IMPROVING THE FATIGUE LIFE OF FASTENER HOLES BY USING COLD EXPANSION TECHNIQUE

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This report is submitted
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DECLARATION

I declare that this project report entitled *"IMPROVING THE FATIGUE LIFE OF FASTENER HOLES BY USING COLD EXPANSION TECHNIQUE"* is the result of my own work except the cited in the references.

Signature : ....

Name : TALAL MAHMOOD OTHMAN AHMED

Date : ....

SUPERVISOR'S DECLARATION

I hereby declare that I have read this thesis and in my opinion this report is sufficient in terms of scope and quality for the award of the Degree of Bachelor of Mechanical Engineering with Honours.

Signature : -------------------------------------

Name of Supervisor:PROF. MADYA ABD SALAM BIN MD TAHIR

Date : --------------------------------------

DEDICATION

Every time when I need them the most,
They are always by my side.
This humble work of mine I would like to dedicate to

My lovely mother,
My lovely father,

The kind, humble and knowledgeable lecturer who I was lucky to be guided by him.

My supervisor,
PROF. MADYA ABD SALAM BIN MD TAHIR

I really appreciate your time, continues help and valuable advice.

My fiancée
The girl who believes in me all the way,

And
All my friends,
For their assistance& support.

ABSTRACT

Fatigue can be defined as the behavior in which the failure takes place in a material due to repetitive applications of loads subjected to that material. Fatigue constitutes a serious concern for engineers as it happens suddenly and cannot be predicted accurately. Cracks are the leading cause of the fatigue failure which happens in many engineering structures and components. Cold expansion technique is one of the techniques that has been used in the last forty years to retard the crack initiation and propagation. As a result of using this technique, the strength of material and fatigue life are improved. In this thesis, Aluminum alloy 6061 is used as the tested material. A total of 15 specimens of dog-bone shaped with centralized holeto act as the stress concentration zone are prepared based on ASTM standards to study the fatigue life before and after applying the cold expansion technique. High carbon steel is the material that was used to produce the cold expansion tools. A set of machining process need to be done in order to prepare the specimens for both tensile and fatigue tests. Three different amount of interferences, which are 1.5% , 2.2% and 2.9%, are generated to study the impact of cold expansion process. The fatigue tests are conducted by using INSTRON 8802 universal testing machine and the test is run at 0.1 stress ratio and 10 Hzresonant frequency. The results obtained from this study are shown in tables and plotted in the form of S-N curve. The findings indicated a remarkable improvement in the fatigue life when the interference is 2.2%. In contrast, there is a decrease in the fatigue life when the interferences are 1.5% and 2.9% respectively.

ABSTRAK

Lesu boleh ditakrifkan sebagai gaya laku di mana kegagalan berlaku dalam suatu bahan disebabkan aplikasi beban berulang yang dikenakan kepada sesuatu bahan. Lesu diambil pertimbangan serius oleh jurutera disebabkan ia boleh berlaku secara mengejut dan sukar diramalkan dengan tepat. Retak adalah merupakan sebab utama kegagalan lesu dimana terjadi kepada komponen dan struktur kejuruteraan. Teknik pengembangan sejuk adalah merupakan salah satu teknik yang telah digunakan sejak lebih 40 tahun lalu untuk menghalang permulaan dan perambatan retak. Sebagai kesan penggunaan teknik ini, kekuatan bahan dan hayat lesu dapat ditingkatkan. Dalam tesis ini, aluminiumaloi 6061 digunakans ebagai bahan yang diuji. Sebanyak 15 spesimen berbentuk tulang-anjing dengan lubang ditetengahnya bertindak sebagai zon konsentrasitegasan telah disediakan berdasarkan piawaian ASTM untuk mengkaji hayat lesus ebelum dan selepas teknik pengembangansejuk dilakukan. Keluliberkarbontinggiadalahbahan yang digunakanuntukmenghasilkanalatpengembangansejuk. Beberapa proses pemesinanperludilakukanuntukmenyediakanspesimenujiantegangan dan ujianlesu. Tigatahapperselisihanbersamaan 1.5%, 2.2% dan 2.9% telahdihasilkanuntukmengkajiimpak proses pengembangansejuk. Ujianlesudijalankandenganmenggunakanmesinujianumum INSTRON 8802 pada nisbahtegasan 0.1 dan frekuensi 10Hz. Keputusan yang didapatidarikajianiniditunjukkandalambentukjadual dan juga graf S-N. Dapatankajianmenunjukkanbahawahayatlesudapatdipertingkatkandenganketarabilaperselisihanadalah 2.2%. Sebaliknya, terdapatpenguranganhayatlesubilaperselisihanadalahbersamaan 1.5% dan 2.9%.

ACKNOWLEDGMENT

I would like to express my deepest appreciation and thanks to my supervisor PROF. MADYA ABD SALAM BIN MD TAHIR for his help and support and for providing me with clear guidance throughout the whole academic year. Without his help I would not have got that far with my work. A lot of thanks and appreciation to the labs staff and my friends who were available during the academic year for the support they offered. Lastly I would like to thank UniversitiTeknikal Malaysia Melaka - faculty of mechanical engineering for giving overall support.

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LIST OF SYMBOLS

NO	TITLE
S	Stress
N	Number of cycles to failure
S_m	Mean stress
S_r	Stress range
S_a	Stress amplitude
S_{max}	Maximum stress
S_{min}	Minimum stress
R	Stress ratio/ Radius of fillet
σ_{max}	Maximum stress
σ_{nom}	Nominal stress
P	Force applied
D	Diameter of test section of specimen
G	Gage length
A	Length of reduced section
P_y	Yield load
P_{ult}	Ultimate tensile load
σ_y	Yield strength
σ_{ult}	Ultimate tensile strength
σ_{min}	Minimum stress
P_{max}	Maximum load
P_{min}	Minimum load
P_{mean}	Mean load
P_{amp}	Load amplitude
Nf	Fatigue life cycles

LIST OF ABBREVIATION

NO	TITLE
CE	Cold Expansion
SCF	Stress Concentration Factor
ASTM	American Society for Testing and Materials
CNC	Computer Numerical Control
ISO	International Organisation for Standardisation
Al	Aluminium
AA6061	Aluminium alloy 6061
Cr	Chromium
Cu	Copper
Fe	Iron
Mg	Magnesium
Si	Silicon
Ti	Titanium
Zn	Zinc
Mn	Manganese

LIST OF APPENDIX

CHAPTER 1

INTRODUCTION

1.1 Background

Deformation and fracture are the two common responses of any material under an external force. The deformation can be elastic,plastic ,viscoelastic (time dependent elastic deformation) or creep (time dependent plastic deformation). With respect to fatigue which finally lead to failure by fracture, which is the dangerous response of the materials since it may occurs suddenly sometimes, typically happen after repeated cycles of loads and this is what is called "Fatigue". (William, M. 2009)

Each material has its static and dynamic behavior in the term of fatigue. To avoid the unpredictable failure and increase the aspect of safety, studies have been conducted to know the properties of materials and the best geometry design for each mechanical part or system. Therefore, the maximum cyclic stress that can be applied need to be known in order toavoid fatigue failure.

Fatigue, as defined by the technology of materials, is a progress in which damage takes place due to the repetitive applications of loads that may be lower than the yield strength of the specific material (David 2008). The progress of fatigue is very dangerous because one cycle of the load applied will not show any ill effects. Thus, the conventional stress analysis may conclude that safety is achieved while it is not. Generally, the fatigue in metals start at an internal or surface point where the stress is concentrated, and includes initially of shear flow along that point or slip planes. After a number of cycles, intrusions and extrusions are generated by this slip to create a crack as a result. This crack will propagate to reach its critical size which immediately end up with a fatigue failure to the mechanical part or system.

There are many methods created to improve the fatigue life. Most of them were made in the time when the initial ideas of design for metal aircraft structures did not take in consideration the advantages provided. In addition, the point of view of the initial ideas is used to deal with the potential increases as a protection. The processes initially were used to improve the life through that otherwise considered safe, or to demand it when premature cracks appeared. All these ideas are not valid anymore. Recently, the established life enhancement is used by the high-tech military aircraft during the manufacturing process. for example, in the McDonnell Douglas F-18 , the aircraft which uses the technique of cold expansion for the hole, ring pad coining , shot peening and the interference-fit fastener. The need for higher performance structure with lower cost now makes it more necessary than before to quantify the life improvements and make sure that they are perfect.

In 1960s, Boeing Company developed the split-sleeve hole cold expansion. This technique has been efficiently used for more than thirty years (Houghton S.J. 2010). Split sleeve cold expansion is an effective way to overcome the problems related to fatigue holes and cracks in the metallic structures. Split sleeve expansion is conducted by pulling a tapered mandrel, pre-fitted with a lubricated split sleeve through a hole in aluminum, titanium or steel. The function of the expendable split sleeve cold expansion is to make sure of the correct radial expansion of the hole, decrease the mandrel pull force and allow uniaxial processing.

1.2 Objectives:

The main objectives of this study are

- To conduct fatigue tests and determine the S-N curve of the tested specimens of aluminum alloy 6061.
- To show clearly the benefit and impact of cold expansion technique in the term of improving the fatigue life.

1.3 Scope

The scopes involving in this study are :

- To identify the suitable materials to conduct the required technical tests for the study.
- To identify the best design for the specimen based on the previous studies and the machines available in the lab of the faculty of Mechanical Engineering.
- To conduct the tensile and fatigue tests for the specimens.
- To develop the S-N Curves.
- To study the effects of the changes in geometry and also the effect of cold expansion technique on the specimens.
- To show clearly all the results produced in order to improve the fatigue life.

1.4 Problem Statement

Due to the need for higher fatigue strength of the mechanical parts especially in some systems like air turbines, aircrafts and automobiles which are subjected to repeated loading and vibration, fatigue has become a serious matter need to deal with. Most of the incidences in the structures, fatigue starts from the holes or stress concentration areas, specially the fasten ones.

In this study, the emphasis is on improving and studying the fatigue life and fatigue behavior for better understanding and enhancement on fatigue life of structures through a cold expansion technique.

CHAPTER 2

LITERATURE RIVIEW

2.1 Overview

According to (Rallis 2014), the purpose of literature review is to provide a theoretical outline and foundation for the related research study. This chapter will discuss the background of this project in a general way. In addition, this chapter will show the published previous studies related to the particular subject area. Moreover, this chapter will be a summary of the sources of this project. Literature review focuses normally on specific issues of an interest and the critical analysis of the connection among different mechanisms and any information related to this project.

2.2 Material Failure

The meaning of deformation failure is the change in the physical dimensions or shape of a component that is sufficient for its function to be lost or impaired (Dowling, N.E., 2013). Deformation failure in materials can be occurred in two basic types which are deformation and fracture. Because of the different causes to these types of failure, it is very important to identify correctly the main reason and determine the compatible analysis method in order to find the suitable solution for the problem. Basic types of deformation and fractures are shown in figure 2.1.

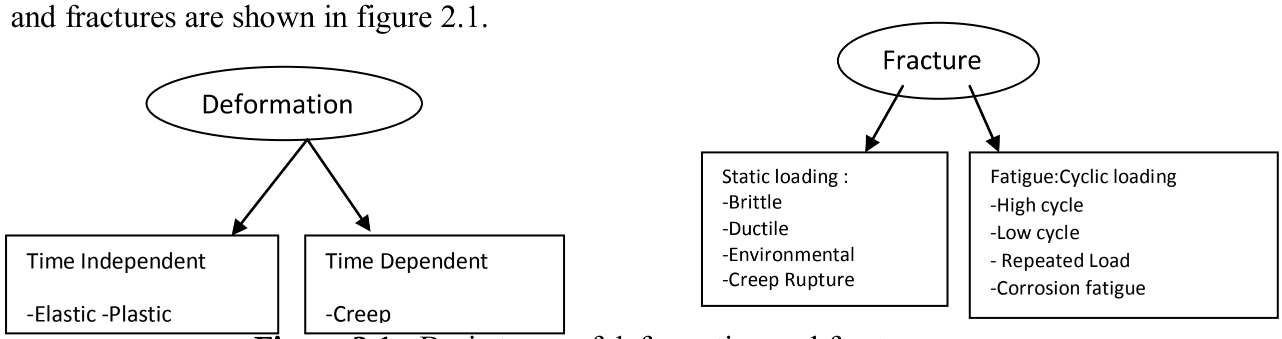


Figure 2.1 : Basic types of deformation and fractures

2.2.1 Static loading and cyclic loading

It is important to differentiate between cyclic loading and static loading. Static loading is normally related to the static fatigue especially in the brittle solids such as ceramics and glasses. Usually this kind of fatigue happened due to the moisture in these materials which cause cracks to grow. Thus, static fatigue is a corrosion response not like the fatigue in this present project which happens due to the cyclic (repeated) loading's effects in the fastener holes where stress concentration factor is located. Cyclic loading affects badly the mechanical structures and components. Over the time, the cracks start to grow and failure occurs as a result.

In general, there are two kind of cyclic loading which are constant amplitude loading and non-constant amplitude loading. (Meyers, M. ,&Chawla, K. K. 2008).

2.2.2Constant Amplitude cyclic loading

This kind of cyclic loading includes constant values of maximum and minimum stresses. It is used to find and study the behavior of the material fatigue. There are some important parameters we should know about constant amplitude cyclic loading which are (Bargiggia.U.,2008) :

- Stress Ratio, R : the ratio of the minimum stress to maximum stress in each cycle.

$$R = \frac{Smin}{Smax}$$

- Stress Range, Sr : the algebraic difference between the maximum stress and the minimum stress in each cycle.

$$Sr = Smax - Smin$$

- Stress Amplitude : the half of Stress Range.

$$Sa = \frac{Smax - Smin}{2}$$

-Mean Stress : the average of the maximum and minimum stresses in one cycle.

$$Sm = \frac{Smax + Smin}{2}$$

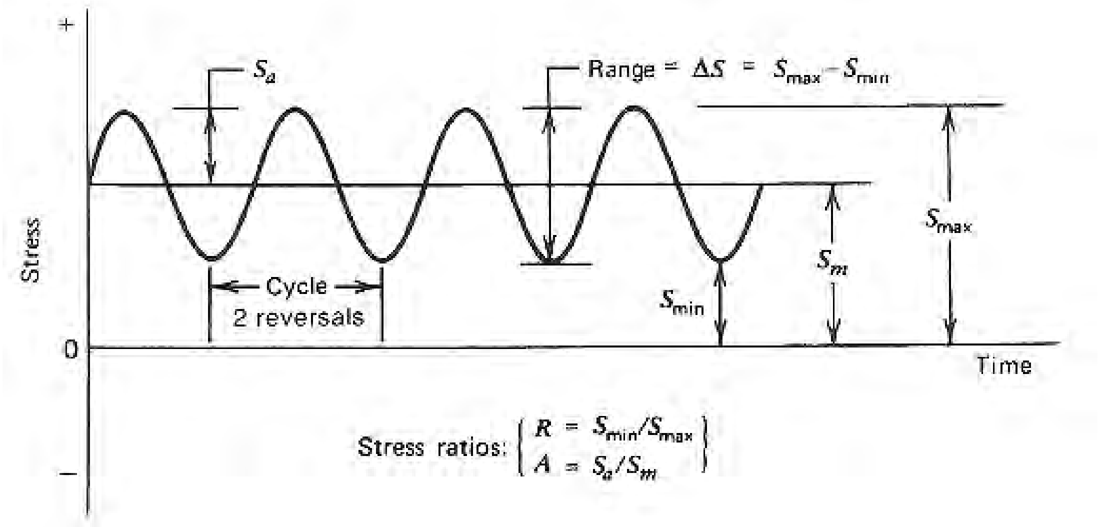


Figure 2.2: Nomenclature for constant amplitude cyclic loading(Stephens, R.I. et al., 2001)

Constant Amplitude loading involves three main types which are,

1- Tensile-to-Tensile Load. (Figure 2.3 (a))

2- Fully-Reversed Load. (Figure 2.3 (b))

3- Zero-to-Full Tensile Load. (Figure 2.3 (c))

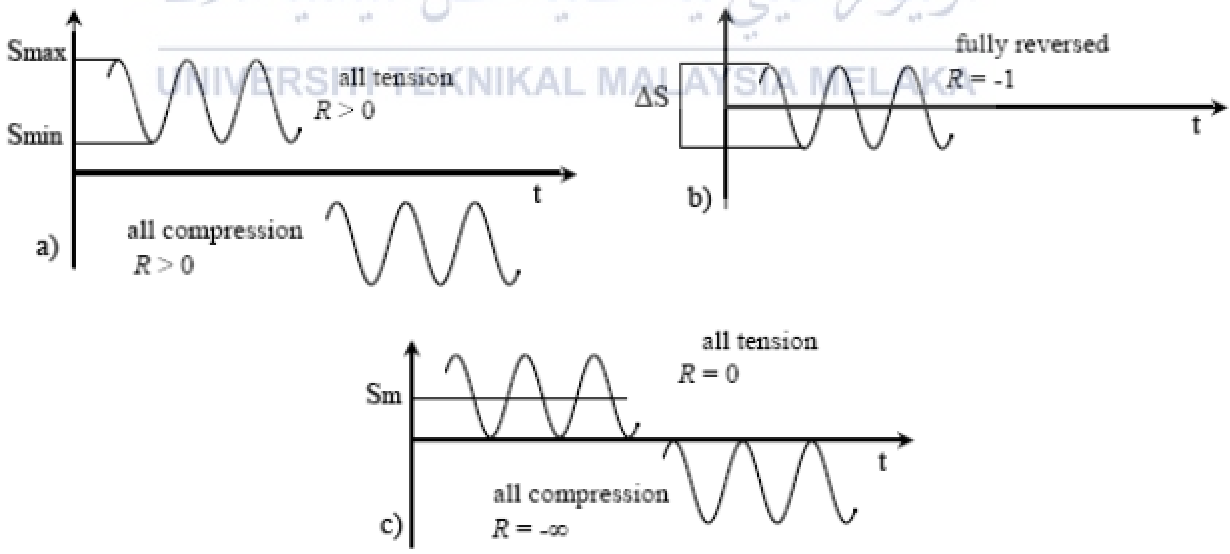


Figure 2.3: Types of constant amplitude, proportional loading. (a) 'tensile-to-tensileload', (b)'fully-reversed load', (c) zero-to-full tensile load'.

2.2.3 Non-Constant Amplitude Cyclic Loading

It is the condition when the load-ratio acts as a time dependent. The normal constant amplitude loading uses a single R to determine the mean and alternating values. In contrast, the non-constant type of cyclic loading is completely random and thus there is no analytical pattern can represent its complexity. On the other hand, the calculations of cumulative damage are used to determine the total value of fatigue damage because the fatigue loading that causes the maximum damage cannot be determined easily. Therefore, the cycle counting is converted to a number of functions to reduce the complex load-recording. After that, these functions can be calibrated with the data of constant amplitude test. Trucks loading over the bridges and wind loading over the aircraft are two common examples of non-constant amplitude cyclic loading. Figure 2.4 shows a schematic load history of this type of loading.

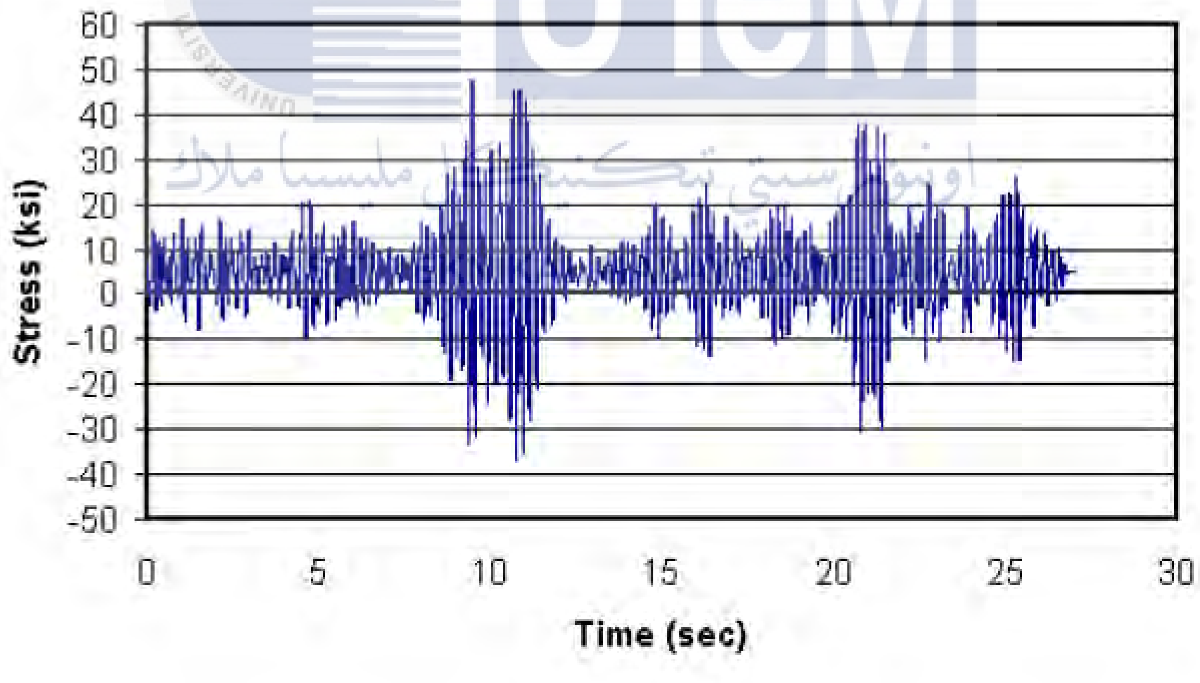


Figure 2.4: Non-Constant Amplitude Cyclic Loading.

2.3 Fatigue

In 1828, Albert W. A. J. tested the first cyclic loading through mine hoist chains in Germany. Since that time until now, the mechanical failures regarding fatigue have the concentration of engineering studies. After a while, in 1839 exactly, the term fatigue used in a book on mechanics by J. V. Poncelet in France. Later on and in the mid of 1800s, fatigue was studied and discussed more by many experts from different countries in order to find a solution for the failure of structures and components. For example, bridge girders, shafts, stagecoach, beams and railway axles.(Dowling, N.E. 2007)

Fatigue in definition is the process of progressive, localized, permanent, structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains, at some point or points, that may culminate in cracks or complete fracture after a sufficient number of fluctuations (ASTM E 1150-1987, Standard Definitions of Fatigue, 1995 Annual Book of Standards, ASTM, 1995, p 753 – 762)

2.3.1 Fatigue under cyclic loading

Fatigue is the main cause of fracture. Initially, one tiny crack begins in the structure of a material. After that, this small crack start to grow till the complete failure happens. For example, if anyone take a piece of wire and bend it then repeat this process for many times, this piece of wire will be broken at the end. Parts like bicycle pedals, sailboat rudders or even trusses in bridges can be failed by fatigue. Thus, all vehicles types such as automobiles, airplanes and tractors are necessarily analyzed and tested periodically to avoid the possibility of fatigue problems. (Dowling, N.E.2007)

High cyclic loading causes a plastic deformation as a result. In contrast, the low cyclic loading causes often an elastic deformation. On the other hand, the fact that the failure happens after a number of cycles just proves that every cycle causes a small and permanent change inside the structure of material. Fatigue, which is one of the high repeated cyclic loading results, requires plastic strain and tensile stress as well. There is no fatigue if any one of these three factors is missing. Fatigue takes three stages to happen. The first one is the initiation or the nucleation of a crack. A crack starts by a small impact of random plastic deformation and this stage is only can be seen by a microscope. The second stage of fatigue is the propagation of cracks and it is a slow growth of the cracks by cyclic stresses. The last stage of fatigue is the sudden fracture. It is occurred once the cracks expand to a critical size (William,F.H. 2009) . Figure 2.5shows the stages of fatigue and the crack development. (Dowling, N.E.2007)

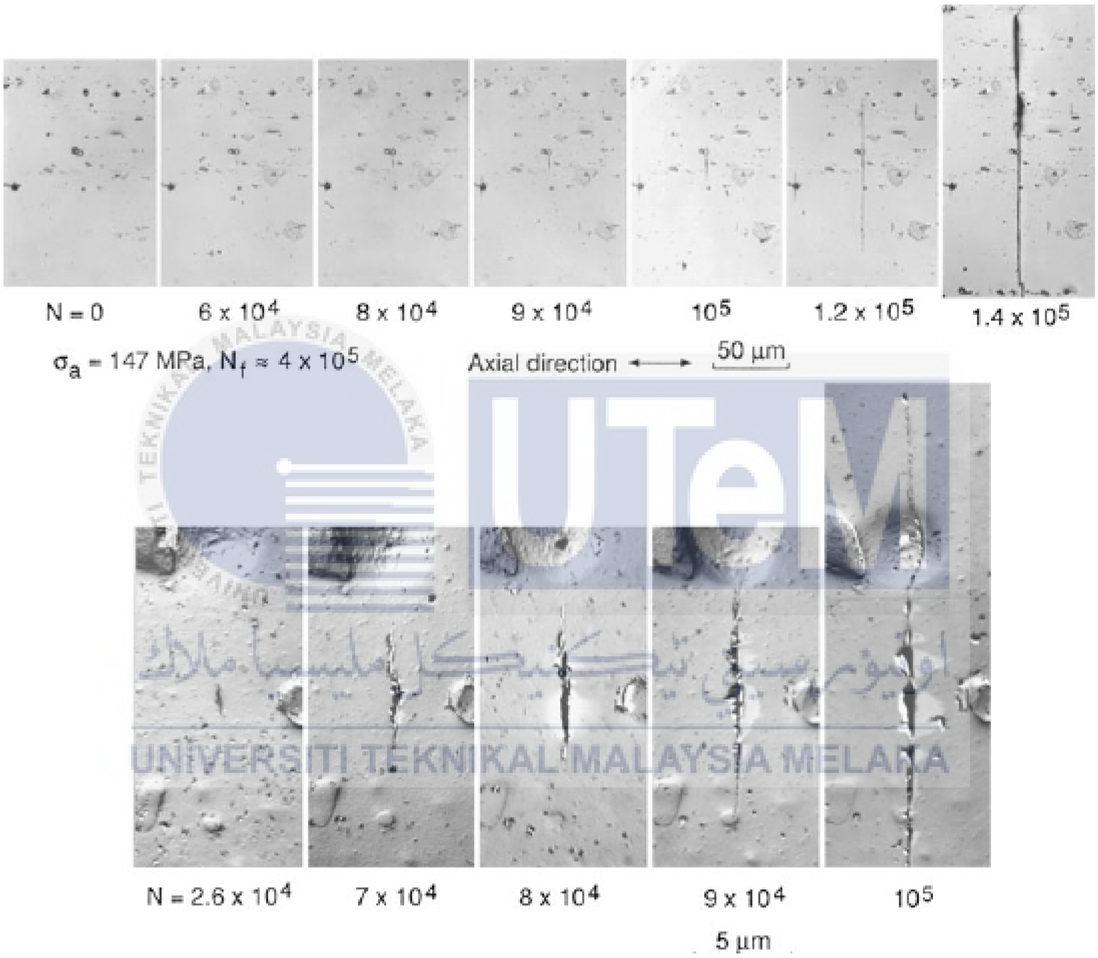


Figure 2.5: The stages of crack's nucleation and development

2.3.2 Crack propagation

After the cracks begin to initiate and under a large value of stress, propagation of cracks spends around 90% of the total fatigue life and a very large fraction start to appear. If the component or structure contains a notch or a hole, the fraction will be larger. In the real structure with holes or even cracklike imperfections, the propagation of cracks considers as a vital aspect of fatigue. The different stages of crack propagation are shown in figure 2.6.(Meyers, M. ,&Chawla, K. K. 2008).

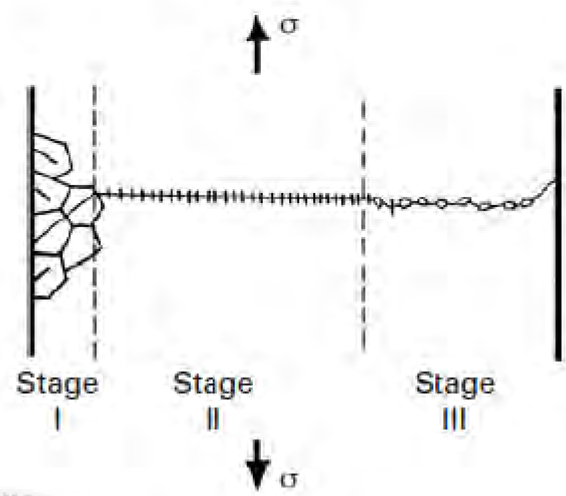


Figure 2.6: Fatigue crack propagation

The first stage of crack propagation is in the crystallographic shear mode as shown in the Stage I above. A small number of cracks nucleate in this stage and start propagating on planes stated approximately 45◦ to the axis of the stress. After a crack is being initiated at the slip planes on the surface, it continues to propagate until it reaches a grain boundary. These crystallographic cracks extend a few tenths of millimeter during this mode. After that, an essential crack start propagating perpendicularly to the stress axis. This process is called Stage II and during this stage the surface of fracture indicates striation markings. As long as the stress amplitude increase the ratio of the extension of Stage I and stage II is decreased. The stress concentration at the tip of the crack makes local plastic deformation in the area in front of the crack. The plastic deformation zone starts to increase due to the cracks growth. This increase in size of plastic deformation is continued until it becomes closely comparable to the specimen's thickness. After that, stage III starts with rapid crack propagation. In this stage, the crack plane will be in a rotation force not in a plane-strain condition as in stage II which is not exist anymore. Thus, during stage III, the final portion of rupture happens in shear mode or plane-stress. By using the microscopic observations, it is possible to see the characteristic striations of fatigue fracture surfaces. Through many observations and studies on metals and alloys (particularly consist of Al and Cu), It is believed that each striation is represented one load cycle.

2.4 Stress-Life Approach

Wolher is the first one who invented stress-life approach in 1860s as the first method to characterize fatigue life. He developed the term of endurance limit which is the applied stress amplitude that the material is expected to have an ideal infinite fatigue life. There are some of important symbols used in this approach and have to be identified. S_e, which is the lowest value where the possibility of fatigue is zero, is the limit needed to be determined by the experimental procedures. The stress amplitude S_a, is plotted in an opposite direction with the number of fatigue cycles to failure, N_f for a fully reversed loading in a zero mean stress, S_m, condition. Figure 2.7(William,F.H. 2009) . This approach is used widely in applications with low-amplitude cyclic loading which produces main elastic deformation in components and structures that designed to last a long life such as HCF applications.

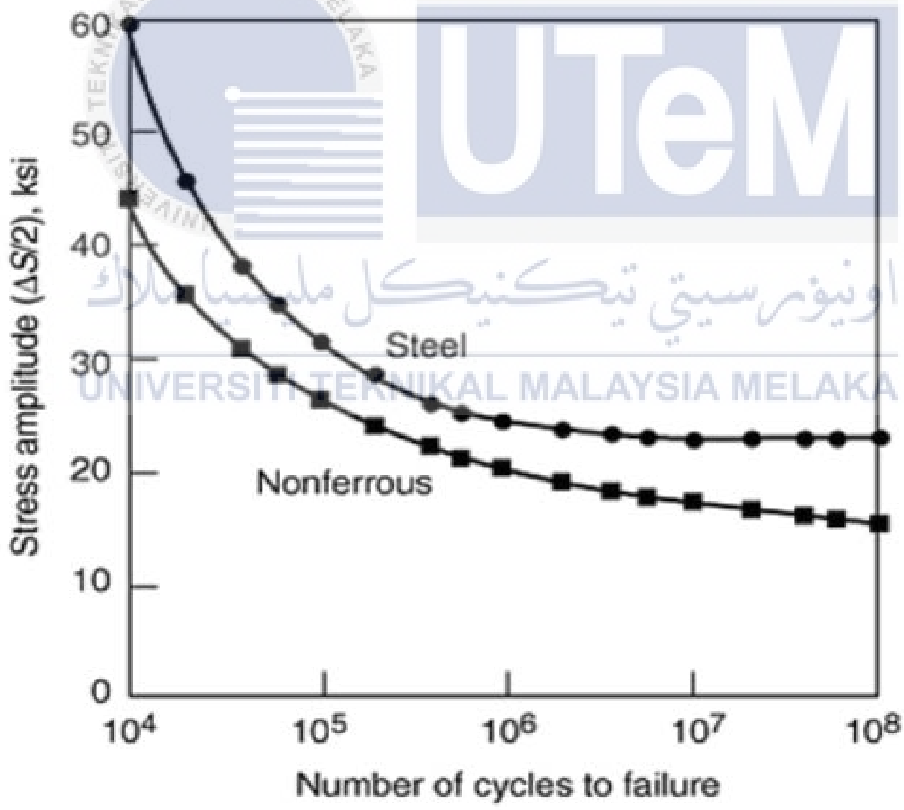


Figure 2.7: Schematic S-N representation of materials having fatigue limit behavior (asymptotically leveling off) and those displaying a fatigue strength response (continuouslydecreasing characteristics).

Almost all fatigue data are presented by S-N curves by plotting the cyclic stress amplitude (S_a) with respect to the number of cycles to failure (N). The stress amplitude increases as the number of cycles to failure decreases. N always is converted and plotted as a logarithmic scale. In addition, S-N curves usually used in tests with mean stress σ_m is equal to zero. Some materials such as annealed 4340 steel and low carbon steels have a stress amplitude (Fatigue limit or endurance) which the fatigue can not be occurred below it. For example, the break of S-N curve of annealed 4340 steel occurs at nearly 10^6 cycles (figure 2.8). In contrast, for some materials like aluminum alloys, the true fatigue limit is not available. The stress amplitude keep decreasing even below a very large number of load cycles and the points in the arrow are the stop of tests before failure as shown in (figure 2.9).. In this situation, the fatigue strength is assumed as the stress amplitude where the failure happens in 10^7 cycles. For the logarithmical calculations, if S-N curve is plotted by Log S against Log N, the relation can be expressed as S = A N^{-b} , where the constant, A, is the approximated value of tensile strength and N is the number of cycles to failure(William,F.H. 2009) .

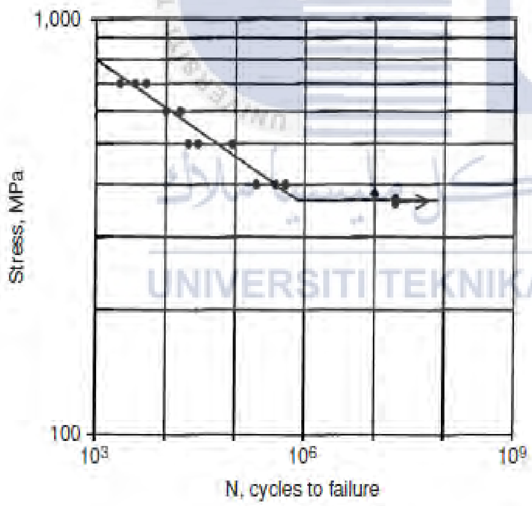


Figure 2.8 : The S-N curve of annealed 4340 steel with a fatigue limit defined at N= 10^6 Cycles.

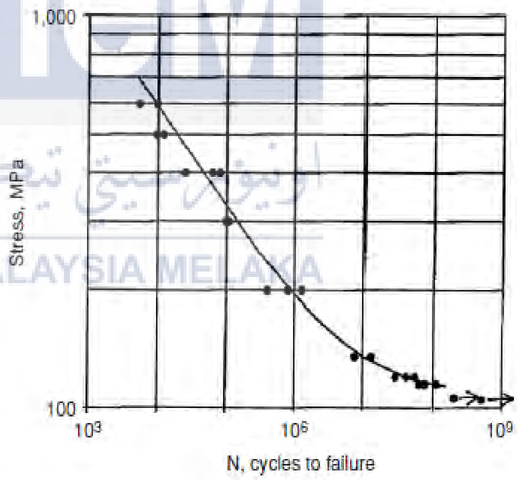


Figure 2.9 : The S-N curve of aluminum alloy 7075 without any true fatigue limit.

2.5 Cold expansion technique

Cold expansion technique, or cold working (forming),is a material processing technique which has been used widely in theindustry of aircraft to improve the fatigue life of thestructural components that contain holes (Renan L. Ribeiro&Michael R. Hill 2017). This technique was firstly developed by Boeing company in Seattle, USA and it has been employed for over 54 years (X. Zhang & Z. Wang 2003). The application of the cold expansion technique can be performed by using many ways such as mandrels (Figure2.10), Indenters(Figure2.11), bearingballs (Figure2.12) or split sleeve (Figure 2.13) . (Fu. Yucan et al. 2015).

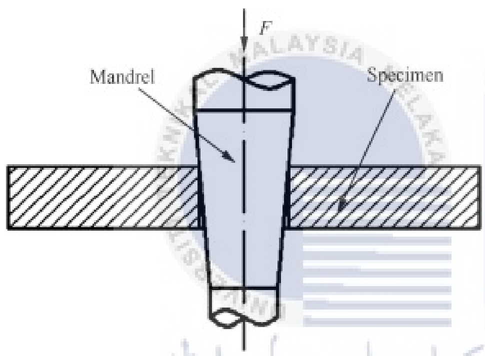


Figure 2.10 : Mandrel Expansion Process

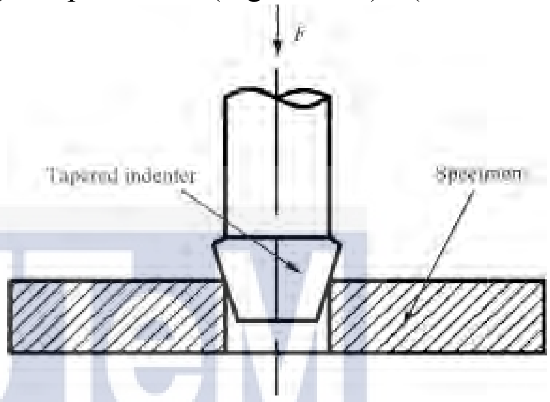


Figure 2.11 :Tapered Indenter Expansion Process

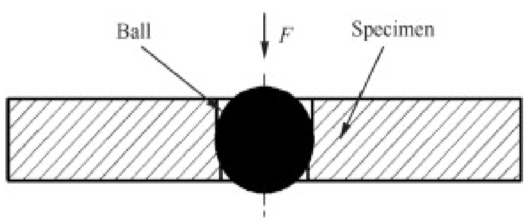


Figure 2.12 : Ball Expansion

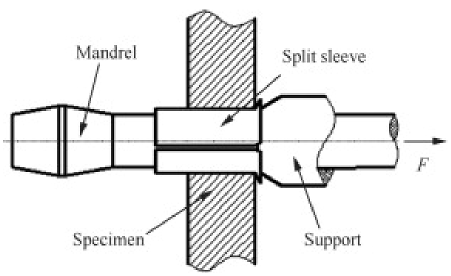


Figure 2.13 : Split sleeve expansion process

The most common way of cold expansion is by forcing an oversized ball through a hole in a metallic material which causes the hole diameter to expand once the ball passes the hole. The term "interference" refers to the difference between the hole diameter and the ball diameter. If the value of interference is relatively small, the expansion happens during the elastic range of material. Hence, the circumferential structure of hole usually returns to its original diameter. However, if the value of interference is large enough to cause a local impact of yielding, then the hole diameter will not return back exactly to its original size. In addition, The corresponding stress distribution will not return back to its normal condition. Thus, the stress distribution varies through a compression stress at the edge of the hole to a tension stress far away from the edge of the hole as depicted in figure 2.14 (Vogwell, D. et al.2001). This process maintains again the status of stress equilibrium in the structure.

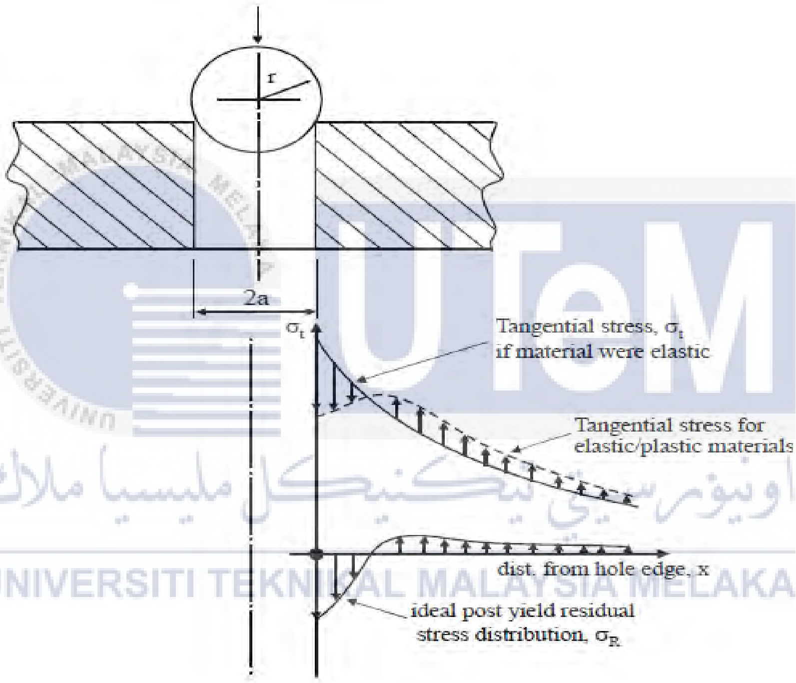


Figure 2.14: Cold expansion technique and the Ideal corresponding residual stress distribution.

The aim of cold expansion technique is to expand the hole by exceeding the local yield stress around the hole. This process is applied usually by using a suitable value of inference to generate a compressive residual stress at the inner circumference when the expansion load is removed. The most desirable results are materialized under tensile loading to maximize the impact of cold expansion so the local stress concentration effect is countered and the tendency of fatigue damage is reduced or suppressed.

Cold expansion technique has many practical applications which have been used to enhance the fatigue resistance of fastener holes, retard cracks initiation, improve fatigue life and reduce fatigue damages. For example, the cold expansion technique has been used for fastening the lengths of railway track with the holes bolt of the lap-joint brackets. Besides, this technique is used by aircraft construction industries especially with the vulnerable bolt and rivet holes. Some applications and devices are only subjected toballising (An oversize ball bearing) where some applications design a pre-fitted pin which is forced directly through the hole. Moreover, other applications use principle of expansion wedge.(Vogwell, D. et al. 2001).

CHAPTER 3

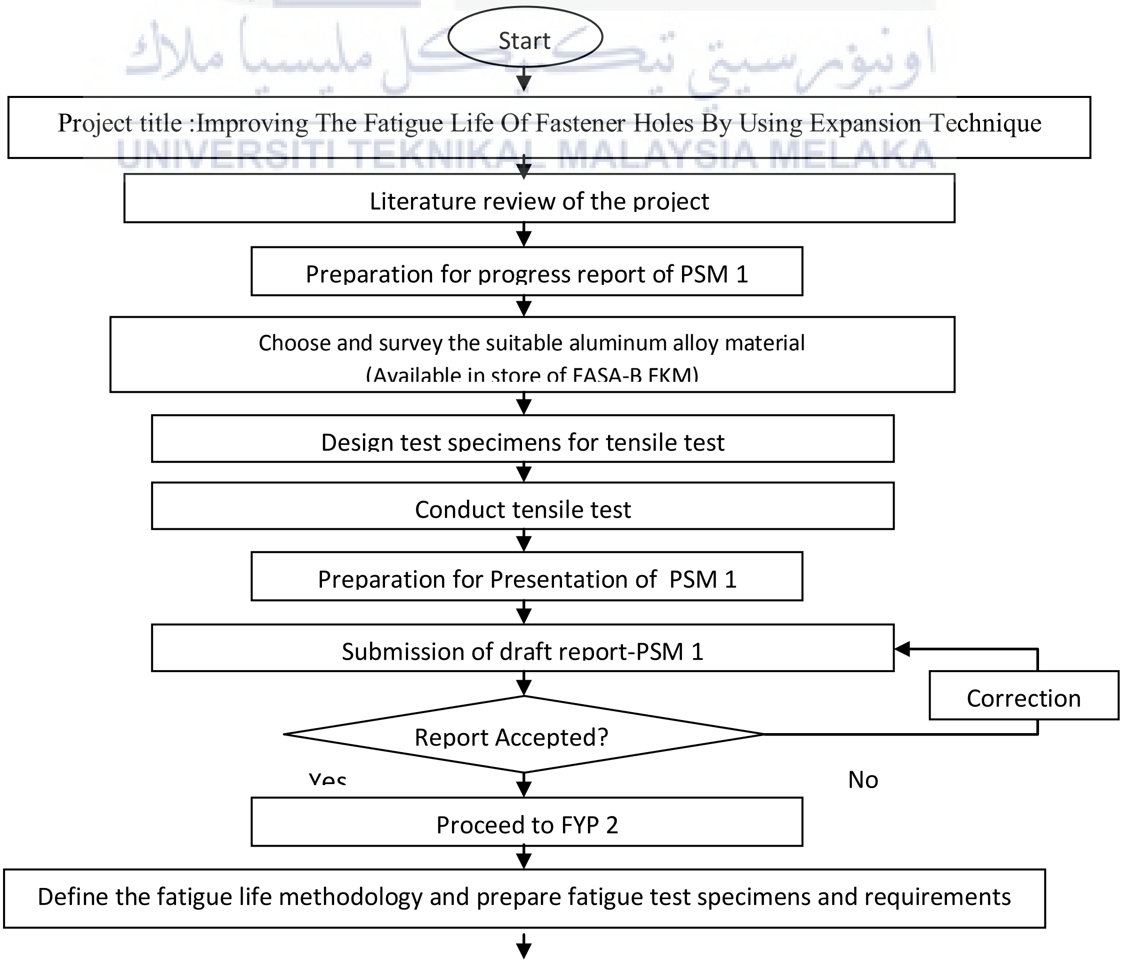
METHODOLOGY

3.1 Overview

This chapter covers the procedures and the experimental details of this project. It is consisted of two parts, Part 1 discusses the tensile test including the procedures, experimental details and the apparatus used. Besides, Part 2 discusses the fatigue test before and after using the cold expansion technique.

3.2 Flow chart

Figure 3.1 shows the flow chart for this project experiment that illustrate the steps to accomplish the objective of this project during two semesters.



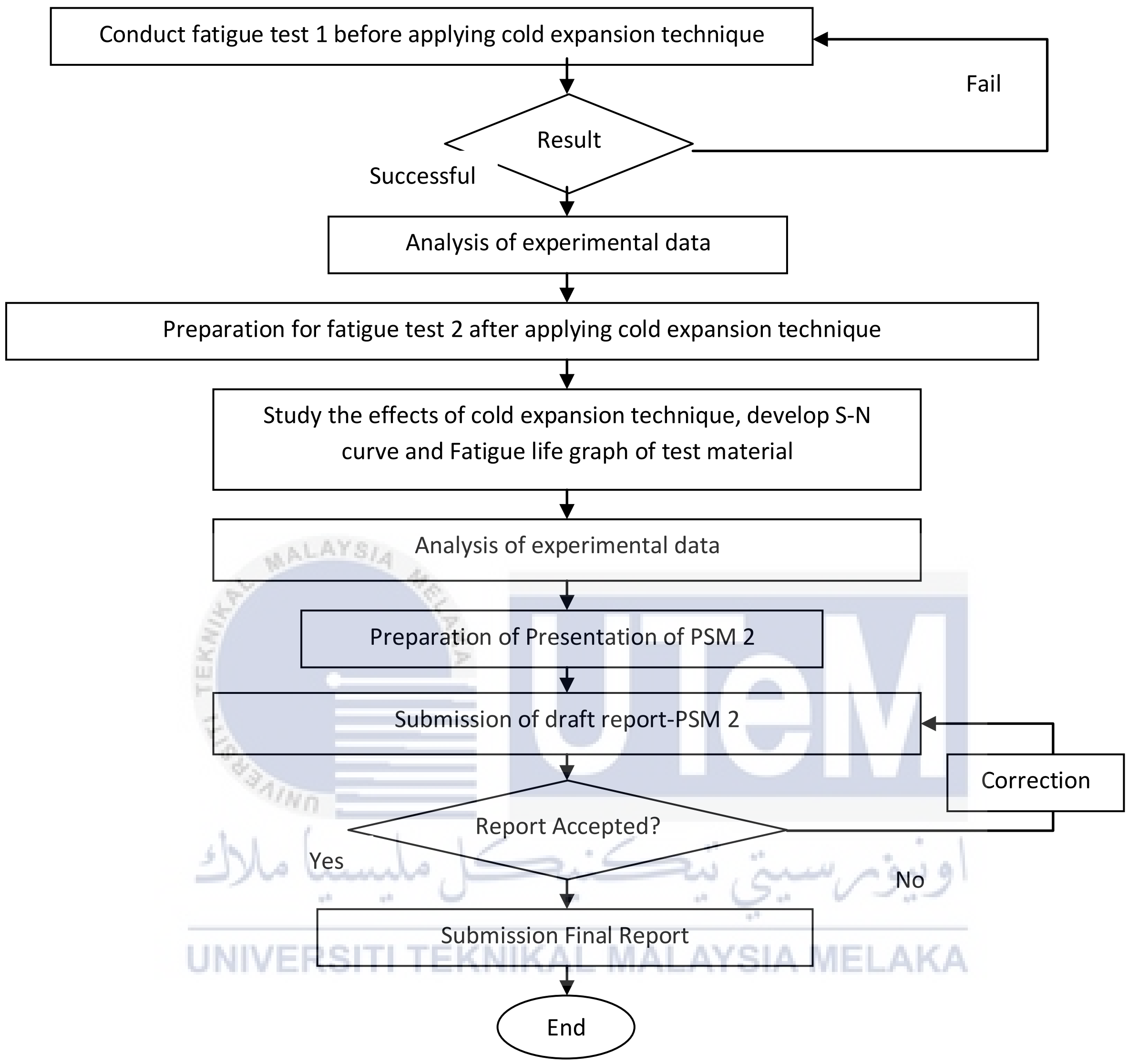


Figure 3.1:Flow chart of the present project

3.3 Test Material

The material of the specimens used in the tests of this project is aluminum alloy 6061. It is provided by the lab of mechanical faculty (FASA B) but without any known prior properties or characteristics for the material. Thus, tensile tests are conducted based on ASTM E8 standards to determine the properties and behavior of the material. Then, the experimentally determined properties are compared with the original properties which are stated in the materials properties references.

3.4 Material Specification

Aluminum alloy 6061 is one of the most commonly used alloys is also a precipitation hardening aluminum alloy. It contains magnesium and silicon as the major components elements. Initiallyit was called "Alloy 61S," which was developed in 1935 (Krishna&Karthik.M 2017) . It has varied common applications such as window frames, cylinder blocks, aircraft fittings, couplings, electrical fittings, brake pistons, bike frames, valves, appliance fittings, hydraulic pistons, camera lens and marines fittings and hardware.The properties of Aluminum alloy 6061 are shown in Table 3.1. (www.tayloredge.com)

Table 3.1 : Aluminum alloy 6061 properties

Name	Aluminum alloy
Category	Metal; Nonferrous Metal; Aluminum Alloy; 6000 Series Aluminum Alloy

Composition

Al	95.8 - 98.6 %
Cr	0.04 - 0.35 %
Cu	0.15 - 0.4 %
Fe	Max 0.7 %

Mg	0.8 - 1.2 %
Mn	Max 0.15 %
Si	0.4 - 0.8 %
Ti	Max 0.15 %
Zn	Max 0.25 %
Others	Max 0.05 %
Physical and Mechanical Properties	
Density	2.7 g/cc
Modulus of Elasticity	68.9 GPa
Passion's Ratio	0.33
Tensile Yield Strength	276 MPa
Ultimate Tensile Strength	310 MPa
Elongation at break	15%
Hardness (Brinell)	95
Hardness (Knoop)	120
Shear Strength	207 MPa
Shear Modulus	26 MPa
Machinability	50%
Fracture Properties	
Fracture Toughness	29 MPa-m ½
Fatigue Strength	96.5 MPa (500,000,000) cycles completely reversed stress

3.5 Experimental Apparatus

The INSTRON 8872 universal testing machine located in structural laboratory in FASA B, FKM-UTeM is a testing machine with a tabletop servo-hydraulic testing system. It has been developed to provide the several demands of static and dynamic testing requirements. The INSTRON 8872 is considered a perfect platform for a variety of metallic, advanced and composite materials.

The INSTRON 8872 can perform an axial force capacity up to ±25 kN (5620 lbf). It can be run with its standard or extra-height frame options. It has a wide collections of grips, fixtures, and accessories. It is also supplied with the digital 8800MT controller which provides a full control to the system, an automatic loop tuning, specimen protect, amplitude control and other specific software application such as low/high cycle fatigue test. Universal Testing Machine (INSTRON 8872) is shown in the figure 3.2.

Figure 3.2 : Universal Testing Machine (INSTRON8872)

3.6 Specimens Preparation and Equipment used

The raw material of aluminum alloy 6061 is supplied by the faculty of mechanical engineering as a rectangular plate of 335 mm length x 155mm width. The raw material is cut into the desired specimens by taking in consideration the effect of surface finishing since the fatigue crack initiation is a surface dependent.

The preparation of specimens in this study is made according to ASTM B308 standard. The geometry, design and size depend on the objectives of the required tests, the laboratory machine (INSTRON 8872) capacity and the specimen type itself. For the specimens in the initial tensile test, they have a simple rectangular shape for simplicity and to avoid the waste of material.The equipments used in preparation of the specimens are L square, scriber and metal ruler. Manual sheet metal cutting machine (Model Q01-1.2X1000) is used to cut the specimens after indicating the desired geometry.

For the fatigue test specimens, they are designed in dog-bone shape with centralized hole to ensure that the fatigue happen in the center of specimens where the holes are located. Water jet cutting machine located in FTK laboratory is used to do the cutting process as it provides precise dimensions with very good surface finishing conditions. Two plate of aluminum alloy 6061 with 290mm Length and 275mm Width (Figure 3.3) are cut into 18 specimens to comprise the required number for overall experiment as stated in Table 3.2. It is necessary to mention that some specifications should be taken in consideration during the drawing process. For example, a minimum of 5mm space should be present between each specimen and 10mm-15mm should be set as margin in each side of the plate. Hence, these specifications ensure the safety and accuracy whereas the careless preparation is the main reason of undesired results and unsatisfactory. Thus, the well preparation of specimens before conducting the tests is necessary to increase the precision and decrease or avoid the limitations.

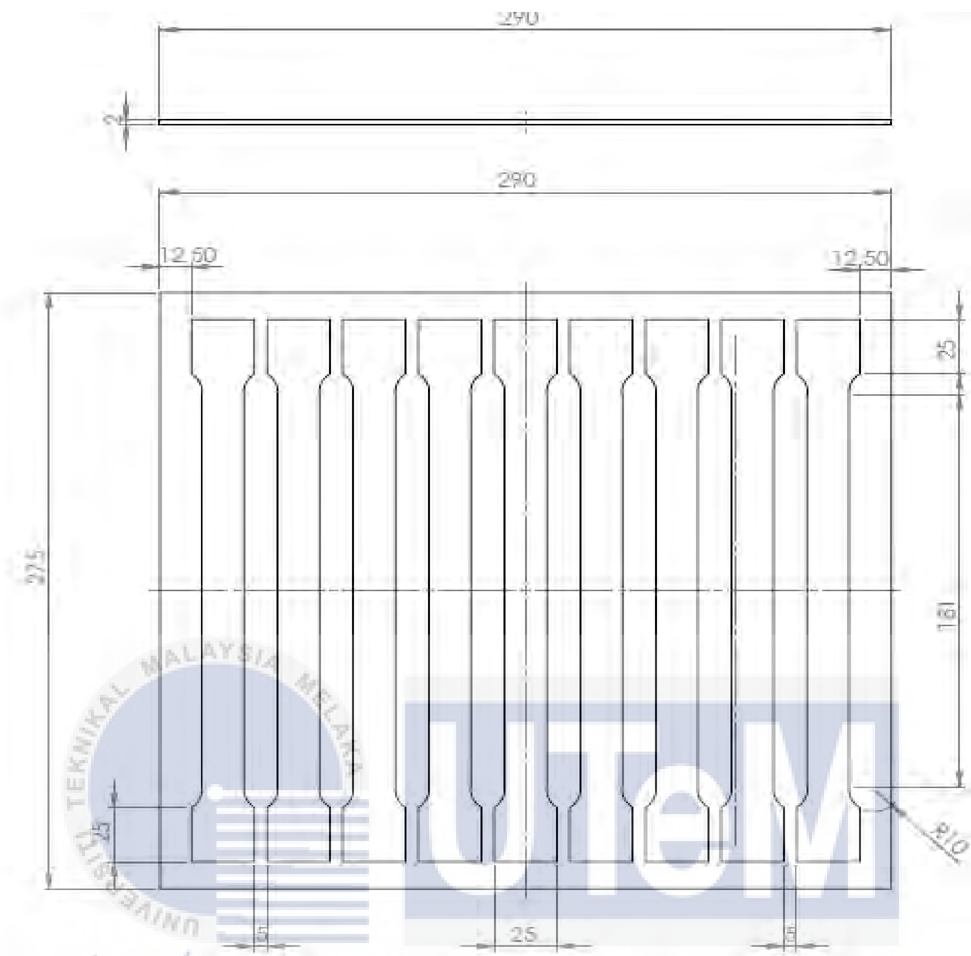


Figure 3.3: AA6061 Plate Cut by Water Jet Cutting Machine

Table 3.2: Number of Test specimens

Type	Number of Units	Remarks
Preparatory Tensile Test	3 Specimens	To set up Fatigue Test
Fatigue Test before Cold Expansion	3 Specimens	To determine the original fatigue life
Fatigue Test after Cold Expansion	9 Specimens (3 Batches)	To determine the improved fatigue life in each batch
Reserve	3 Specimens	To support results

3.7 Tensile Test Specimen

The initial tensile test specimens have been designed in rectangular shapes (25cm L x 25mm W) to avoid waste of material and also there is no need to reduce the section of centre since the tensile test is only to determine the basic mechanical properties of the material. Tolerance and accuracy in dimensions have been taken in consideration to ensure that the specimens are typically the same. Thus, the results of the test will not be varied significantly in each specimen. The average values from 3 specimens results are taken to obtain the mechanical properties of the material. Figure 3.4 and Table 3.3 are shown specimen details used in this initial tensile test.

Figure 3.4: Dimensions of AA 6061 specimen for initial tensile test

Table 3.3: Configuration of Initial Tensile Test Specimens

Specimen No.	Length, L (mm)	Width, W (mm)	Thickness (mm)	Gauge L (mm)	Grip L (mm)
1	250	25	2	25	30
2	250	25	2	25	30
3	250	25	2	25	30

Another tensile test is conducted as a preparatory test to set up the fatigue test. This tensile test is just carried out to obtain the maximum load, ultimate tensile strength and yield stress for the material. The specimens are design in dog-bone shaped as shown in Figure 3.5 and table 3.4.

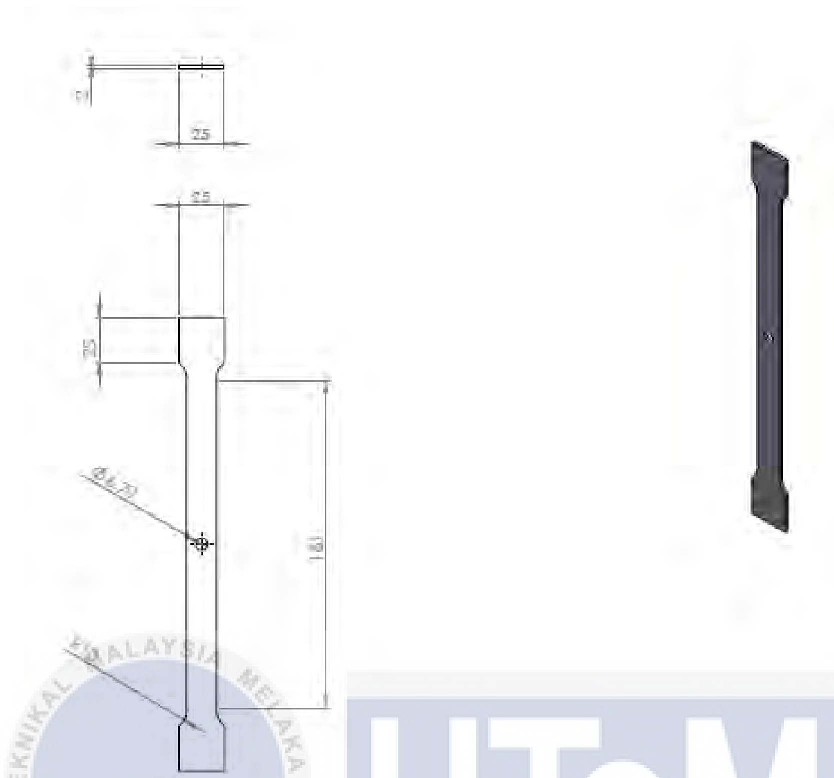


Figure 3.5: Dimensions of AA 6061 specimen for preparatory tensile test

Table 3.4 : Configuration of Preparatory Tensile Test Specimens

Specimen No.	Length, L (mm)	Width, W (mm)	L of parallel part (mm)	W of parallel part(mm)	Thickness (mm)	Gauge L (mm)	Hole D (mm)	Grip L (mm)
1	250	25	181	16.7	2	25	6.7	25
2	250	25	181	16.7	2	25	6.7	25
3	250	25	181	16.7	2	25	6.7	25

3.8 Tensile Test

Tensile test or tension test is a fundamental test which is used to obtain the material properties and characteristics. In this project, the tensile test is conducted to determine maximum load, modulus of elasticity, tensile strain, tensile strength, and yield strength. There are various standards called "ASTM international" that arrange different kinds of materials test. The suitable standards for the tensile test of this project is the International published technical standards ASTM E 8B-04 and ASTM B209-07. Based on the results of this test, several required parameters will be determined to conduct the fatigue test which is the second phase of this project.

3.8.1 Tensile Test procedures

1. Check that the machine is operating normally by trying a sample specimen before conducting the test to the three main specimens.
2. The dimensions of the specimens are measured with metal ruler.
3. The ends of gauge lengths are marked with marker pen.
4. The grip section is marked at the center of the plate where the extensometer will be located.
5. The position of the crossheads is adjusted by using the control panel to install the specimen correctly.
6. The specimen is gripped by using gripping holders of the universal testing machine. Make sure that the specimen is straight and clamped properly without any misalignment
7. The extensometer is fixed over the specimen. Make sure that position of the extensometer pins are positioned on the gauge length markings and at the center of the specimen. Next, the computer software is setting up and tensile test is ready to start.
8. The speed of the test is set to be 5 mm/min with the sample specimen and 2.5 mm/min with the three main specimens.
9. The START button is clicked to start the test. When the test specimen has reached a strain value of 0.5 mm %, the extensometer is removed quickly.
10. The STOP button is clicked to halt the test once the fracture occurred.

11. The fractured specimen is removed from the testing machine.
12. The results from the test are printed out.
13. The test is repeated by following the procedures above for other test specimens.

3.9 Cold Expansion Process

As mentioned in literature review (Section 2.5), cold expansion process can be made by many ways such as mandrels, indenters, bearing balls or pre-fitted pins. In this current project, pre-fitted pins have been used to perform the cold expansion forming.

3.9.1 Cold Expansion Material and Tool Preparation.

A bar of High Carbon Steel has been obtained from the store of Welding Lab at FASA B FKM-UTeMto prepare the 3 cold expansion tools needed for cold expansion operations. CNC turning machine is used to produce the 3 pins with heads of 7mm diameter (Figure3.6) while the manual lathe machine is used to produce the final desired diameter for each pin.

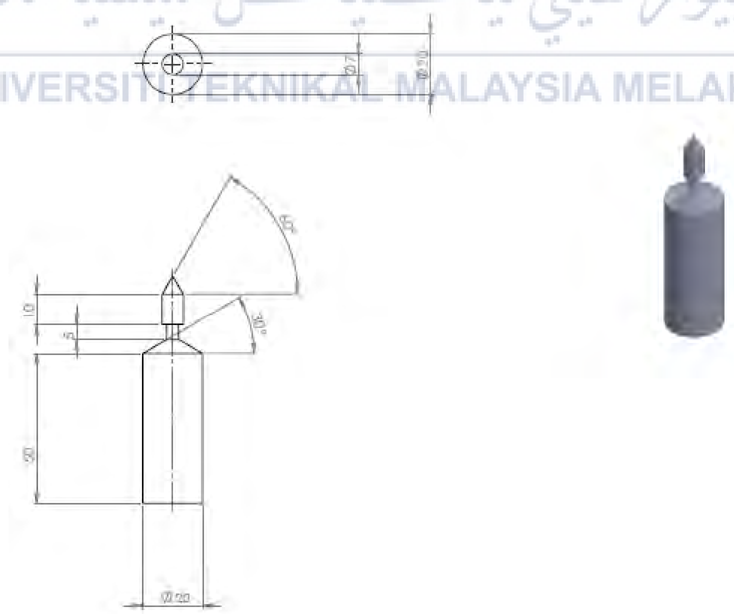


Figure 3.6: Cold Expansion pin made by CNC Turning Machine

3.9.2 Cold Expansion Implementation.

Before the application of cold expansion process, it is very important to ensure the accurate dimensions for the hole since the impact of this process depends on every sub-millimeter. Hence, Dino-Lite Digital Microscope is used to measure the precise diameter of the holes of the specimens. Edge margin is the magnitude which can be calculated directly by using the ratio of the distance from the edge of the hole to the edge of margin over the diameter of the hole (e/D). According to the latest recommendations provided by FTI Fatigue Technology (2010) and stated that 0.75 edge margin have shown considerable fatigue life improvement, the diameter of the specimens was designed to be 6.7mm. Figure 3.7 shows the photo of the hole with the accurate dimension captured by the Dino-Lite Digital Microscope.

Figure 3.7: Accurate diameter measured by Dino-Lite Digital Microscope

After that, Column Drilling Machine located at FASA B labis used to perform the cold expansion process. Everyspecimenis hold tight by two G clamps to avoid any harmful vibration of the structure. Then, three differentpins are used to make the cold expansion forming. Each size will differ slightly in the diameter to make the required interferences for

each batch of specimens. For example, the first batch (3 specimens) are formed by using a pin with 6.8mm diameter to generate 1.5% interference. Then, the second batch (3 specimens) will be formed by using a pin with 6.85mm diameter to perform 2.2% interference. After that, The third batch (3 specimens) will be formed by using a pin with 6.9mm to perform 2.9% interference. The amounts of interference are calculated based on previous studies in order to be suitable with the thickness of the material because using exaggerate interference may harm the structure of the material instead of improving its fatigue life.
Dimensions of the holes diameter have been measured by using digital caliper after the cold forming process and the average of each batch has been calculated as shown in Table 3.5.

Table 3.5: Average diameter for each batch after the cold expansion.

Original hole Diameter	1.5% Interference-hole	2.2% Interference-hole	2.9% Interference-hole
6.7mm	6.91 mm	6.93 mm	6.96 mm

3.10 Fatigue Test

Fatigue test is used to determine the fatigue life of the materials. It is conducted to observe the behavior of the material, which in this study, is subjected to constant amplitude loading. The overall procedures of this test are as follow:

i. Conducting fatigue test for three specimens before the process of cold expansion.
ii. Conducting fatigue test for nine specimens after the process of cold expansion.
iii. Both results are compared to observe the improvement in fatigue life and see the impact of cold expansion technique.

The comparison is made based on the difference of how many cycles the specimens can sustain before fatigue failure. All specimens simulate actual components of fastener holes applications. Moreover, all specimens are tested at a constant low stress ratio (R =0.1) and a constant resonant frequency of 10 Hz.

3.10.1 Fatigue Test Procedures

1. The Universal Testing Machine is warmed up for at least half an hour to satisfy the normal operating temperature.
2. The grip section is marked for each specimen.
4. The position of the crossheads is adjusted using the control panel and manual knob to install the specimen.
5. The specimen is placed in the centre of the grips and positioned properly in order to avoid the undesirable bending stress during the test.
6. A value of maximum stress needs to be estimated before starting the test. It is important to define the level of applied load for the fatigue test before running the actual fatigue test.
7. Next, the test parameters such as stress ratio, maximum and minimum load applied, mean load and load amplitude need to be calculated as discussed in Section 2.2.2.
8. The test is fully controlled using the control panel instead of the computer software. Load control mode is chosen during the testing.
9. From the control panel, the WAVEFORMis clicked to insert the value of the calculated load amplitude and the frequency used during the test.
10. Then, the value of mean load is inserted at the LOAD CONTROL option.
11. The START button is clicked to start the test. The specimens are vibrated and subjected to alternating stresses that vary between speed limits of maximum and minimum load until failure occurs.
12. Trip limits of maximum and minimum load of the test need to be set if the machine is left to run itself to avoid the machine from tripped.
14. Test is considered completed or fully done once the specimen failure is happened and the value of the total cycles is recorded.
15. The test for a new specimen can be carried out by following the above procedures.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Overview

This chapter includes the results and discussion of this project. The chapter also discusses the impact of using cold expansion technique by providing detailed tables and graphs. At the end of this chapter, an S-N curve of the specimens is drawn based on the determined results.

4.2 First Tensile Test

The first tensile test was carried out for 3 specimens with rectangular shape just to study the main properties of the material and to use that results for the design of fatigue test dog-bone shape specimens. The results of the first tensile test are shown in Table 4.1. The stress-strain curve of this tensile test is shown in AppendixB.

Table 4.1: Tensile Tests Results for 3 rectangular specimens without holes

No.	P_{max} (KN)	σ_{max} (MPa)	P_y (KN)	σ_y (MPa)
1	7.515	150.307	7.364	147.288
2	7.284	145.672	7.125	142.493
3	7.281	145.623	7.102	142.032
Av.	7.356	147.202	7.197	143.938

4.3 Second Tensile Test

The fundamental results which are necessary to find the main data to conduct the fatigue later are shown in Table 4.2. Three specimens were tested under the same conditions to find out the mechanical properties of AA6061 dog-bone specimens.

Table 4.2: Tensile Tests Results for 3 dog-bone specimens with holes

No.	P_{max} (KN)	σ_{max} (MPa)	P_y (KN)	σ_y (MPa)
1	1.3922	41.6840	1.3327	39.9003
2	1.4129	42.3036	1.3438	40.2339
3	1.4128	42.3003	1.3486	40.3769
Av.	1.406	42.096	1.3417	40.1704

The tensile results are typical with the mathematical calculation by using the following equations where Appendix H shows the set-up calculation for the fatigue test.

$$\text{Maximum tensile strength, } \sigma_{max} = \frac{\text{Ultimate tensile load, } P_{max}}{\text{Cross sectional area ,A}}$$

$$\text{Yield strength, } \sigma_y = \frac{\text{Yield load , } P_y}{\text{Cross sectional area ,A}}$$

The stress-strain curve of the tensile tests is shown in Appendix C. It shows homogenous behaviors for the 3 dog-bone specimens. By comparing these results with the rectangular specimen's results shown in Table 4.1, there is a significant difference in the strength of material. This weakness is because of the effect of the stress concentration factor which is a result of the hole and the change of the geometry of the specimen.

4.4 Fatigue Test Results

To observe a persuasive improvement in the fatigue life, each batch of the specimens have been tested at the same load, the same stress ratio (R = 0.1) and the same resonant frequency of10Hz. Table 4.3 shows the results obtained from the fatigue tests conducted for the three specimens with 1.5% interference. Table 4.4 shows the results obtained from the fatigue tests conducted for the three specimens with 2.2% interference. Table 4.5 shows the results obtained from the fatigue tests conducted for the three specimens with 2.9% interference. On the other hand, Table 4.6 shows the results obtained from the fatigue tests conducted for the original specimens prior the cold expansion. Finally, a comparison of fatigue life before and after using the cold expansion technique is shown in Table 4.7.

It is necessary to mention that a number ofspecimens are canceled or ignored because they gave anomalous results compared with the other two specimens in each batch as shown in the respective tables.

Table 4.3 Fatigue tests results for specimens formed by tool with 6.8mm diameter

No.	P_{max} (KN)	P_{min} (KN)	P_{mean} (KN)	P_{Amp} (KN)	Original hole D (mm)	Tool D(mm)	Interference of CE %	Formed hole D(mm)	Av.formed hole D(mm)	Fatigue Life (Cycles) (Nf)	Remarks
1	1.202	0.12	0.661	0.541	6.7	6.8	1.5	6.91	6.91	27,009	Accepted
2	1.202	0.12	0.661	0.541	6.7	6.8	1.5	6.93	6.91	55,442	Canceled
3	1.202	0.12	0.661	0.541	6.7	6.8	1.5	6.90	6.91	18,010	Accepted
				Average of accepted fatigue life , Nf						22,509	

Table 4.4 Fatigue tests results for specimens formed by tool with 6.85mm diameter

No.	P_{max} (KN)	P_{min} (KN)	P_{mean} (KN)	P_{Amp} (KN)	Original hole D (mm)	Tool D(mm)	Interference of CE%	Formed hole D(mm)	Av.formed hole D(mm)	Fatigue Life Cycles (Nf)	Remarks
1	1.202	0.12	0.661	0.541	6.7	6.85	2.2	6.94	6.93	40,444	Canceled
2	1.202	0.12	0.661	0.541	6.7	6.85	2.2	6.92	6.93	87,075	Accepted
3	1.202	0.12	0.661	0.541	6.7	6.85	2.2	6.93	6.93	82,724	Accepted
				Average of accepted fatigue life , Nf						84,899	

Table 4.5 Fatigue tests results for specimens formed by tool with 6.9mm diameter

No.	P_{max} (KN)	P_{min} (KN)	P_{mean} (KN)	P_{Amp} (KN)	Original hole D (mm)	Tool D(mm)	Interference of CE%	Formed hole D(mm)	Av.formed hole D(mm)	Fatigue Life Cycles (N)	Remarks
1	1.202	0.12	0.661	0.541	6.7	6.9	2.9	6.96	6.96	56,531	Accepted
2	1.202	0.12	0.661	0.541	6.7	6.9	2.9	6.95	6.96	56,626	Accepted
3	1.202	0.12	0.661	0.541	6.7	6.9	2.9	6.96	6.96	84,414	Canceled
				Average of accepted fatigue life , Nf						56,578	

Table 4.6 Fatigue tests results for the original specimens prior cold expansion

No.	P_{max} (KN)	P_{min} (KN)	P_{mean} (KN)	P_{Amp} (KN)	Original hole D (mm)	Fatigue Life Cycles (N)	Remarks
1	1.202	0.12	0.661	0.541	6.7	72,753	Accepted
2	1.202	0.12	0.661	0.541	6.7	66,755	Accepted
3	1.202	0.12	0.661	0.541	6.7	64,128	Accepted
	Average of accepted fatigue life , Nf					67,878	

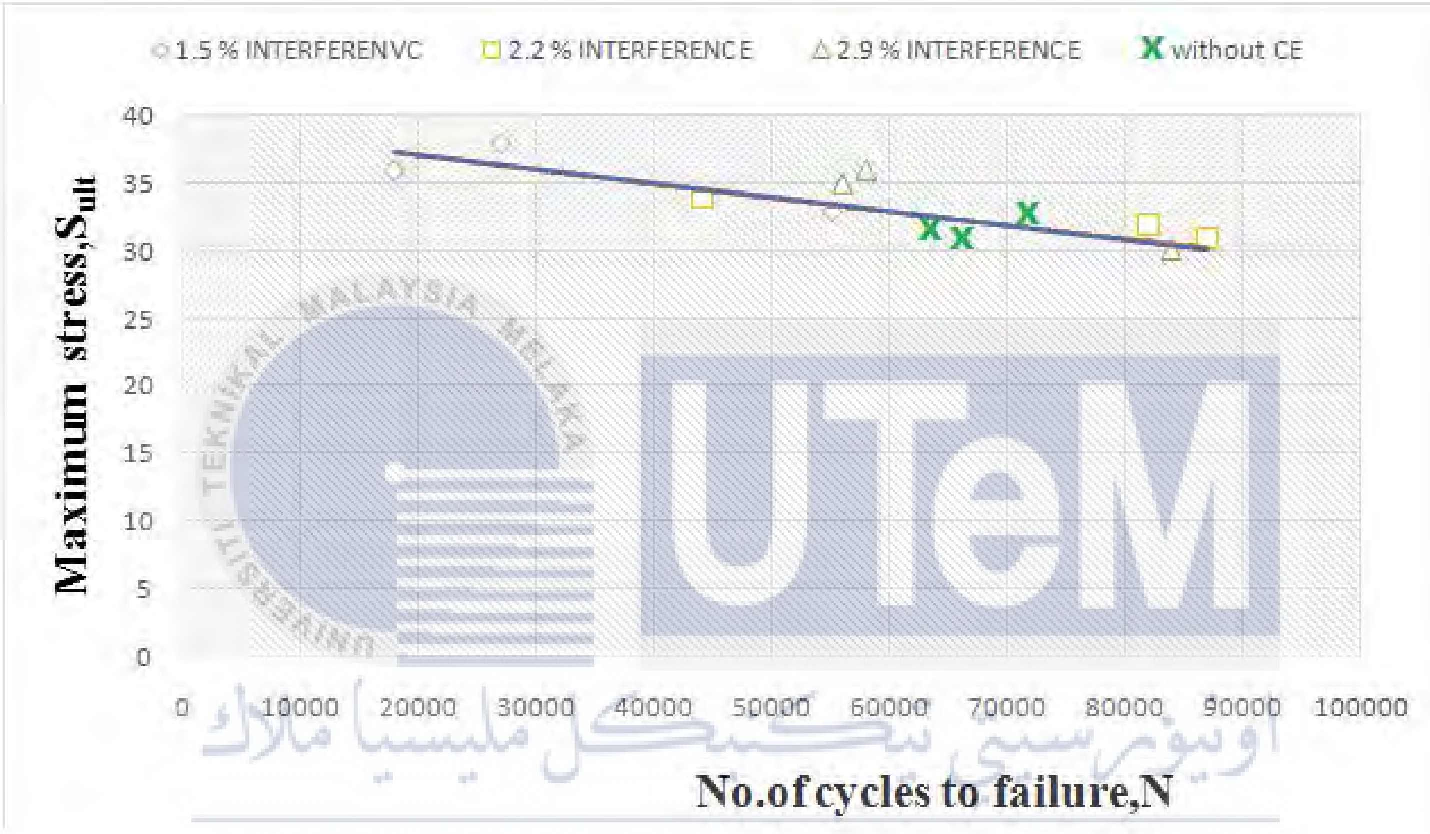


Figure 4.1:S-N Curve for all specimens.

4.5 Analysis of Tensile Test Results.

Enough results have been recorded to observe a significant difference between the initial rectangular specimens and dog-bone shaped specimens which are tabulated in Table 4.1 and Table 4.2. The necessary parameters were the maximum tensile load, ultimate tensile stress, yield tensile load and yield tensile stress.

The average ultimate strength tensile stress for rectangular specimens and dog-bone shaped specimens are 147.202 MPa and 42.096 MPa respectively. This anticipated difference shows clearly that dog-bone shaped specimens with a hole are weaker than rectangular specimens. In other words, the strength of specimens with rectangular design is higher than the specimens with dog-bone design. This is because of the stress concentration generated around the hole and the decrease in the section area in the dog-bone shaped specimens. Thus, a lower axial stress is needed to perform the fracture.

It was also observed that all fractures are happened in the centre of each doge-bone shaped specimen. During the test and when the tensile stress magnitude reaches the yield strength level, the crack roots appear obviously as an indication that the area of hole is deformed plastically in a parallel direction from the tensile loading axis. That particular region which includes the hole consist of the stress raisers where the high stresses are concentrated. This is one of the main reasons why dog-bone shaped specimens were chosen rather than the rectangular shape specimens. In contrast, one fracture of rectangular specimens occurred at the edge and just near to the grip section however the applied stress through the three specimens is design to be uniform through the cross section of each specimen. This is probably because of material defects which cannot be realized in the structure unless such engineering tests are conducted.

4.6 Analysis Of Fatigue Test Results.

The Results of fatigue tests for the batches of 1.5%, 2.2% and 2.9% interferences are tabulated in Tables 4.3, 4.4, 4.5 respectively while the results obtained for the specimens prior the cold expansion are tabulated in Table 4.6. To analyze clearly the overall data, each patch of interference was compared with the original specimens to see the effect of cold expansion technique.

For the first batch of 1.5% interference and contrary to expectations, the average number of cycles to failure was 22,509 cycles while the average number of cycles to failure for the original specimens was 67,878 cycles. This finding means that the number of cycles to failure is decreased rather than increase as it was predicted. A possible explanation for this might be that, the cold working produced by the 6.8mm tool and generated 1.5% interference was not effective enough to create a localized yielding region which strengthens the material. On the other hand, It caused a negative impact for the structure of specimens and this leads to this undesired weakness by -66.8%.

For the second batch of 2.2% interference, the results were very encouraging because of the enhancement of fatigue life recorded. It is found that the number of cycles to failure is increased by + 25.1% which broadly supports the work of other studies in this field. An average of 84,899 cycles to failure was recorded as the longest fatigue life produced in this study. These findings may help us to understand the benefit of cold expansion technique. In addition, these results show that 2.2% interference is the optimal interference which can be used for this specific diameter and thickness of structure.

Surprisingly, 2.9% interference amount was found to lead to a decrease in the cycles to failure from 67,878 cycles to 56,578 cycles by a percentage of -16.6%. It is difficult to explain this result, however it might be related to the effects and quality of cold working. As it is suggested in some previous studies, generate a small amount of interference may not be enough to create the required impact. Instead of that, it may produce an elastic region which returns to its original state when loading is removed. Moreover, generating excessive amount of interference may weaken the structure rather than strengthen it. For this thin plate with 2mm thickness, 2.9% interference might not be a good choice.

A comparison of fatigue life before and after cold expansion (CE) technique is shown in Table 4.7 and Figures 4.2 and 4.3respectively.

Table 4.7 Comparison of Fatigue Life before and after Cold Expansion

Set	Av. N of Original specimens	Interference of CE %	Av. N with Cold Expansion	Decrease/Increase %
1	67,878	1.5	22,509	-66.8
2	67.878	2.2	84,899	+25.1
3	67,878	2.9	56,578	-16.6

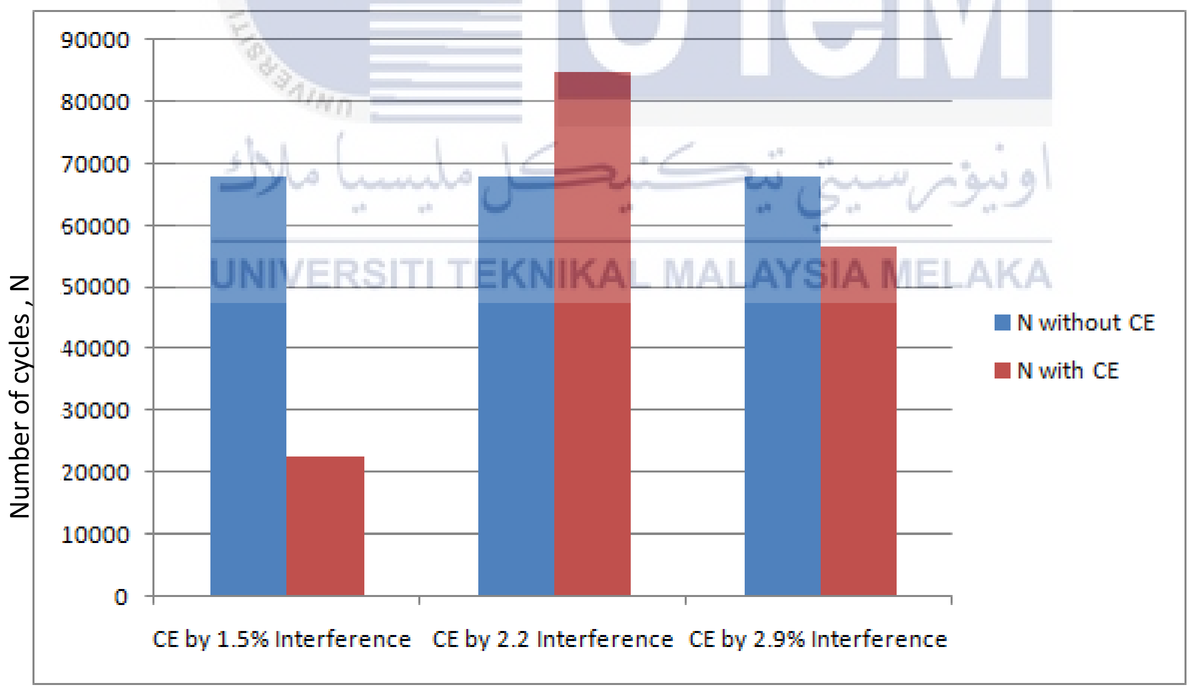


Figure 4.2: Comparison of fatigue lifebefore and after cold expansion

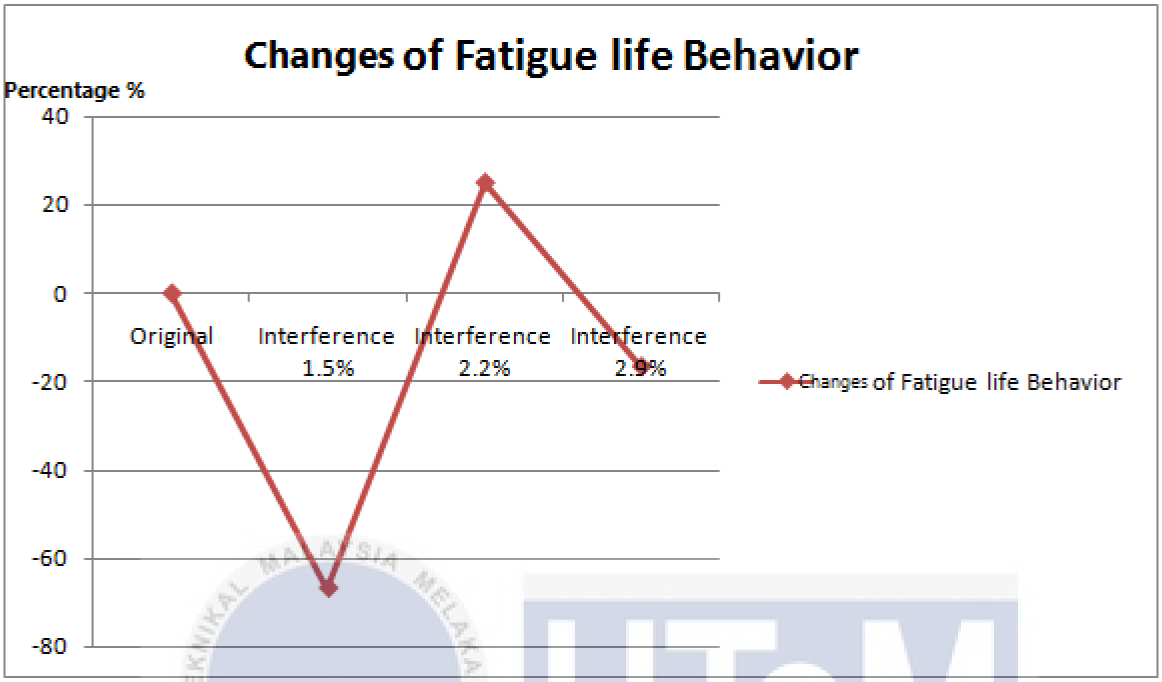


Figure 4.3: Changes of Fatigue Life Behavior

4.7 Factors Influencing Fatigue

Based on the findings of this experiment, it is observed that there are a number of main factors which influenced the fatigue test results. Some of these factors were desired and required to improve the fatigue performance such as the cold working effect. On the other hand, there were some undesired factors which is been avoided during the preparing stage and fatigue testing stage such as the effect of imperfectness of surface conditions and the internal tensile residual stresses.

4.7.1 Effect of Cold Expansion Technique

Theoretically, the impact of cold expansion or cold working was proven positively in the regards of improving the fatigue life. However, the challenging part was in the utilization of this technique so that it will support previous findings. That is why three different amounts of interference were applied for three batches of specimens. As it is mentioned in the literature review, cracks are the main reason of fatigue failure and fatigue cracks usually start at the region where the stress concentration is high. The presence of this stress concentration causes a weakness in the resistance of any structure to fatigue failure. In this study, the fastener holes were the critical area where the stress raiser is located. Thus, as a consequence, cracks initiate in such location due to the localized high stresses. Cold expansion effect strengthens this materials without adding any structural weight. Once the cold forming tool is removed, a biaxial residual stress is produced as a reaction of the elastic deformation on the area of annulus. As a result, a permanent localized compressive residual stresses around the fastener holes are generated which can be maximized wisely by using suitable amount of interference.

4.7.2 Effect of Surface Condition

Generally, the cracks which cause the fatigue failure initiate from the surface especially when the load is axial unless there are some internal manufacturing defects in the structure of the material. Thus, the effect of surface condition should be taken seriously in consideration. Therefore, in each stage of specimens preparing, this effect has been minimized and avoided.

However, a slight effect remains present due to unavoidable vibration which is normal especially during the cold expansion process.

Starting from the cutting process, the water jet machine was chosen because it provides precise dimensions with a good surface finishing. After that, during the cold forming process, two G clamps were used to hold the specimens tight from each side so that the vibration level is reduced. Moreover, the minimum rotating speed which is 250 rpm was used for the cold forming tools so that the inner surface of holes does not harm due to any consequences that may induce due to the massive friction between the two surfaces. Finally, polishing is required to provide a surface free of scratches and roughness.

All procedures mentioned above are only to overcome the effect of surface condition factors. It has been known that fatigue life increases as the surface roughness decreases. This is because of the minimization which happened to the local stress raisers due to the decreasing of surface roughness. As a result, the desired residual stresses only remain in the structure after the fabrication work is done. These residual stresses are compressive because of the plastic deformation which is produced by the cold expansion technique. Unlike the tensile residual stresses, these compressive residual stresses are determined beneficial to the strength of material thereby the improvement of fatigue life.

4.8 Fracture Behavior of Materials Before and after cold Expansion

To see clearly the internal effect of cold expansion technique, a microscopic study has been done for a specimen before and after cold expansion. At a macroscopic level, it was obvious that the specimen before cold expansion exhibits a ductile fracture around the hole with a flat and perpendicular fracture surface to the plane of the maximum tensile stress (Figure 4.4)

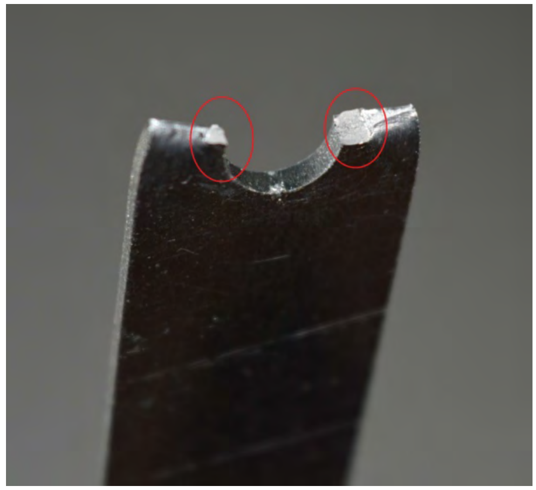


Figure 4.4:Macroscopic Fracture of a specimen before Cold Expansion

At a microscopic level, this fast fracture zone is clearer than the macroscopic view which cannot be seen to naked eye (Figure 4.5). This flat fracture around the hole indicates that cracks initiated in this region first then they propagated and grew in the other margins of specimen where there is a necking behavior.

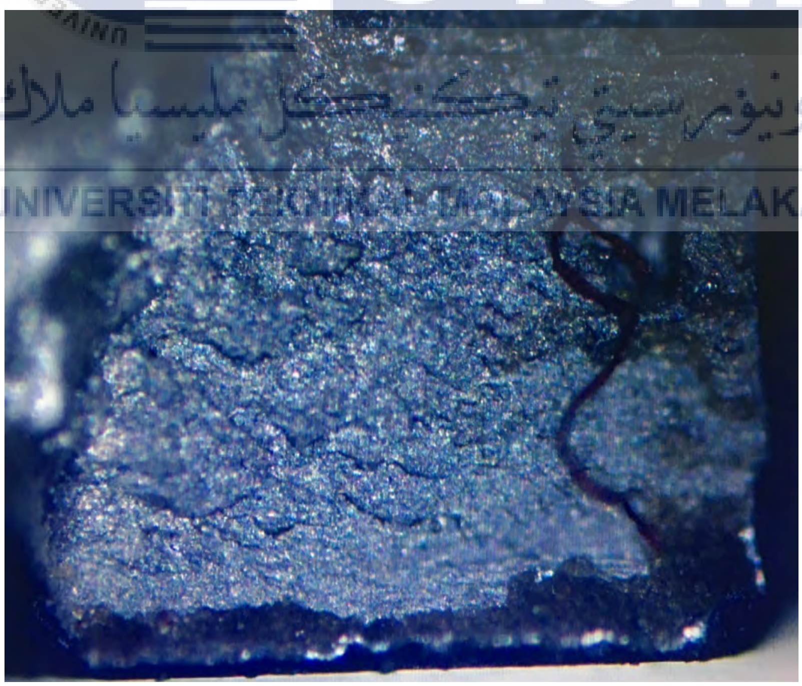


Figure 4.5: Microscopic Flat Fracture for specimen before Cold Expansion

After the implementation of cold expansion, it was clearly observed the impact of the technique on the structure of specimen especially the circumferential area around the hole where the localized plastic deformation is happened. Figures 4.6, 4.7 and 4.8 showa necking behavior across the whole area of fracture which can be approximately assumed to be 45 degree to the applied load. This explains why the specimen sustain more time before fatigue failure and proves the previous findings of positive effect of cold expansion around the hole.

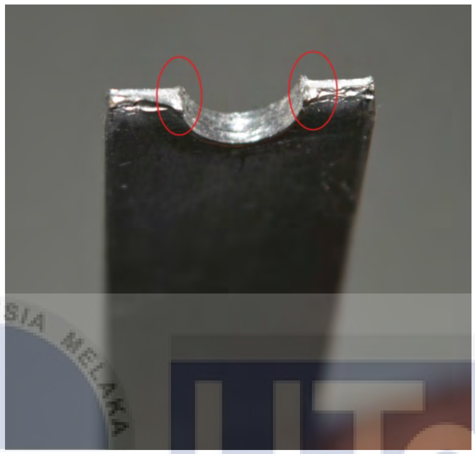


Figure 4.6 : Macroscopic Fracture of a specimen after cold expansion

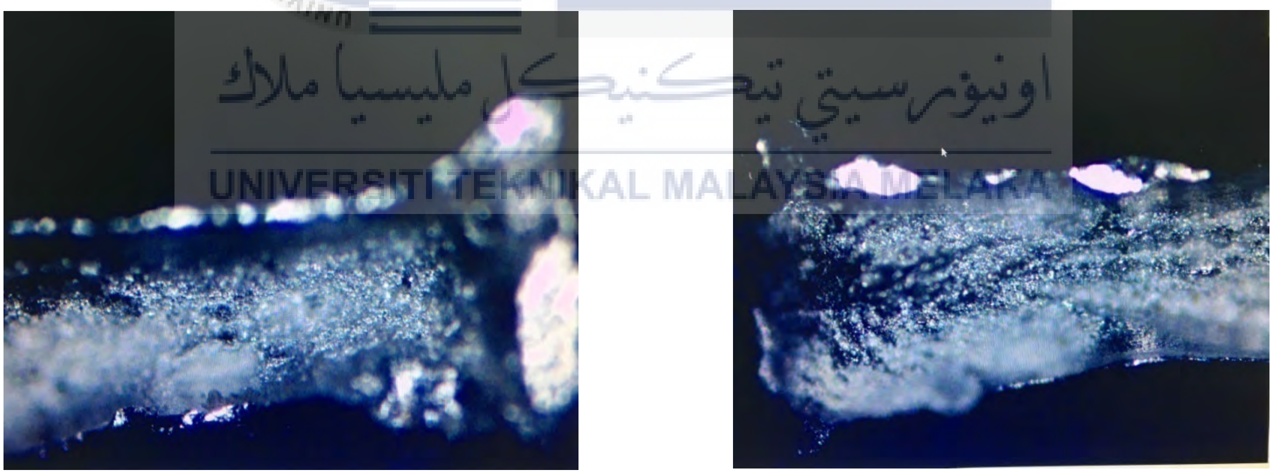


Figure 4.7, 4.8: Microscopic Ductile Fracture for specimen after Cold Expansion

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Generally, all objectives of this project have been accomplished. The essential purpose of this study was to examine improvement in the fatigue life of fastener holes by using the cold expansion technique. The sub-objectives of this thesis were to create the S-N curve of the test specimens and to determine supporting information and data for the study according to stress-based approach. The study discussed the fatigue as a serious sudden problem happens in the structures and components and needs practical solutions. Cold expansion or cold working is one of the techniques which has been widely used and proved a remarkable improvement in the fatigue life of materials. Aluminum alloy 6061 is the tested material which was chosen in this study as it is one of common aluminum alloys that does not has true fatigue limit. Beside, high carbon steel was chosen to produce the cold expansion tools because it is significantly harder than aluminum alloy. The design of rectangular and dog-bone shaped test specimens as well as cold expansion tools was proposed based on ASTM standards and previous studies in this field.

Initially, tensile test was carried out for three rectangular and three dog-bone shaped specimens to obtain the fundamental mechanical properties of the material. Then, fatigue test was conducted for three dog-bone shaped specimens to determine the fatigue life of the material prior the effect of cold expansion technique. After that, another fatigue test has been carried out for three different batches of dog-bone shaped specimens where each batch consists of three specimens with specific amount of interference. Finally, the overall results have been tabulated and illustrated by using detailed graphs in addition with the S-N curve.

The findings of this study has shown significant improvement in the fatigue life after the implementation of cold expansion technique. In contrast, some results indicated contradictory findings compared with the anticipated results. This inconsistency may be due to the suitability of the amounts of interferences used in each batch of specimens with the structure of material. Hence, the batch of specimens which cold formed by using 2.2% interference showed positive and supporting findings regarding the enhancement of fatigue life by a percentage of 25.1%. On the other hand, the two other batches which cold formed by using 1.5% and 2.9% interferences showed negative results by reducing the fatigue life by 66.8% and 16.6% respectively. Notwithstanding these differences, the study has found that 2.2% interference is the optimum amount that can be applied in the cold expansion technique to generate the required improvement in the fatigue life.

5.2 Recommendations for further studies

This current study had been concentrated on determining an improvement regarding the fatigue life of the Aluminum alloy 6061. As a recommendation for future works in this field, it is suggested that a further study may explain and analyze the effects of cold expansion technique by using the Finite Element Analysis (FEA). This analysis will help to understand what really happened in the structure and how the residual stresses were distributed around the fastener holes after cold forming. Therefore, the implications of the three interferences in the structure will be elaborated. In addition, a constant amplitude loading and a low stress ratio were subjected to the specimens during this project whereas in practical, variable cyclic loading is subjected to the most engineering applications and structures. Thus, it is recommended that another study may be conducted in such conditions to simulate the reality.

Cold expansion technique was the strategy which has been used to produce the improvement of fatigue life in this current study. In this technique, high carbon steel tools (pins) were used to generate the localized plastic deformations by prescribed amounts of interferences. Therefore, as a recommendation for further studies to use an oversize ball (ballising) to provide the same function of cold expansion.

Besides, good preparing for test specimens and surface finishing is one of important things that required a special attention. In this study, the Water Jet Machine was used to produce the test specimens. It is a high-tech machine with the tightest of 0.1mm to .03mm tolerance. However, It is better to use Laser Cutting Machine since it provides a 0.1 mm as the tightest tolerance. Accuracy and high precision play an important role in order to find high quality results.

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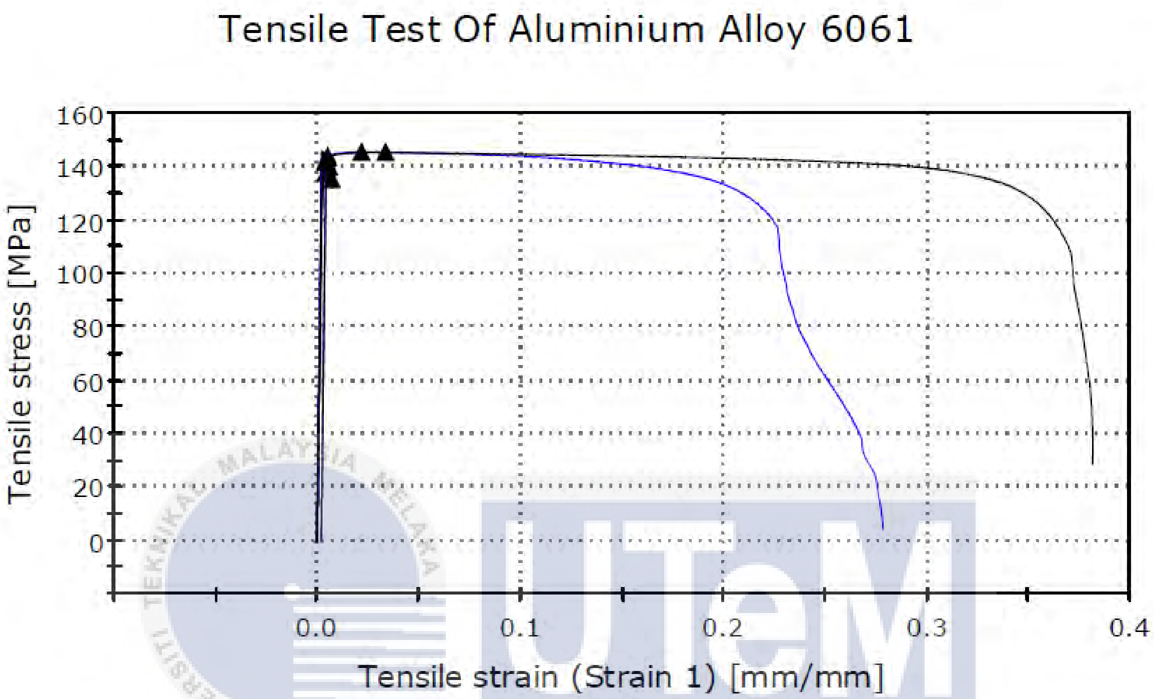
APPENDICES

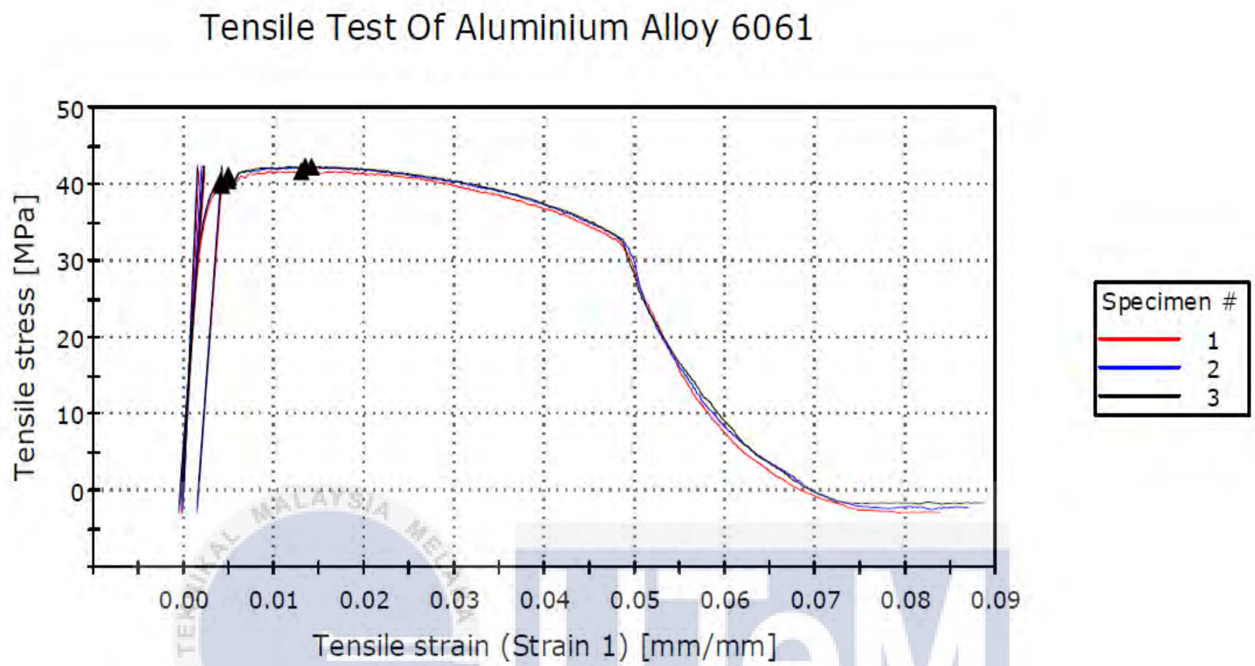
Appendix A : Gantt Chart of Final Year Project

NO.	Activities	2017				2018				
		Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
1	Title approval									
2	Research background study									
3	Literature review									
4	Research methodology									
5	Initial Tensile Test and Presentation FYP1									
6	Specimens drawing									
7	Specimens preparation and fabrication									
8	Preparatory Tensile test and initial Fatigue test									
9	Cold Expansion preparation									
10	Fatigue Tests									
11	Comparison of results									
12	Report writing and submission									

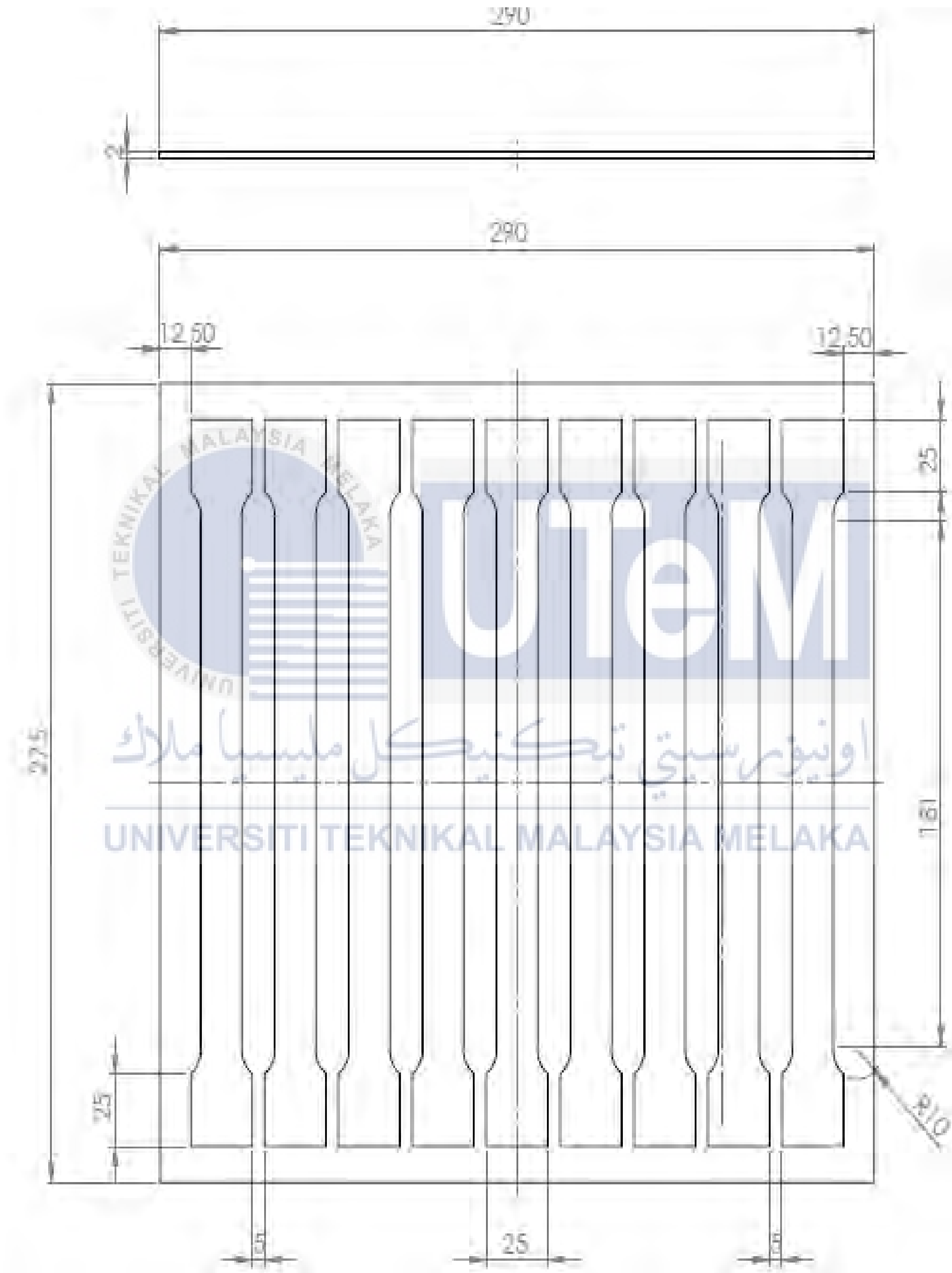
Appendix B : Results of initial Tensile Test



Appendix C : Results of preparatory Tensile Test

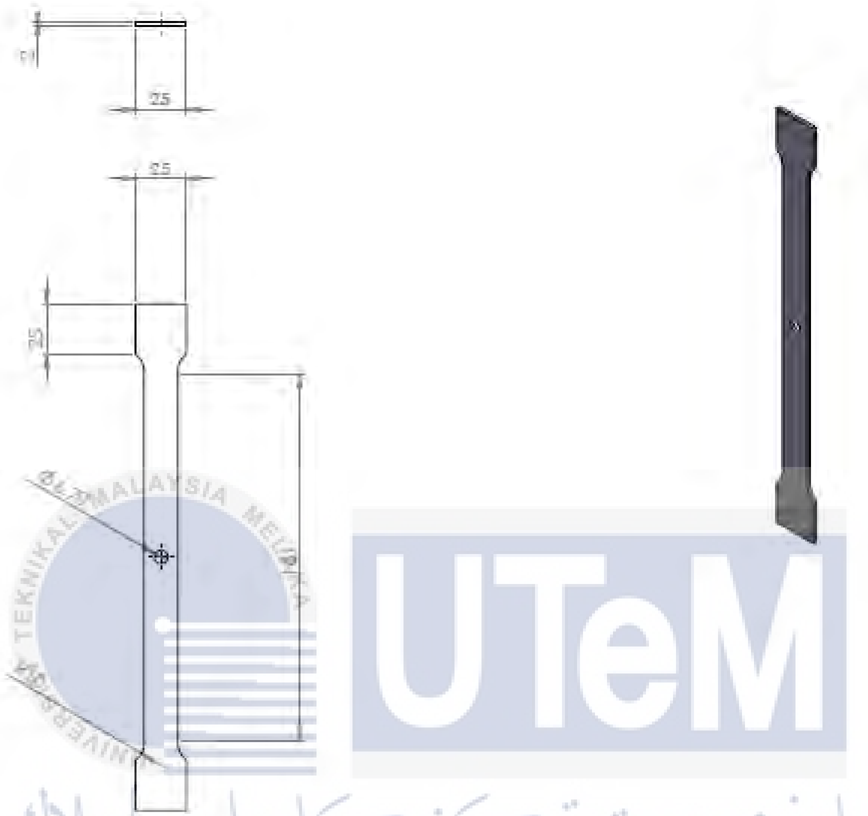


Appendix D :Detailed drawing of dog-bone shaped specimens

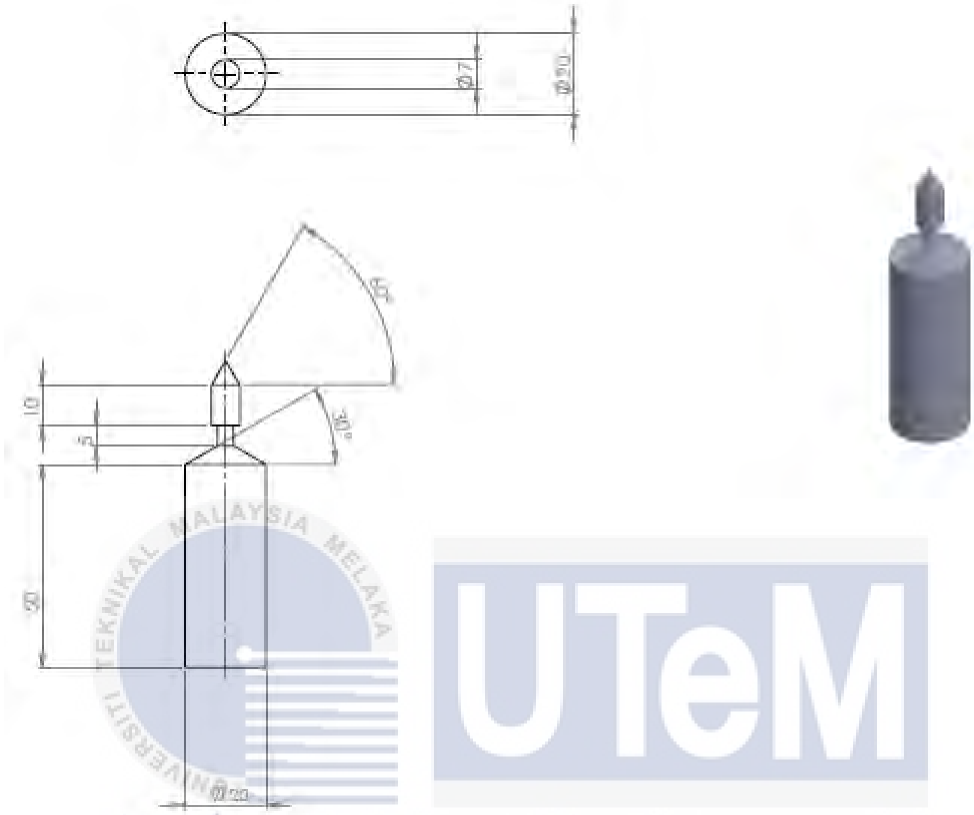


Appendix E : DXF drawing file for Water Jet Cutting Machine

Appendix F : Detailed drawing of doge-bone shaped specimen



Appendix G : Detailed drawing of Cold Expansion Tool



Appendix H: Set-up Calculation for Fatigue Test

Form the preparatory tensile test:

Yield stress,σ_y = 40 MPa

Tensile Stress, σ_{ult}= 42 MPa

for the test applied stress or load, it should not exceed 90 % of the Maximum limits.
Thus,

40 MPa X .9 = 36 MPa

$$\sigma = \frac{P}{A}$$

$$36 \times 10^6 = \frac{P}{2 \times 10^{-3}\ X\ 16.7 \times 10^{-3}}$$

$$Pmax = 1202.4\ N = 1.202\ KN$$

The stress ratio ,R = 0.1.
Thus,

$$R = \frac{\sigma_{min}}{\sigma_{max}}$$

$$0.1 = \frac{\sigma_{min}}{36\ MPa}$$

$$\sigma_{min} = 3.6\ MPa$$

$$The\ coressponding\ load\ ratio, \qquad R = \frac{P_{min}}{P_{max}}$$

Thus, Pmin =0.12 KN

- For Load Amplitude.

$$P_{amp} = \frac{Pmax - Pmin}{2} = 0.541$$

-Mean Load : the average of the maximum and minimum stresses in one cycle.

$$P_{meam} = \frac{Pmax + Pmin}{2} = 0.661$$