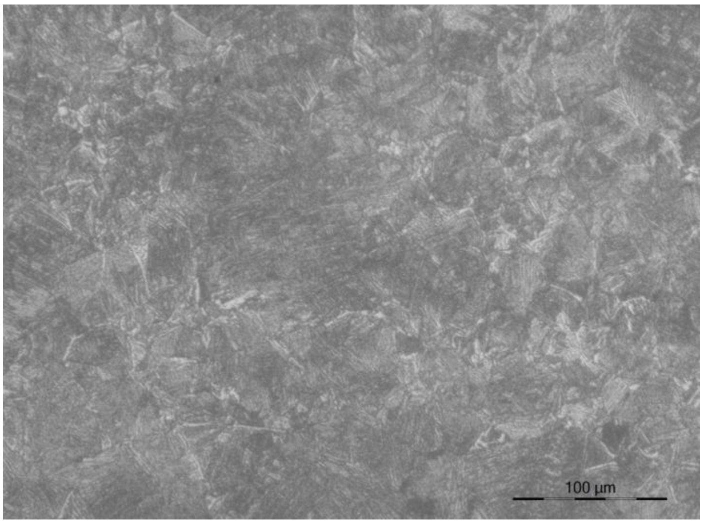


**Figure 4.9:** Microstructure under 20× magnification

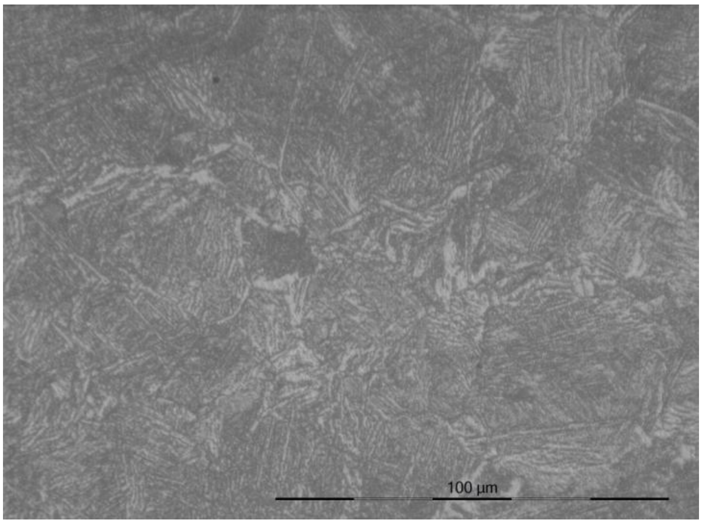


**Figure 4.10:** Microstructure under 50× magnification

## 4.4 VICKERS HARDNESS TEST

After the microstructure has been invesigated, Vickers hardness test was performed in order to analyse the hardness number of heat treated specimens. The Vickers hardness test is done by using Vickers Hardness testing machine. To investigate the hardness of the specimen, five points have been selected where the distance between each points is approximately 1 mm. The first point for this test is taken at the center of the specimen. Some calibrations has been done to make sure the point is located exactly at the center of the specimen. The end point for the test is at the edge of the specimen. The load for the Vickers hardness test used is 500 g force. The indention time was fixed to 10 seconds. Figure 4.11 shows the screen of Vickers hardness machine that displays the Vickers hardness number. Figure 4.12 shows the method used for Vickers hardness test.

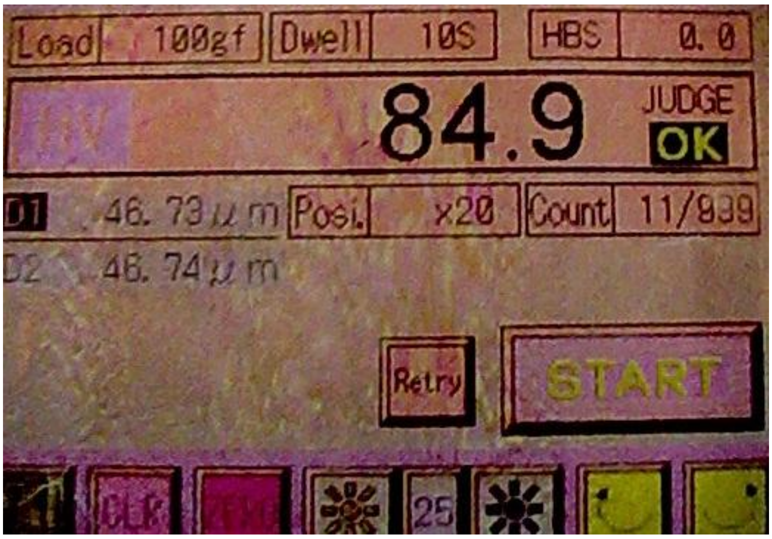


**Figure 4.11:** Vickers hardness machine screen showing Vickers Hardness Number

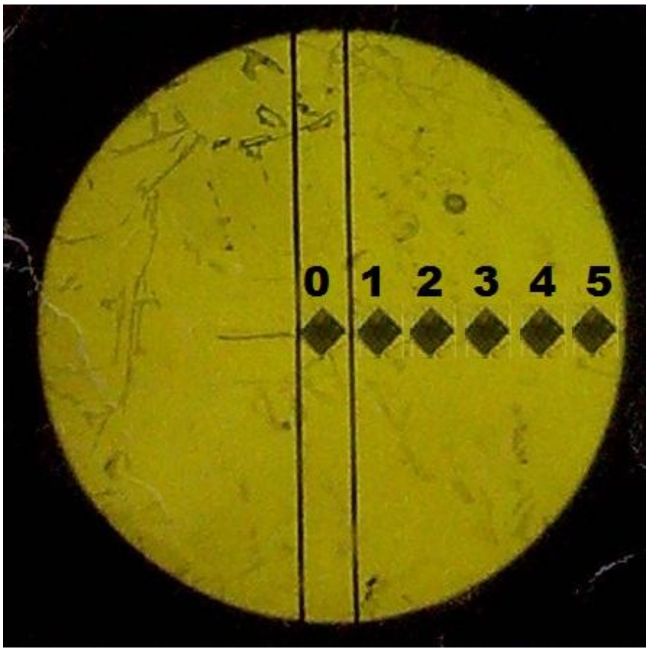


**Figure 4.12:** Method for Vickers hardness test

**Table 4.2:** Vickers Hardness Number for 5 points

| **Heat treatment process** | **Vickers Hardness Number** | | | | | |
|---|---|---|---|---|---|---|
| | **0** | **1** | **2** | **3** | **4** | **5** |
| **No heat treatment** | 128.9 | 140.2 | 142.8 | 148.7 | 146.9 | 150.6 |
| **Quenching** | 200.4 | 224.9 | 236.5 | 245.1 | 259.2 | 262.9 |
| **Tempering** | 250.2 | 252.1 | 268.4 | 271.6 | 276.0 | 284.7 |

Table 4.2 shows the reading of Vickers Hardness Number for different heat treatment processes. Figure 4.13, 4.14 and 4.15 show the Vickers Hardness Number curve for three different condition. Figure 4.16 shows the comparison between the Vickers Hardness Number for three different specimen's condition.

The data from three different heat tratment process shows that from the edge to the center of the specimen, the hardness is decreasing. It shows that the heat treatment processes is done from the edge to the center of the specimen and also show that the heat treatment processes is a success. From Figure 4.16, the tempered specimen shows the highest hardness, followed by oil quenched specimen and finally the specimen with no heat treatment. The specimen with no heat treatment curve does not goes smoothly because the exact hardness is unknown unlike the oil quenched and tempered specimens. Theoritically, the hardness of the heat treated specimens will increase from center to the edge and it is the same for every side.

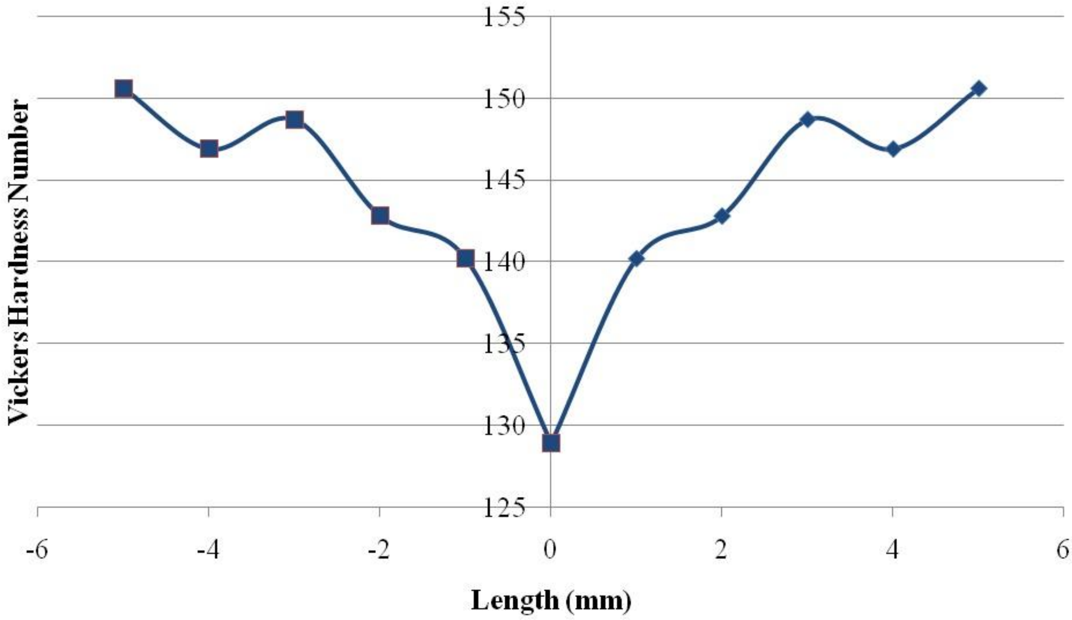


**Figure 4.13:** Vickers Hardness Number for mild steel with no heat treatment

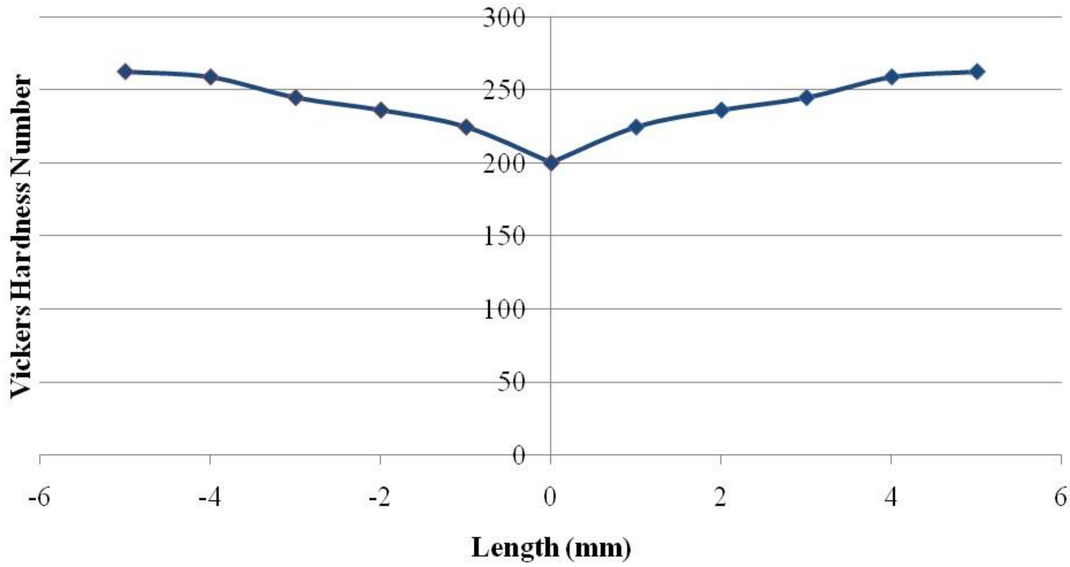


**Figure 4.14:** Vickers Hardness Number for oil quenched mild steel at temperature 870°C

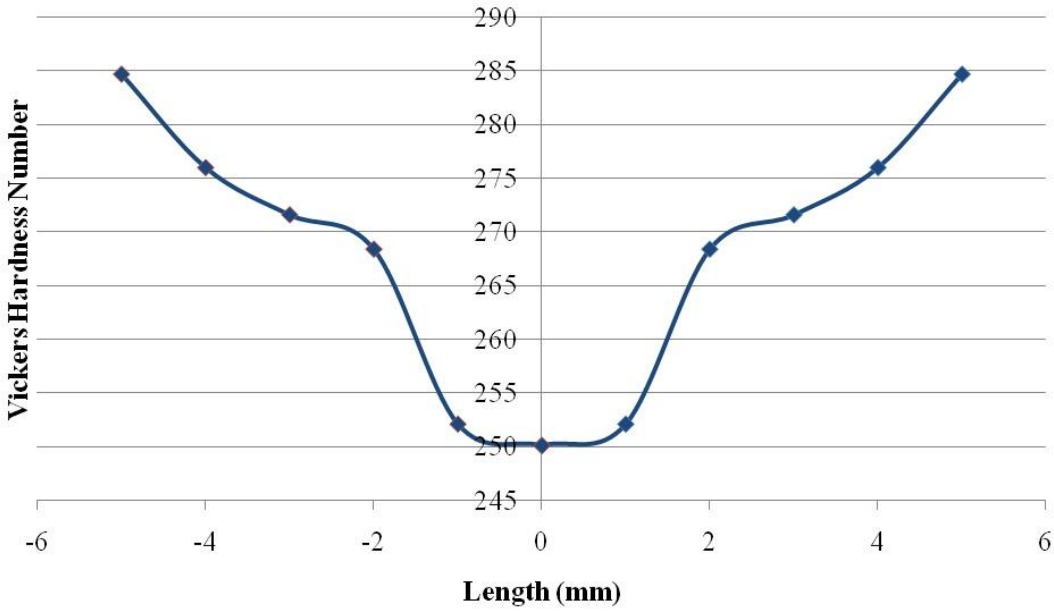


**Figure 4.15:** Vickers Hardness Number for tempered mild steel at temperature 450°C

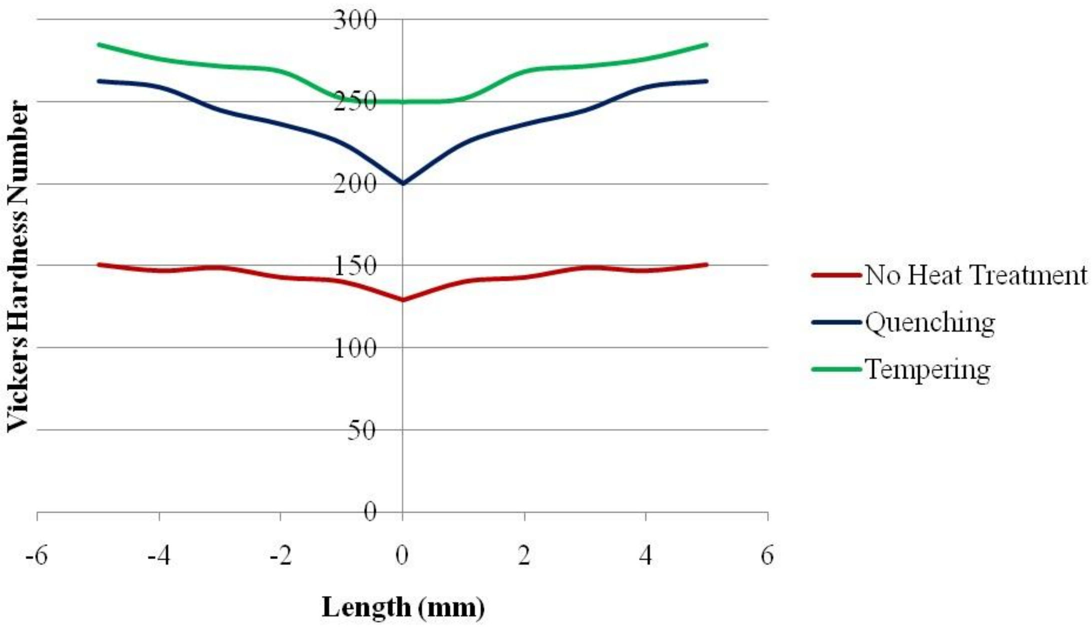


**Figure 4.16:** Comparison of Vickers Hardness Number for three different heat treatment processes

## 4.5 ROTATIONAL BENDING FATIGUE TEST

The rotational bending fatigue test was conducted to study the number of cycles to failure for mild steel specimens in different condition of heat treatment. It is to make the comparison between the effects of heat treatment to the fatigue life. The data taken will show the fatigue life for each heat treatment processes with the different stress applied to the specimens. The force is calculated theoretically using equation referred from Shigley's Mechanical Design book. Figure 4.17 and 4.18 show the experimental setup.

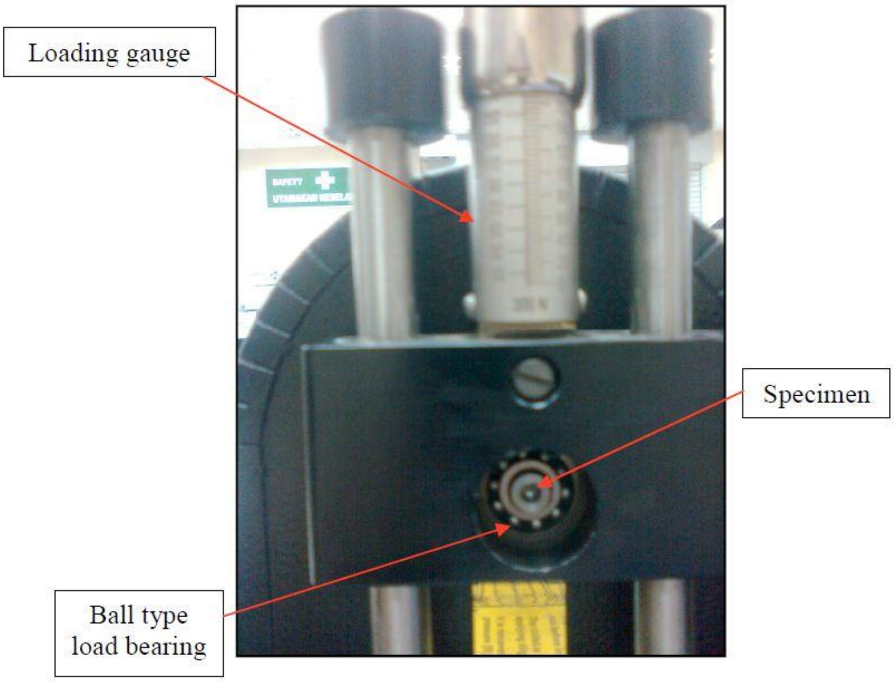


**Figure 4.17:** Applied load

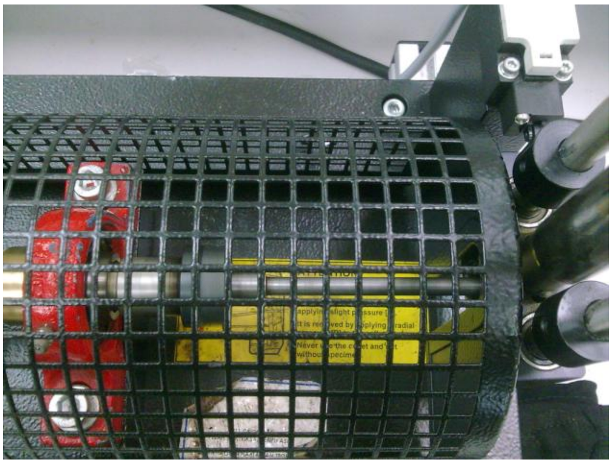

**Figure 4.18:** Experiment setup

### 4.5.1 Determination of Normal Stress Due To Bending

To select the right force to be used in the experiment for all specimens with three different heat treatment conditions, endurance limit was determined. It is to make sure that the stress under endurance limit was not selected. This section will also be discussing about the calculation used to convert the load applied to stress value. Figure 4.19 shows the detail dimension of the specimen.

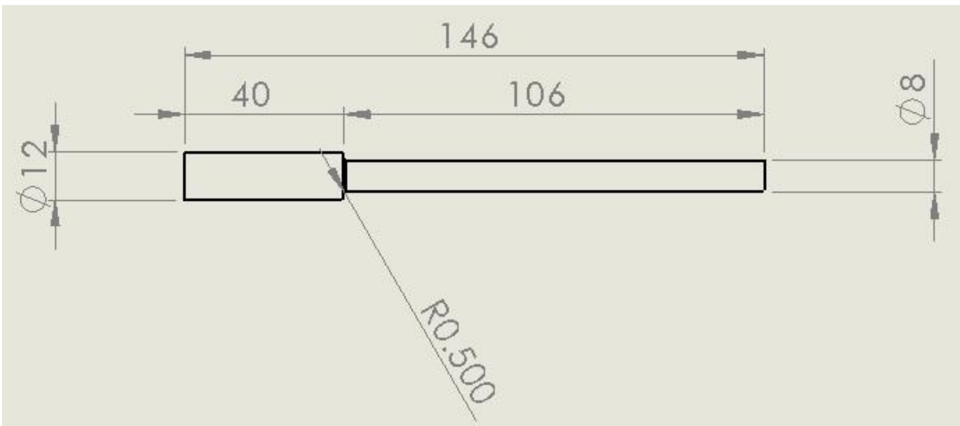


**Figure 4.19:** Detail dimension of the specimen

***Sample of calculation:***

To determine the endurance limit:

Properties:

$S_{ut}$ = 440 MPa

$S_{yield}$ = 370 MPa

$$S_e' = 0.5S_{ut} \tag{4.1}$$

Where:

$S_e'$ = Endurance limit

$S_{ut}$ = Minimum Tensile Strength (MPa)

Take the value of $S_{ut}$ = 440 MPa and then substitute in Equation 4.1:

$$S_e' = 0.5(400) = 220 \text{ MPa}$$

To determine the stress concentration and notch sensitivity:

$$K_f = 1 + q(K_t - 1) \tag{4.2}$$

Where:

$K_f$ = reduced stress-concentration factor because of lessened sensitivity to notches (fatigue stress-concentration factor)

$q$ = notch sensitivity

$K_t$ = stress-concentration factor

To get the value of *Kt* and *q*, we need to refer from Figure A-13-9 and Figure 6-20 respectively:

For $q$, we need to consider $r/d$ and $D/d$

$$\frac{r}{d} \tag{4.3}$$

$$\frac{D}{d} \tag{4.4}$$

Where:

$r$ = notch radius (mm)

$D$ = Diameter of front part (mm)

$d$ = Diameter of back part (mm)

$$\frac{r}{d} = \frac{0.5}{8} = 0.0625$$

$$\frac{D}{d} = \frac{12}{8} = 1.5$$

Thus, from figure A-13-9, the value of $K_t$ = 1.9

To determine the notch sensitivity value, we need to consider the value of $K_t$ and the value of $S_{ut}$ to see the intersection point.

Thus, from Figure 6-20, the value of $q$ = 0.62

Then, substitute the value of $K_t$ = 1.9 and $q$ = 0.62 into Equation 4.2:

$$K_f = 1 + 0.62\ (1.9 - 1) = 1.558$$

To determine the minimum force that needs to be applied in the experiment:

$$S_e' = K_f \frac{My}{I} \tag{4.5}$$

It can also be written as:

$$S_e' = K_f \frac{(F \times l)(\frac{d}{2})}{\frac{\pi d^4}{64}} \tag{4.6}$$

$F$ = Minimum force to be used in the experiment (N)

$l$ = length of the back part of the specimen (mm)

$d$ = diameter of back part of the specimen (mm)

$K_f$ = fatigue stress-concentration factor

Substitute all the parameters that have been determined into Equation 4.6:

$$220 \times 10^6 = 1.558 \frac{(F \times 106)(\frac{8}{2})}{\frac{\pi (8)^4}{64}}$$

$$F = 66.96 \text{ N}$$

The minimum force that can be applied for specimen with no heat treatment is 66.96 N. If the force applied lower than the endurance limit, the specimen will not fail. For quenching and tempering, the step is the same but by making $S_{ut}$ as the factor to get the stress value.

## 4.6 EXPERIMENT RESULTS

The experiment reading was taken after all of the specimens have failed. Table 4.3, 4.4 and 4.5 show the number of cycles to failure for the specimens with different heat treated condition. Figure 4.20, 4.21 and 4.22 show the S-N curve plotted after the data have been analysed.

### 4.6.1 Mild Steel With No Heat Treatment

**Table 4.3:** Number of cycles to failure for mild steel with no heat treatment

| Load (N) | Stress, σ (MPa) | Number of cycles to failure, N ($\times 10^3$) |
|---|---|---|
| 80 | 262.84 | 4290 |
| 90 | 295.70 | 1930 |
| 100 | 328.55 | 509 |
| 120 | 394.27 | 132 |
| 150 | 492.83 | 37.3 |
| 180 | 591.40 | 8.31 |

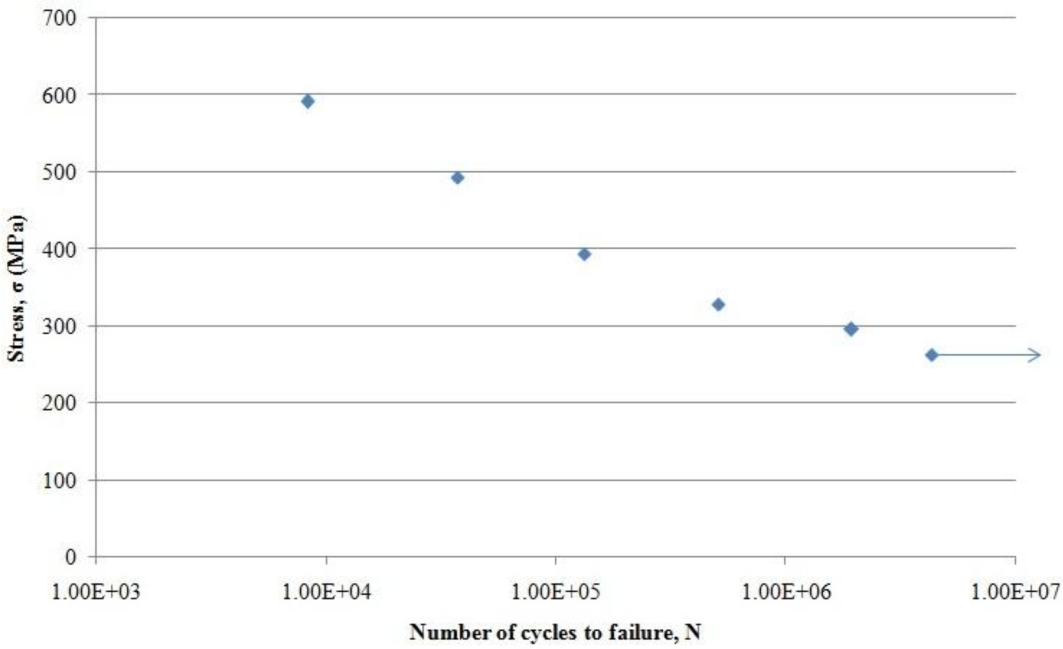


**Figure 4.20:** S-N curve for mild steel with no heat treatment

### 4.6.2 Oil Quenched Mild Steel

**Table 4.4:** Number of cycles to failure for oil quenched mild steel

| Load (N) | Stress, σ (MPa) | Number of cycles to failure, N ($\times 10^3$) |
|---|---|---|
| 110 | 361.41 | 1560 |
| 130 | 427.12 | 380 |
| 140 | 459.98 | 250 |
| 150 | 492.83 | 89.7 |
| 180 | 591.40 | 26.3 |
| 200 | 657.11 | 5.00 |

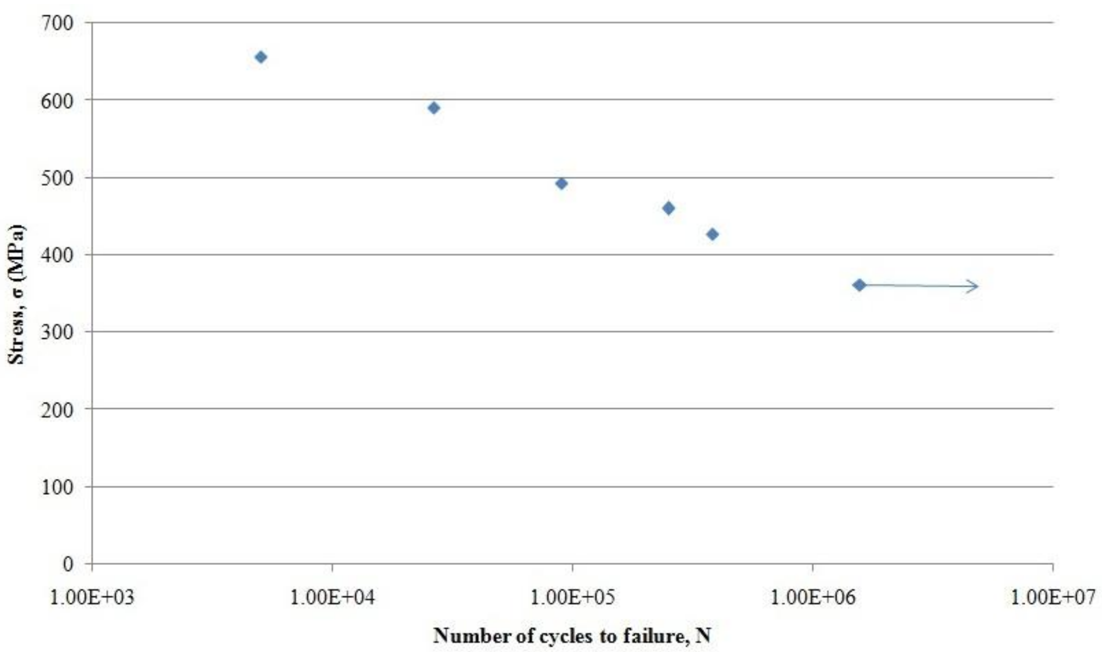


**Figure 4.21:** S-N curve for oil quenched mild steel

### 4.6.3 Tempered Mild Steel

**Table 4.5:** Number of cycles to failure for tempered mild steel

| Load (N) | Stress, σ (MPa) | Number of cycles to failure, N ($\times 10^3$) |
|---|---|---|
| 110 | 361.41 | 2800 |
| 120 | 394.27 | 680 |
| 140 | 459.98 | 430 |
| 150 | 492.83 | 250 |
| 180 | 591.40 | 57.6 |
| 220 | 722.82 | 6.13 |

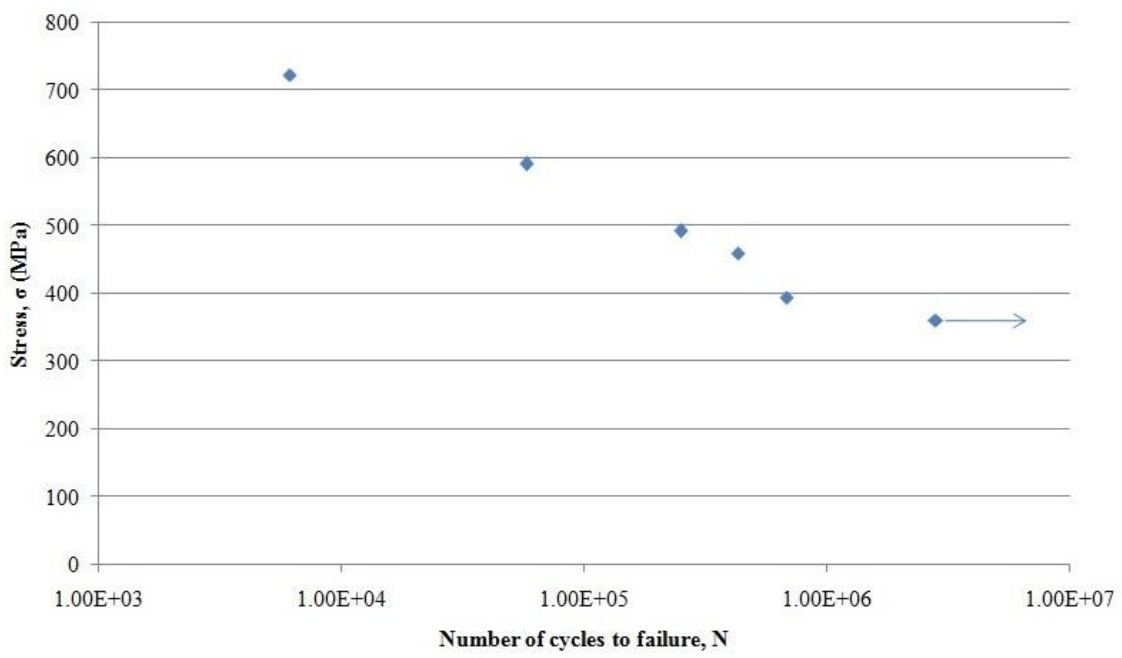


**Figure 4.22:** S-N curve for tempered mild steel

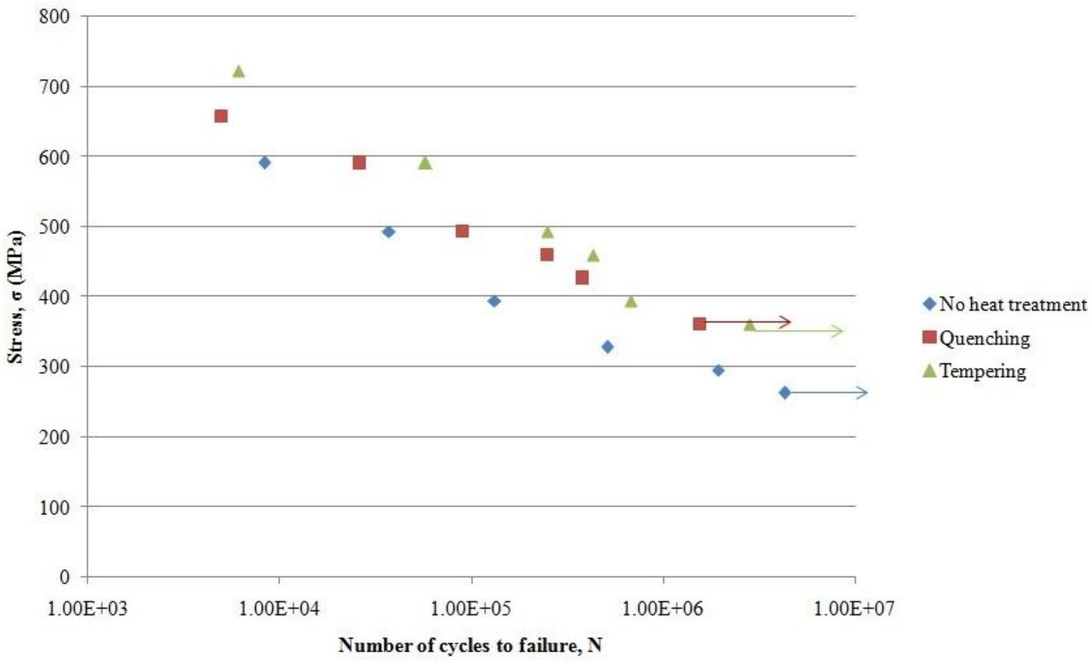


**Figure 4.23:** Comparison of S-N curve for three different heat treatment condition

From Figure 4.23, it is clearly shown that at the same stress level, tempering process shows the highest number of cycles to failure, followed by quenching process and the specimen with no heat treatment. Higher load was needed for the tempering processes specimen to fail. The stress value varies according to the calculation shown and from the result, the specimens will not fail under the endurance limit.

Htun (2008) stated that gradual decrease in hardness, ultimate tensile strength and increase in elongation of the specimen as quench steel has been observed by increasing time and temperature. For this experiment, the tempered specimen has the highest fatigue life. It is because the time taken for tempering process is only 1 hour and the hardness does not gradually decreases. If the temperature was rised and the time taken for tempering process is longer, only the hardness will gradually decrease. The specimen will become more ductile if the heat treatment process was further continued. In this respect, the tempered specimen has highest fatigue life compared to other processes.

## 4.7 FRACTURE SURFACE

The fracture surface on failed specimens have been analyzed by using optical measurement machine and optical microscope. Figure 4.24 shows the failed specimens after the rotational bending fatigue test.

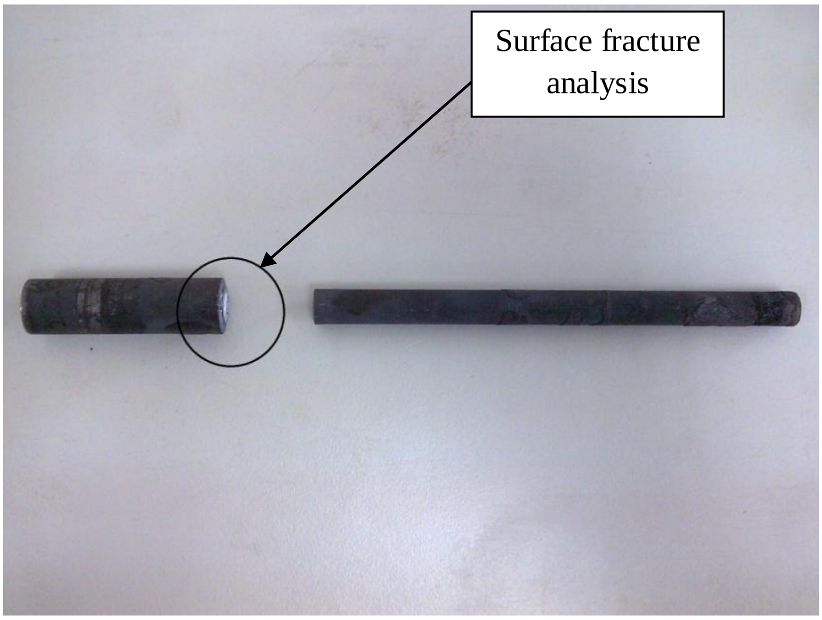


**Figure 4.24:** Failed specimen

### 4.7.1 Fracture Surface At High Stress Amplitude

Figure 4.25, 4.26, and 4.27 show images taken by using optical microscope machine which shows the fracture surface that fails at high nominal stress. As shown in the figure, the rapid fracture region at the dark area fails at high nominal stress is bigger than medium and low nominal stress rapid fracture. The crack initiation may be occur at any point and it is visible to naked eye.

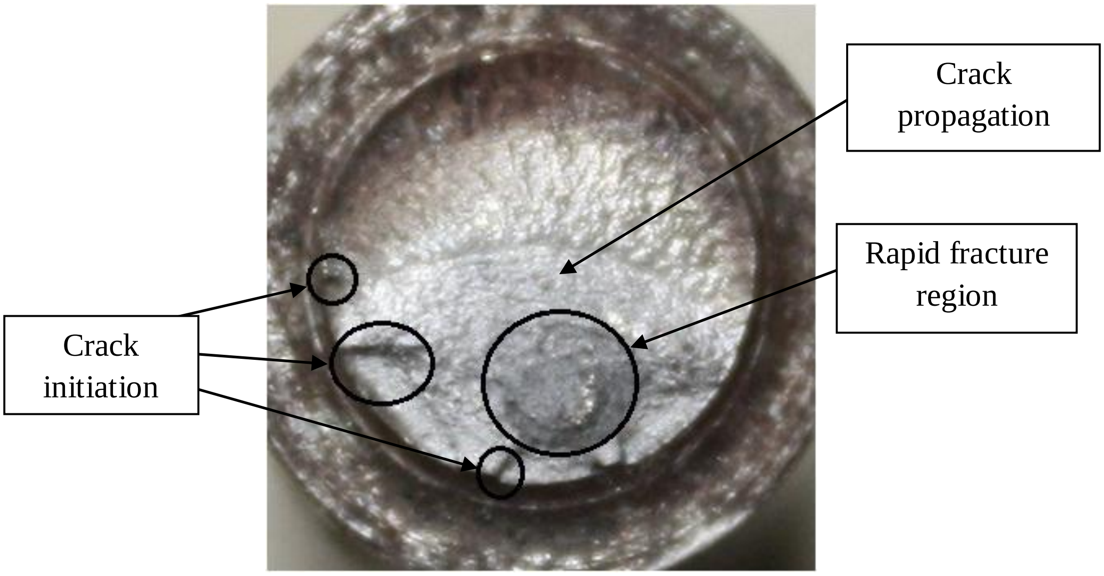


**Figure 4.25:** Fracture surface of specimen with no heat treatment at high nominal stress, $\sigma$ = 591.40 MPa

**Figure 4.26:** Fracture surface of oil quenched specimen at high nominal stress, $\sigma$ = 591.40 MPa

**Figure 4.27:** Fracture surface of tempered specimen at high nominal stress, $\sigma$ = 591.40 MPa

### 4.7.2 Fracture Surface At Medium Stress Amplitude

Figure 4.28, 4.29 and 4.30 show images of fracture surface with medium stress amplitude applied to the specimens. The rapid fracture region for these medium applied stress amplitude that are the dark region shows that the area of the region is bigger than the low nominal strees but it is smaller than the high nominal stress. The crack initiation is same with high stress condition where it may occur at any points which are normally visible to naked eye.

**Figure 4.28:** Fracture surface of specimen with no heat treatment at medium nominal stress, $\sigma$ = 394.27 MPa

**Figure 4.29:** Fracture surface of oil quenched specimen at medium nominal stress, $\sigma$ = 459.98 MPa

**Figure 4.30:** Fracture surface of tempered specimen at medium nominal stress, $\sigma$ = 394.27 MPa

### 4.7.3 Fracture Surface At Low Stress Amplitude

Figure 4.31, 4.32 and 4.33 show images of fracture surface with three different heat treatment that subjected to low nominal stress. The rapid fracture region is smaller compared to the specimens that subjected to medium and high nominal stress. The crack initiation pattern is like arrows lines which points toward the origins of initial cracks. This failure occurs when each part of the specimens is subjected to compression and tension load. A crack can initiate at any point of the surface where the stress is raised.

**Figure 4.31:** Fracture surface of specimen with no heat treatment at low nominal stress, σ = 262.84 MPa

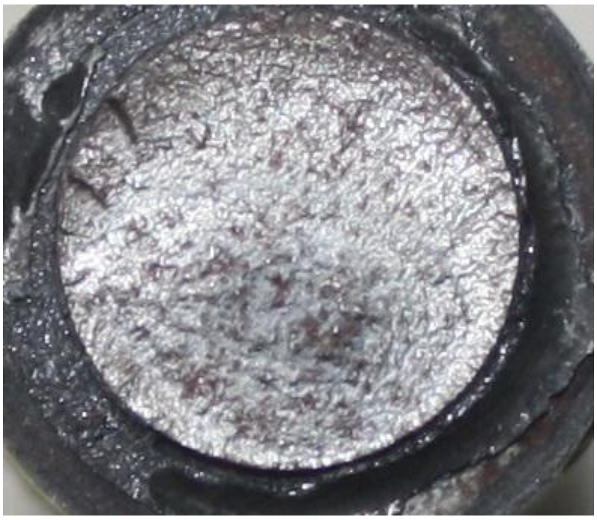

**Figure 4.32:** Fracture surface of oil quenched specimen at low nominal stress, σ = 361.41 MPa

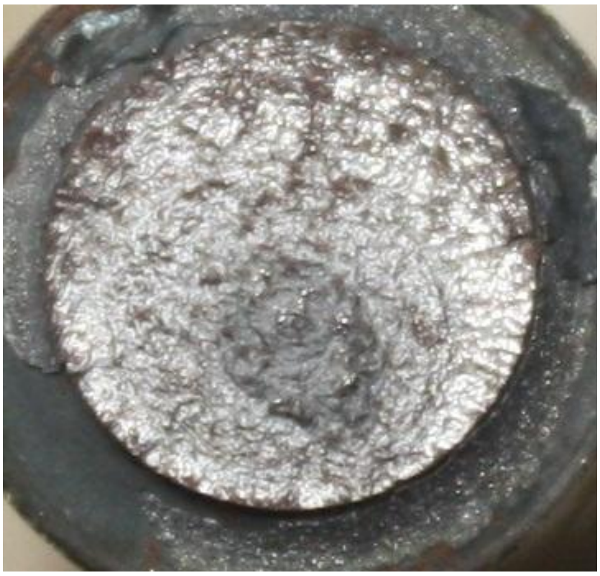

**Figure 4.33:** Fracture surface of tempered specimen at low nominal stress, $\sigma$ = 361.41 MPa

From all of the fracture surface presented, the rapid fracture region for tempered process is the largest compared to the quenching process and specimen with no heat treatment. The crack initiation region for high stress amplitude has more in number than the crack initiation region for medium and low stress amplitude applied. It is because the first initiation point does not crack the specimen and then another initiation point existed. The mechanism will be repeated until the specimens failed. The rapid fracture region size shows that when the applied stress is larger the rapid fracture region will also become larger.

To compare between the heat treatment processes, the tempered specimen shows the largest rapid fracture region compared to oil quenched and specimen with no heat treatment. It shows that the tempered specimens have the highest strength than other two processes.

The observation on the fracture surface on this specimen indicates that there are two region generated when the specimen was subjected to the fatigue stress. At first region, it shows the stable crack propagation as the stress applied on the specimen. After a certain length, the specimen cannot withstand the stress and it will cause the specimen to fail rapidly when entering second region that is the crack propagation region. Finally, it goes to the last phase that is the rapid fracture region. The type of fracture for these specimens that subjected to fatigue stress is transgranular fracture that represented at the crack initiation region. The transgranular fracture is a fracture that goes through the grains and does not go along the grain boundary.

# CHAPTER 5

# CONCLUSIONS & RECOMMENDATIONS

## 5.1 INTRODUCTION

This chapter concludes the overall project from the beginning to the end. Some recommendations on the project to improve the result will be discussed.

## 5.2 CONCLUSION

The effect of various heat treatment processes on fatigue life of low carbon steel has been investigated. Rotating bending fatigue test under constant stress amplitude has been performed for this purpose. This project was done successfully and the objectives have been achieved. However, during the time of the project, there are some problems occurred such as machining processes problem and a few experiments apparatus problem. These problems need to be solved in order to get a better and more accurate result in the future. Based on the rotational bending fatigue test conducted for this project, some conclusions from the results can be drawn.

1. Based on the fatigue test results, the tempered specimens show longer fatigue life than the oil quenched specimens and the specimens with no heat treatment.
2. Based on the Vickers hardness test, the result shows that the Vickers Hardness Number for tempered specimen is the highest followed by oil quenched specimen and specimens without heat treatment.

3. Based on the heat treatment processes, the type of microstructure for oil quenched specimens observed under optical microscope is martensite. The tempered specimen's microstructure type is cementite. The type of microstructure for specimens without heat treatment processes is observed to be ferrite with some pearlite.
4. Based on the observation of the fracture surface of the specimens, the size of rapid fracture region for the tempered specimens is larger than the oil quenched specimens and specimens without heat treatment.

## 5.3 RECOMMENDATIONS

There are some recommendations needed to be improved in order for the results to be more accurate. For this section, some recommendations will be discussed.

### 5.3.1 Machining process

In order the specimen finishing specifically following the design, more accurate method or apparatus needed to be done. In this case, we should use CNC because the product of this machine is accurate. When using the conventional lathe machine, there are not all machines that are working well and we need to use only one machine to avoid errors. To measure the specimens after machining process, only one vernier calliper need to be used in order to avoid errors.

### 5.3.2 Future works

The fatigue life of material is depending on many factors such as notch sensitivity, the stress applied and the heat treatment processes. As the calculation to obtain the value of stress include the usage of notch concentration factor, then, different notch is affecting the fatigue life of the specimen. Therefore in the next research, by using different notch diameter, results for another factor affecting the fatigue life of material can be seen. Another factor that affecting fatigue life of the material is heat treatment processes. For the next research, a different heat treatment method can be used.

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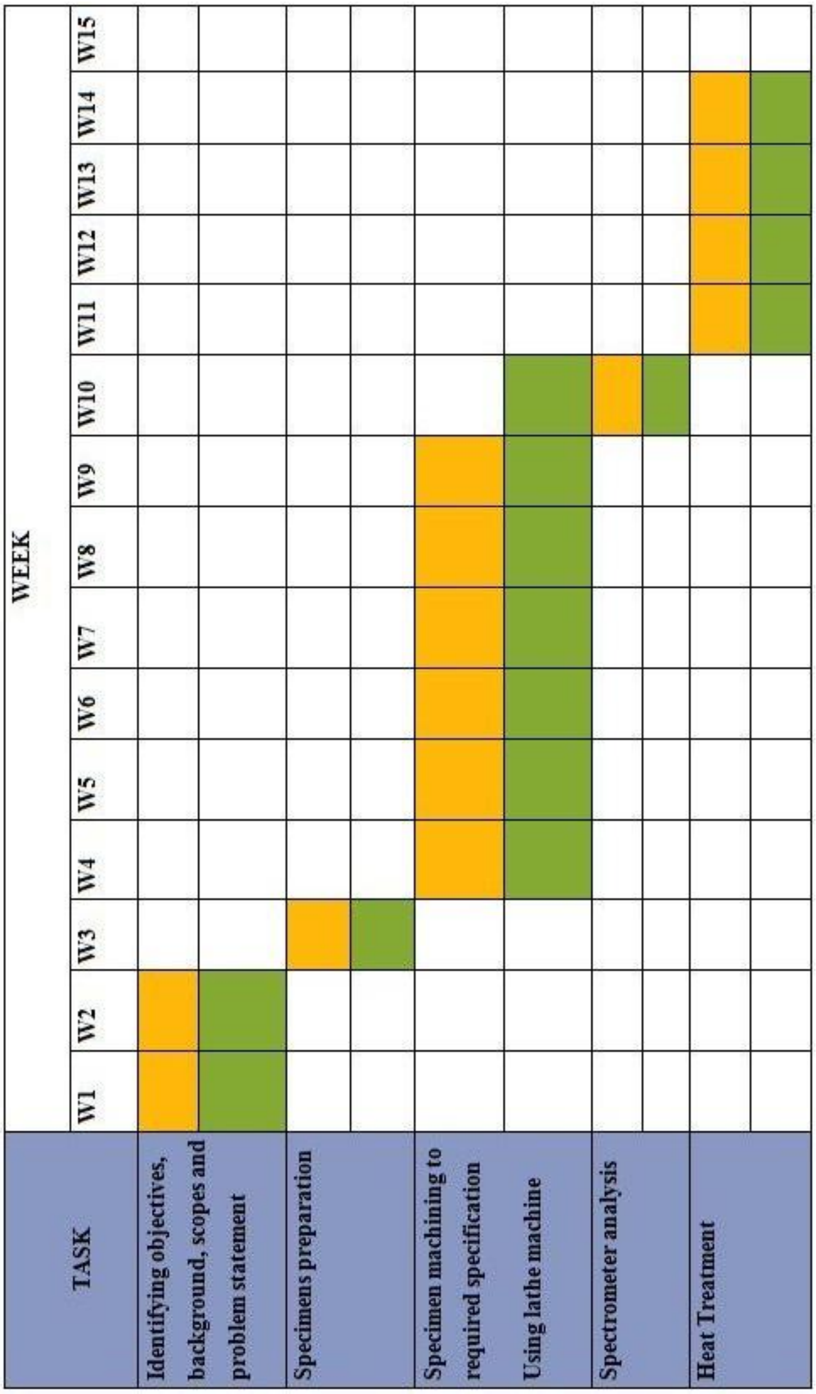
# APPENDICES

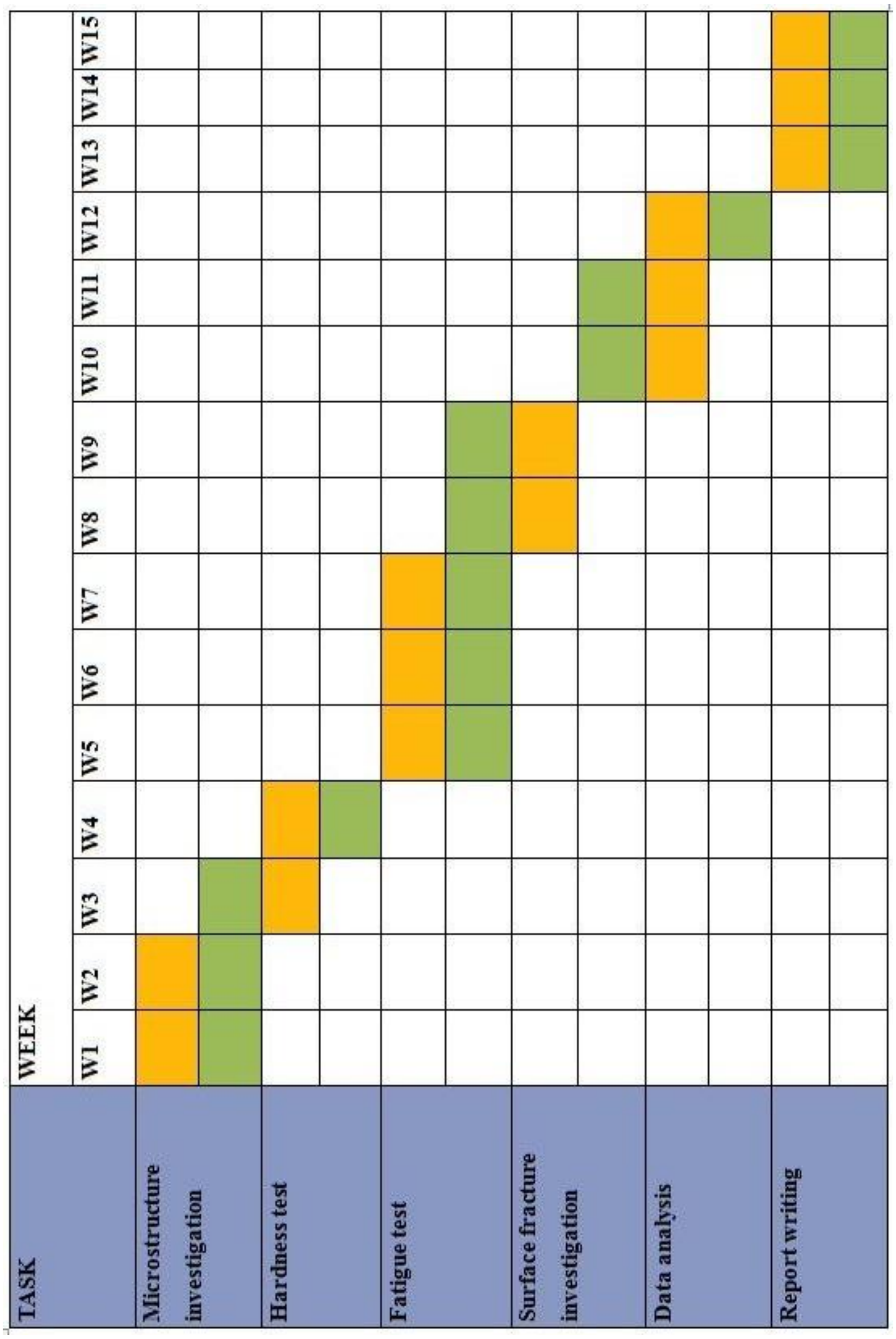
## APPENDIX A1

## GANTT CHART FOR FINAL YEAR PROJECT 1



# APPENDIX A2

## GANTT CHART FOR FINAL YEAR PROJECT 2



# APPENDIX B

# MATERIAL COMPOSITION

**FOUNDRY LABORATORY**
**FACULTY OF MECHANICAL ENGINEERING**
**UNIVERSITI MALAYSIA PAHANG**

Universiti Malaysia PAHANG

## Chemical Results

| | |
|---|---|
| Sample ID: | Material: |
| Customer: | Dimension: |
| Commision: | Filler metals: |
| Lab-no.: | Heat treatment: |
| Reference no.: | Heat-no: |

Spectrometer Foundry-MASTER Grade :

| | Fe | C | Si | Mn | P | S | Cr | Mo |
|---|---|---|---|---|---|---|---|---|
| 1 | 98,2 | 0,253 | 0,0711 | 0,448 | 0,0190 | 0,0084 | 0,132 | 0,0226 |
| 2 | 98,2 | 0,235 | 0,0632 | 0,462 | 0,0216 | 0,0088 | 0,135 | 0,0237 |
| 3 | 98,2 | 0,231 | 0,0616 | 0,447 | 0,0220 | 0,0090 | 0,136 | 0,0290 |
| Ave | 98,2 | 0,240 | 0,0653 | 0,453 | 0,0209 | 0,0087 | 0,134 | 0,0251 |

| | Ni | Al | Co | Cu | Nb | Ti | V | W |
|---|---|---|---|---|---|---|---|---|
| 1 | 0,111 | < 0,0010 | 0,0062 | 0,616 | < 0,0020 | < 0,0020 | < 0,0020 | < 0,0150 |
| 2 | 0,109 | < 0,0010 | 0,0059 | 0,613 | < 0,0020 | < 0,0020 | < 0,0020 | < 0,0150 |
| 3 | 0,111 | < 0,0010 | 0,0058 | 0,632 | < 0,0020 | < 0,0020 | < 0,0020 | < 0,0150 |
| Ave | 0,110 | < 0,0010 | 0,0060 | 0,620 | < 0,0020 | < 0,0020 | < 0,0020 | < 0,0150 |

| | Pb | Sn | B | Ca | Zr | As | Bi |
|---|---|---|---|---|---|---|---|
| 1 | < 0,0250 | 0,0119 | 0,0012 | 0,0006 | < 0,0020 | < 0,0050 | < 0,0300 |
| 2 | < 0,0250 | 0,0121 | 0,0012 | 0,0003 | 0,0033 | < 0,0050 | < 0,0300 |
| 3 | < 0,0250 | 0,0130 | 0,0013 | 0,0004 | < 0,0020 | < 0,0050 | < 0,0300 |
| Ave | < 0,0250 | 0,0123 | 0,0012 | 0,0004 | < 0,0020 | < 0,0050 | < 0,0300 |

Date: 08/12/2011 Test by: Verify by:

Foundry Laboratory
Faculty of Mechanical Engineering
Universiti Malaysia Pahang
26600 Pekan, Pahang, MALAYSIA

# APPENDIX C

## SPECIMEN DESIGN