EFFECT OF SURFACE TREATMENT ON FATIGUE LIFE OF PISTON

AHMAD MAZRUL BIN KAMARUDIN

UNIVERSITI MALAYSIA PAHANG

UNIVERSITI MALAYSIA PAHANG

BORANG PENGESAHAN STATUS TESIS

JUDUL: **EFFECT OF SURFACE TREATMENT ON FATIGUE LIFE OF PISTON**

SESI PENGAJIAN: 2007/2008

Saya AHMAD MAZRUL BIN KAMARUDIN
(HURUF BESAR)

mengaku membenarkan tesis (PSM/Sarjana/Doktor Falsafah)* ini disimpan di Knowledge Management Centre dengan syarat-syarat kegunaan seperti berikut:

1. Tesis adalah hakmilik Universiti Malaysia Pahang.
2. Knowledge Management Centre dibenarkan membuat salinan untuk tujuan pengajian sahaja.
3. Perpustakaan dibenarkan membuat salinan tesis ini sebagai bahan pertukaran antara institusi pengajian tinggi.
4. **Sila tandakan (✓)

☐ SULIT (Mengandungi maklumat yang berdarjah keselamatan atau kepentingan Malaysia seperti yang termaktub di dalam AKTA RAHSIA RASMI 1972)

☐ TERHAD (Mengandungi maklumat TERHAD yang telah ditentukan oleh Organisasi/badan dimana penyelidikan dijalankan)

☑ TIDAK TERHAD

Disahkan oleh

______________________________ (TANDATANGAN PENULIS)

______________________________ (TANDATANGAN PENYELIA)

Alamat Tetap:
NO 271 BLOK 3,
FELDA CHINI 2,
26690 PEKAN,
PAHANG.

Nama Penyelia:
Dr. Md. Mustafizur Rahman

Tarikh: ____________________________

Tarikh: ____________________________

CATATAN: * Potong yang tidak berkenaan
** Jika tesis ini SULIT atau TERHAD, sila lampirkan surat daripada pihak berkuasa/organisasi berkenaan dengan menyatakan sekali sebab dan tempoh tesis ini perlu dikelaskan sebagai SULIT atau TERHAD
υ Tesis dimaksudkan sebagai tesis bagi Ijazah Doktor Falsafah dan Sarjana secara penyelidikan, atau disertasi bagi pengajian secara kerja kursus dan penyelidikan, atau Laporan Projek Sarjana Muda (PSM)

EFFECT OF SURFACE TREATMENT ON FATIGUE LIFE OF PISTON

AHMAD MAZRUL BIN KAMARUDIN

Report submitted in partial fulfillment of the requirements
for the award of the degree of
Bachelor of Mechanical Engineering with Automotive Engineering

Faculty of Mechanical Engineering
UNIVERSITI MALAYSIA PAHANG

NOVEMBER 2008

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this project and in our opinion this report is satisfactory in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering with Automotive.

Signature : …………………………….
Name of Supervisor: DR MD. MUSTAFIZUR RAHMAN
Position : SENIOR LECTURER
Date : 14 NOVEMBER 2008

PANEL'S DECLARATION

I hereby declare that I have checked this project and in our opinion this report is satisfactory in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering with Automotive.

Signature : ……………………………

Name of Panel: MR LEE GIOK CHUI

Position : LECTURER

Date : 14 NOVEMBER 2008

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 : …………………………………..
Name : AHMAD MAZRUL BIN KAMARUDIN
ID Number : MH05001
Date : 14 NOVEMBER 2008

Dedicated to my beloved

Parents and Siblings

For their endless support in term of motivation,

Supportive and caring as well throughout the whole project

ACKNOWLEDGEMENTS

I feel grateful to Allah S.W.T because this project has successfully completed. In completion this final year project, I was in contact with many people that contributed toward my understanding and problem solving. In particular, I wish to express my sincere appreciation to my project supervisor, Dr. Md. Mustafizur Rahman for his guidance, advice and encouragement.

Besides that, I also would like to dedicate my appropriation to all my fellow friends for their support and encouragement. Particular mention is due to Hilmee, Ahmad Mursyidi Hamzah, Mohd Saiful Mohd Stizic Tengku Mohamed Hairi, Ahmad Shahril Ashraf Mohamed, Nik Mohd Ariff Nik Nasir and especially to my sister Mazlina Bt.Kamarudin.

Not forgetting my lovely mother and father in giving me lots of supports in the aspects of moral, social and financial during my degree. This project definitely not exists without full encouragement from her

ABSTRACT

Prediction of fatigue life on piston for four stroke engine using variable amplitude loading is presented. The piston is the crucial part of the internal combustion engine. The objectives of this project are to predict fatigue life of piston for four stroke engine using strain-life method, to identify the critical locations, to investigate the effect of mean stress and to optimize the component material. The structural and finite element modeling has been performed using a computer aided design and finite element analysis software package. The finite element model of component then analyzed using the Strain method approach. Finally, the stress-strain state of component obtained previously will be use as input for the fatigue life. The effected mean stress and materials optimize was also too investigated. The failure of piston can result in devastating damage to the engine including all the components from a tiny screw till a huge belting system. Life of piston needs to be improved to prevent from any unpleasant problems. The results of the analysis showed that there are no serious failure occurs at the part of the piston. However it is observed that the minimum predicted life at the critical location is $10^{2.38e-7}$ under variable amplitude loading for strain-life approach. The optimization results showed 7075 T6 aluminum alloy that is the most superior material among the others.

ABSTRAK

Ramalan jangka hayat bagi piston enjin empat lejang dipersembahkan. Objektif untuk projek ini ialah untuk meramal jangka hayat bagi piston untuk enjin empat lejang, untuk mengenal pasti lokasi kritikal yang terdapat pada piston, untuk menyiasat hubungan dan kesan ketegangan purata daripada jangka hayat keterikan dan untuk mengoptimumkan pemilihan bahan. Model struktur dan elemen finiti telah dibuat menggunakan perisisan lukisan secara berkomputer dan analisis elemen finiti. Model bagi elemen finiti tersebut kemudian dianalisa menggunakan pendekatan *Ketegangan*. Akhir sekali, keterikan dan ketegasan bagi komponen tersebut yang telah dicapai akan digunakan sebagai input untuk jangka hayat lesu. Kesan keterikan purata dan bahan yang optimum akan diperiksa. Piston ialah bahagian yang paling penting sekali di dalam sesebuah enjin. Kegagalan piston untuk berfungsi dengan baik akan menyebabkan kerosakan teruk kepada enjin termasuklah semua komponen samada dari sekecil bahagian seperti skru hinggalah kepada system enjin. Jangka hayat piston perlulah diperbaiki untuk mengelakkan daripada berlakunya masalah-masalah yang tidak diingini. Keputusan analisa menunjukkan tiada kegagalan yang serius berlaku pada mana-mana bahagian piston. Walau bagaimana pun daripada pemerhatian menunjukkan jangka hayat paling minima di lokasi kritikal ialah $10^{2.38e-7}$ dibawah tindakan amplitud yang berubah untuk hayat ketegangan. Akhir sekali, bahan yang terbaik hasil daripada analisa ialah aluminum alloy 7075 T6 berbanding dengan baha-bahan lain.

TABLE OF CONTENTS

	Page
TITLE	ii
SUPERVISOR DECLARATION	iii
PANEL'S DECLARATION	iv
STUDENT DECLARATION	v
ACKNOWLEGEMENTS	vii
ABSTRACT	viii
ABSTRAK	ix
TABLE OF CONTENT	x
LIST OF TABLE	xiii
LIST OF FIGURE	xiii
LIST OF SYMBOL	xv

CHAPTER 1 INTRODUCTION

1.2	Project Background	1
1.3	Problem Statement	2
1.4	Scopes of Project	2
1.2	Objectives of Project	2
1.3	Overview of Project	3

CHAPTER 2 LITERATURE REVIEW

2.1	Introduction	4
2.2	Piston	4
2.3	Piston Material	5
	2.3.1 Aluminum Alloy	6
2.4	Fatigue Life	7
2.5	Strain-Life	7
2.6	Surface Treatment	8
2.7	Nitriding Processes	9

2.8	Cold Rolled Processes	10
2.9	Shot Peened Processes	11

CHAPTER 3 METHODOLOGY

3.1	Introduction	12
3.2	Finite Element based Fatigue Life Prediction	12
3.3	Finite Element based Fatigue Analysis	13
3.4	Strain Life Method	14
3.5	Loading Information	16
	3.5.1 Variable amplitude loading	16
3.6	Project Methodology	18
3.7	Structural Modeling	19
3.8	Finite Element Modeling	19
3.9	Analysis Data	20
3.10	Conclusion	21

CHAPTER 4 RESULTS AND DISCUSSION

4.1	Introduction	22
4.2	Structural Modeling Result	22
4.3	Finite Element Method	24
4.4	Selection of Mesh Type	24
	4.4.1Comparison maximum of stress between global edge lengths for TET10	26
4.5	Result for Finite Element Analysis	28
	4.5.1 Material Information	2.8
	4.5.2 Result for finite element analysis	29
4.6	Result of Fatigue Analysisi	29
4.7	Optimization	30
	4.7.1 Strain-Life with Mean Stress Correction	30

4.7.2 Strain-life with comparison of Surface Treatment 31

4.7.3 Strain-life with material comparison 33

CHAPTER 5 CONCLUSION

5.1 Introduction 35

5.2 Recommendation 36

REFERENCES 62

LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	Mechanical Properties of Aluminum Alloys at Room Temperature	5
4.1	Maximum stress between TET types	26
4.2	Maximum of stress between global edge lengths for Tet 10	27
4.3	Material Information of Aluminum Alloy 6061 T6	28

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
2.1	Piston	5
2.2	Schematic Diagram of Fatigue Life Estimation	7
3.1	Flow Chart of Project	13
3.2	Schematic diagram of fatigue life estimation	14
3.3	The typical strain-life curve	14
3.4	Time-load-history	17
3.5	3D Piston Drawing	19
3.6	Typical Engine Piston	20
4.1	3D Piston Model	23
4.2	3D Drawing Piston after import to the MSC Patran Software	23
4.3	Structural and finite element modeling of piston loading and boundary condition	24
4.4	Types of meshing element used in finite element method	25
4.5	Stress versus type of topology	26
4.6	Graph maximum stress versus global edge length	27
4.7	Von-Misses stress contours (a) TET4 and (b) TET10 at high load level	29
4.8	Predicted fatigue life contours plotted for TET10 Using Strain Method	30
4.9	Life (repeats) versus pressure	31
4.10	Life (repeats) versus pressure of surface treatments	32
4.11	Life (repeats) versus pressure of materials	33

LIST OF SYMBOLS

C_p	Specific heat of constant pressure
C_v	Specific heat of constant volume
N	Engine speed
P	Pressure
P	Power
Q_{HHV}	Higher heating value
Q_{LHV}	Lower heating value
R	Gas constant
T	Temperature
T_o	Standard temperature
V	Cylinder volume
V_{BDC}	Cylinder volume at bottom dead center
V_d	Displacement volume
V_{TDC}	Cylinder volume at top dead center
W	Work
k	Ratio of specific heats
m	Mass
m_a	Mass of air
m_f	Mass of fuel
m_m	Mass of gas mixture
n_r	Number of crank revolutions
q	Heat transfer per unit mass
r_c	Compression ratio

v	Specific volume
v_{BDC}	Specific volume at bottom dead center
v_{TDC}	Specific volume at top dead center
w	Specific work
η_t	Thermal efficiency
ρ	Density

CHAPTER 1

INTRODUCTION

1.1 Project Background

Every engineering product is not just made or is made, but it must follow the sequence step to achieve good product. The steps are design, manufacture and lastly perform specific function to human needs. Design engineering is actually a decision-making process to developed or improved product at a reasonable cost. Parameters included in such an analysis are:

- Geometry and dimensions of different parts,
- Types of materials used in manufacturing and their specifications,
- Fabrication and assembling techniques
- Service conditions.

In real life to developed a product, high cost is need because the product must follow a few testing using a few materials and a few design to get a good product. Because of that, engineers nowadays use a modern computational approach based on finite element analysis to reduce the testing cost. This paper describes the finite element analysis techniques to predict the fatigue life and identify the critical locations of the piston that have been treatment using a few surface treatment processes. This surface treatment method is important to increased loads (mechanical, thermal, etc.), longer lifetime, weight reduction, friction reduction, and corrosion resistance are demanded for modern automotive systems.

The finite element modeling and analysis has been performed using a computer-aided design and a finite element analysis software package, and the fatigue life prediction was carried out using finite element based fatigue life prediction codes. The results showed the contour plots of the fatigue life histogram and damage histogram at the most critical location.

1.2 Problem Statement

Nowadays, manufacturers are utilizing different surface treatments to enhance the surface properties of engineering materials so this problem is to increases the fatigue life of piston are demanded for modern automotive systems.

1.3 Objectives of Project

The objectives of this project are as follows;

i. To predict fatigue life of piston for four stroke engine using strain-life method and to identify critical locations
ii. To investigate the effect of surface treatment
iii. To optimize the material of the component

1.4 Scopes of Project

To fulfill this project, some jobs are including such as:

- Structural modeling of piston by using SolidWork software
- Finite Element modeling and Analysis
- Fatigue Analysis
    1. Strain-life method
    2. Variable amplitude loading
    3. Surface treatment
- Optimization

1.5 Overview of Report

Chapter 1 is explanation about introduction of the project. In this chapter also include the objectives and scope of the project. Chapter 2 discusses on the literature review of piston, type of surface treatment and Strain method. Chapter 3 provides the project methodology for analysis the fatigue life of the piston. The methodology consists of piston model using SolidWork software, and all the analysis included finite element analysis, fatigue analysis and optimization using MSC.Patran and MSC.Nastran. Chapter 4 discuss about the fatigue life of piston and optimization of the results. Finally, Chapter 5 concludes the result of analysis. The recommendation is provided for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter provides the review of the past research selected to the fatigue Analysis, finite element analysis and surface treatment include nitriding, cold rolled and shot peened on the fatigue life. The past research effort can be properly guided to justify the scope and direction of the present effort

2.2 Piston

Engine pistons are one of the most complex components among all automotive or other industry field components. The engine can be called the heart of a car and the piston may be considered the most important part of an engine. There are lots of research works proposing, for engine pistons, new geometries, materials and manufacturing techniques, and this evolution has undergone with a continuous improvement over the last decades and required thorough examination of the smallest details.

Notwithstanding all these studies, there are a huge number of damaged pistons. Damage mechanisms have different origins and are mainly wearing, temperature, and fatigue related. Among the fatigue damages, thermal fatigue and mechanical fatigue, either at room or at high temperature, play a prominent role.

This work is concerned only with the analysis of fatigue-damaged pistons. Pistons from petrol and diesel engines, from automobiles, motorcycles and trains will be analyzed. Damages initiated at the crown, ring grooves, pinholes and skirt are assessed. A compendium of case studies of fatigue-damaged pistons is presented. An analysis of both thermal fatigue and mechanical fatigue damages is presented and analyzed in this work.

A linear static stress analysis, using finite element analysis software Package MSC.PATRAN /MSC.NASTRAN, is used to determine the stress distribution during the combustion. Stresses at the piston crown and pinholes, as well as stresses at the grooves and skirt as a function of land clearances are also presented. A fractographic study is carried out in order to confirm crack initiation sites.

Figure 2.1: Piston

2.3 Piston Material

The materials that piston are made from should meet certain requirement such as good cast ability: high hot strength; high strength to mass ratio; good resistance to surface abrasion, to reduce skirt and ring-groove wear; good thermal conductivity, to keep down piston temperatures; and a relatively low thermal expansion, so that the piston to cylinder clearance can be kept to a minimum. Some of these properties will now be considered.

For many years the eutectic Al–Si alloy has been used for pistons (because only aluminum pistons have been assessed in this work only aluminum alloys will be presented). With increased piston temperatures, the need for equal or improved fatigue strength could no longer be satisfied. New alloys with increased Si content and Cu content, and other alloying elements, have been proved be satisfactory to the new requirements. Use of metal matrix composites is already in use and also under investigation.

For the future, additional improvements of the materials properties may be expected. New technologies are also promising such as PM since its components exhibit excellent strength properties. PM has a significant potential for further development. However, these changes must take into account that an efficient heat transport from the piston to the liner and to the oil is needed. Other technologies and die-casting processes are also being developed.

The development of new materials and processing technologies with improved high temperature mechanical and fatigue performance would help solving the different fatigue damages identified in this work.

Table 2.1: Mechanical Properties of Aluminum Alloys at Room Temperature

Materials properties For Aluminum Alloy	**Value**
Young's modulus, E, GPa	68 - 79
Ultimate tensile strength, S_u , MPa	90 - 600
Tensile Yield Strength	35 - 550
Elongation in 50 mm	0.065

2.3.1 Aluminum Alloy

The important factors in Aluminum Alloy are their high strength-to-weight ratio, their resistance to corrosion by many chemicals, their high thermal and electrical conductivity, their nontoxicity, reflectivity, appearance, and their ease of formability and of machinability; they are also nonmagnetic.

Aluminum Alloy are available as mill products, that is, as wrought products made into various shapes by rolling, extrusion, drawing, forging and form for power-metallurgy applications. Techniques have been developed whereby most aluminum alloys can be machined, formed and welded with relative ease.

2.4 Fatigue Life

Fatigue is a localized damage process of a component produced by cyclic loading. It is the result of the cumulative process consisting of crack initiation, propagation, and final fracture of a component. During cyclic loading, localized plastic deformation induces permanent damage to the component and a crack develops. As the component experiences an increasing number of loading cycles, the length of the crack (damage) increases. After a certain number of cycles, the crack will cause the component to fail (separate). The required inputs for the fatigue analysis process are shown in Fig. 2.2.

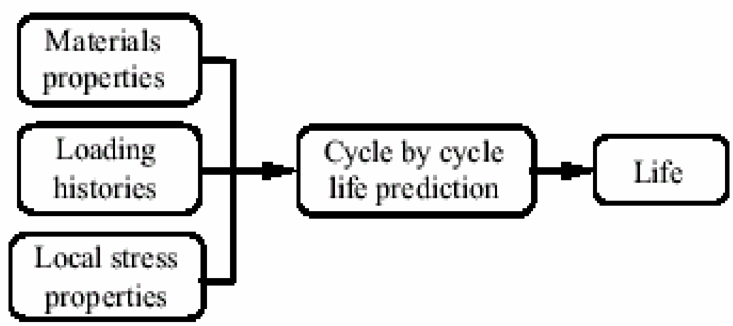


Figure 2.2: Schematic Diagram of Fatigue Life Estimation

2.5 Strain-Life

The local strain-life method was developed in late 1950s and has been shown to be more effective in predicting the fatigue life of a component. The local strain-life method is based on the assumption that the life spent on crack nucleation and small crack growth of a notched component can be approximated by a smooth laboratory specimen under the same cyclic deformation at the crack initiation site.

This concept used to determine the fatigue life at a point in a cyclically loaded component if the relationship between the localized strain in the specimen and fatigue life is known. This relationship is typically represented as a curve of strain versus fatigue life and is generated by conducting strain-controlled axial fatigue tests on smooth, polished specimens of the material. Strain-controlled axial fatigue testing is recommended because the material at stress concentrations and notches in a component may be under cyclic plastic deformation even when the bulk of the component behaves elastically during cyclic loading.

The local strain-life method can be used proactively for a component during early design stages. Fatigue life estimates may be made for various potential design geometries and manufacturing process prior to the existence of any actual component provided the material properties are available. The local strain-life approach is preferred if the load history is irregular or random and where the mean stress and load sequence effects are thought to be importance. This method also provides a rational approach to differentiate the high-cycle fatigue and the low-cycle fatigue regimes and to include the local notch plasticity and mean stress effect on fatigue life.

2.6 Surface Treatment

Surface treatments used in daily manufacturing of parts for the automotive industry are selected to serve functional and decorative requirements achieved by mass production. Increased loads (mechanical, thermal, etc.), longer lifetime, weight reduction, friction reduction, and corrosion resistance are demanded for modern automotive systems. Within the last decade, improved and new deposition techniques were developed in PVD, PECVD, thermochemical heat treatment and thermal spraying.

These new treatments are becoming more and more common in power train and engine applications. Generating optimized surfaces for different types of substrate materials (e.g. Al-alloys, case hardened steels, etc.) and geometries (e.g. bores) also impacts the running costs. Due to the new developments within these competing surface treatments, it becomes more and more common to substitute traditional treatment-substrate-systems with advanced treatments.

2.7 Nitriding Process

Nitriding is a surface-hardening heat treatment that introduces nitrogen into the surface of steel at a temperature range (500 to 550°C, or 930 to 1020°F), while it is in the ferrite condition. Thus, nitriding is similar to carburizing in that surface composition is altered, but different in that nitrogen is added into ferrite instead of austenite. Because nitriding does not involve heating into the austenite phase field and a subsequent quench to form marten site, nitriding can be accomplished with a minimum of distortion and with excellent dimensional control.

The mechanism of nitriding is generally known, but the specific reactions that occur in different steels and with different nitriding media are not always known. Nitrogen has partial solubility in iron. It can form a solid solution with ferrite at nitrogen contents up to about 6%. At about 6% **N**, a compound called gamma prime (γ'), with a composition of Fe_4N is formed.

At nitrogen contents greater than 8%, the equilibrium reaction product is ε compound, Fe_3N. Nitrided cases are stratified. The outermost surface can be all γ' and if this is the case, it is referred to as the white layer. Such a surface layer is undesirable: it is very hard profiles but is so brittle that it may spall in use. Usually it is removed; special nitriding processes are used to reduce this layer or make it less brittle. The ε zone of the case is hardened by the formation of the Fe_3N compound, and below this layer there is some solid solution strengthening from the nitrogen in solid solution.

The advantages and disadvantages of these techniques are similar to those of carburizing. However, times for gas nitriding can be quire long, that is, from 10 to 130 h depending on the application, and the case depths are relatively shallow, usually less than 0.5 mm. Plasma nitriding allows faster nitriding times, and the quickly attained surface saturation of the plasma process results in faster diffusion. Plasma nitriding can also clean the surface by sputtering.

2.8 Cold Rolling Process

Cold rolling is a method of cold working a metal. When a metal is cold worked, microscopic defects are nucleated through out the deformed area. These defects can be either point defects (a vacancy on the crystal lattice) or a line defect (an extra half plane of atoms jammed in a crystal). As defects accumulate through deformation, it becomes increasingly more difficult for slip, or the movement of defects, to occur. This results in a hardening of the metal.

If enough grains split apart, a grain may split into two or more grains in order to minimize the strain energy of the system. When large grains split into smaller grains, the alloy hardens as a result of the Hall-Petch relationship. If cold work is continued, the hardened metal may fracture.

During cold rolling, metal absorbs a great deal of energy; some of this energy is used to nucleate and move defects (and subsequently deform the metal). The remainder of the energy is released as heat.

A metal that has been hardened by cold rolling can be softened by annealing. Annealing will relieve stresses, allow grain growth, and restore the original properties of the alloy. After annealing, the metal may be further cold rolled with out fracturing.

The surfaces of the component are cold-worked by hard and highly polish roller or rollers. This process is used on various flat, cylindrical or conical surfaces. This process improves surface finish by removing scratches, tool marks, and pits. Consequently, corrosion resistance is also improved, since corrosive products and residues cannot be entrapped. This process also is used to improved the mechanical properties of surfaces, as well as their surface finish

2.9 Shot Peened Process

Shot peening is a process used to produce a compressive residual stress layer and modify mechanical properties of metals. It entails impacting a surface with shot (round metallic, glass or ceramic particles) with force sufficient to create plastic deformation. It is similar to sandblasting, except that it operates by the mechanism of plasticity rather than abrasion: each particle functions as a ball-peen hammer. In practice, this means that less material is removed by the process, and less dust created.

Peening a surface spreads it plastically in the manner of a rivet, causing changes in the mechanical properties of the surface. Shot peening is often called for in aircraft repairs to relieve tensile stresses built up in the grinding process and replace them with beneficial compressive stresses. Usually, peening can increase life-time of parts up to 15%.

Plastic deformation induces a residual compressive stress in a peened surface, along with tensile stress in the interior. Surface compressive stresses confer resistance to metal fatigue and to some forms of corrosion. The tensile stresses deep in the part are not as problematic as tensile stresses on the surface because cracks are less likely to start in the interior.

Shot peening may be used for cosmetic effect. The surface roughness resulting from the overlapping dimples causes light to scatter upon reflection because peening typically produces larger surface features than sand-blasting, the resulting effect is more pronounced.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this methodology, a detail description on the work progress and flows are presented. The analysis also included in this chapter and consists of finite element modeling, fatigue analysis and strain-life method.

3.2 Finite Element Based Fatigue Life Prediction

Figure 3.1 shows the methodology that began with computational process modeling the structure of the piston. The original piston four stroke engine was modeled using SOLIDWORKS® and the structure then was imported to PATRAN®. The process then continued to finite element modeling. Appropriate mesh was selected for the structure to be modeled and the process was finalized with finite element analysis where all the boundary conditions and loads were included in this first stage analysis. The second process of the analysis was continued simultaneously with fatigue analysis. The analysis was done in NASTRAN® where the cyclic material properties and component load histories were considered. Fatigue life of the component was computed and yield contour of stresses and life cycle where the life prediction had just been made. The critical location can be identified through the observation of contour plotted. Fatigue life was examined and checked at the critical location whether the life was in good prediction condition or it was totally broken. The critical location predicted life emphasizes the prediction life of the entire component. The optimization will be made if the fatigue life was not in good expectation. Thus, certain parameters in the analysis need to be set to improve the fatigue life such scaling factor, mean stress correction method and material.

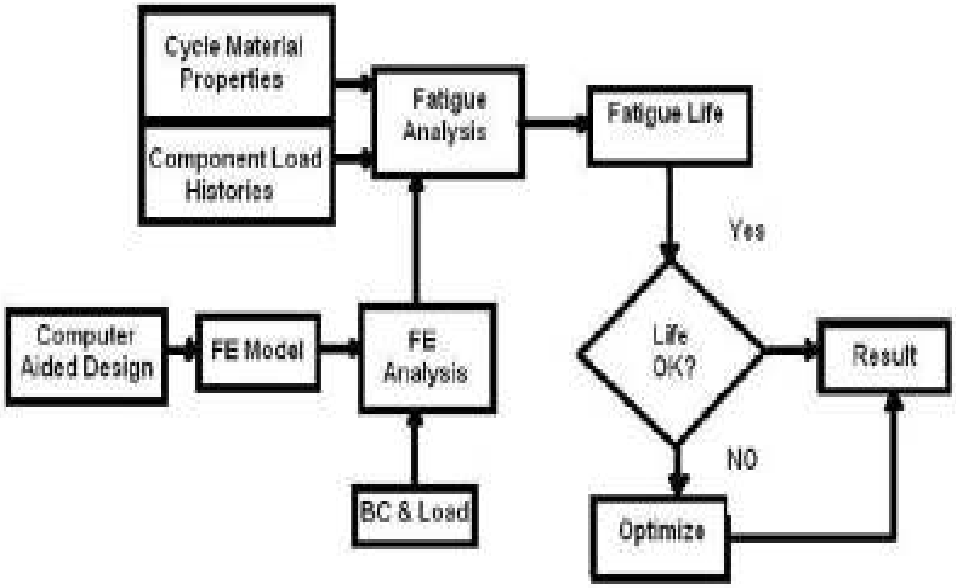


Figure 3.1: Flow Chart of Project

3.3 Finite Element Based Fatigue Analysis

In this case, two computational processes are utilized to perform the analysis including early structural modeling. The purposes of analyzing the structure model are to reduce cost and other any addition factor that may lead to waste in production. The processes due to analysis are as followed:

i. Finite element analysis (FEA) – to determine the stress/strain state of a component in a given load condition.
ii. Fatigue analysis – to calculate the fatigue life for the component of interest and identify the critical locations.

The fatigue life is used to compute the fatigue life of the component. The required inputs for the fatigue analysis are shown in Figure 3.2.

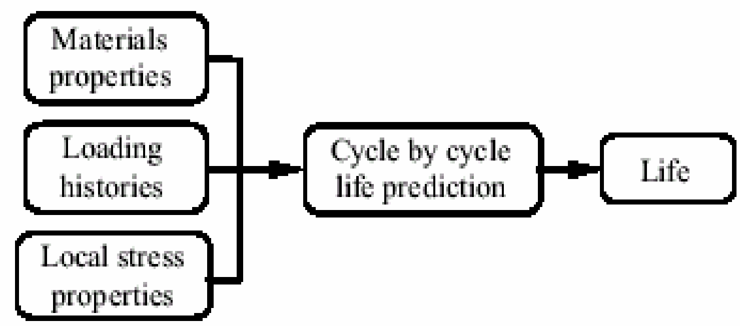


Figure 3.2: Schematic diagram of fatigue life estimation

3.4 Strain Life Method

Strain-life method is based on the observation that is many components the response of the material in critical locations (notches) is strain or deformation dependent. When load levels are low, stresses and strains are linearly related. Consequently in this range, load controlled and strain-controlled test results are equivalent. Early fatigue research showed that damage is dependent on plastic deformation or strain. In the strain-life approach the plastic strain or deformation is directly measured and quantified.

Crack growth is not explicitly accounted for in the strain life method. Rather, failure of the component is assumed to occur when the “equally stressed volume of material” fails. Because of this, strain-life methods are often considered “initiation” life estimates. For some application the existence of a crack is an overly conservative criterion for component failure. In this situation, fracture mechanics method maybe employed to determine crack propagation life from an assumed initial crack size to a final crack length. Total lives are then reported as the sum of the initiation and propagation segments.

The typical strain-life curves based on Coffin-Manson relationship are shown in Figure 3.3.

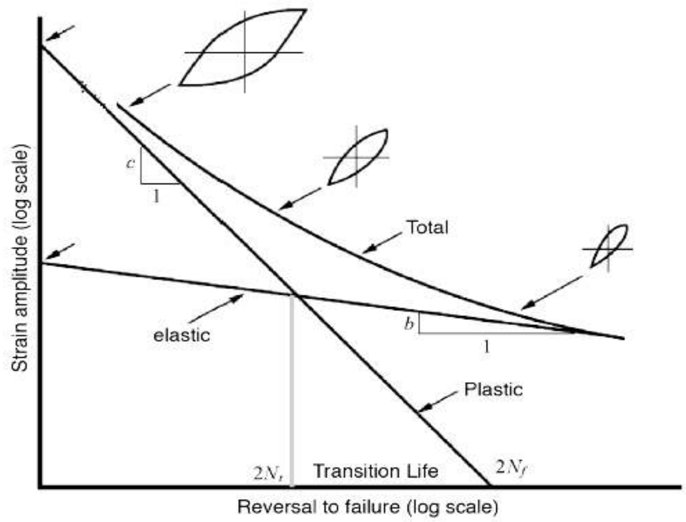


Figure 3.3: The typical strain-life curve

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c \tag{3.4}$$

The relationship between the total strain amplitude, $\Delta\varepsilon/2$, and the reversals to failure, $2N_f$. where N_f is the fatigue life; σ'_f is the fatigue strength coefficient; E is the modulus of elasticity; b is the fatigue strength exponent; ε'_f is the fatigue ductility coefficient; and c is the fatigue ductility exponent. Morrow (1968) suggested that the mean stress effects could be considered by modifying the elastic term in the strain-life equation by mean stress, σ_m.

$$\varepsilon_a = \frac{\sigma'_f - \sigma_m}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c \tag{3.5}$$

Then Smith-Watson-Topper (SWT) mean stress correction is mathematically defined as in Equation (3.6)

$$\sigma_{max}\varepsilon_a E = (\sigma'_f)^2(2N_f)^{2b} + (\sigma'_f)(\varepsilon'_f)E(2N_f)^{b+c} \tag{3.6}$$

where, σ_{max} is the maximum stress, and ε_a is the strain amplitude.

The strain-life method assumes that smooth specimens tested under strain-control can simulate fatigue damage (and fatigue life) is assumed to occur in the material at the notch root and in the smooth specimen when both are subjected to identical stress-strain histories. The local strain-life approach has gained acceptance as a useful method of evaluating the fatigue life of a notched component. Both the American Society for Testing and Materials (ASTM) and the Society of Automotive Engineers (SAE) have recommended procedures and practices for conducting strain-controlled tests and these data predict fatigue lives.

3.5 Loading Information

3.5.1 Variable Amplitude Loading

Variable-amplitude random-sequence load histories are very complex functions in which the probability of the same sequence and magnitude of stress ranges recurring during a particular time interval is very small. Such histories lack a describable pattern and cannot be represented by an analytical function. Between the extremes of constant-amplitude cyclic-stress histories and variable-amplitude random-sequence stress histories, there are a multitude of stress patterns of varying degrees of complexity. Many of these histories can be described by analytic functions and represented by various parameters. Some simple variable-amplitude stress histories are those corresponding to a single cycle or multiple high-tensile-load cycles superimposed upon constant-amplitude cyclic-load fluctuations. The constant and variable amplitude loading are shown in Figure 3.4.

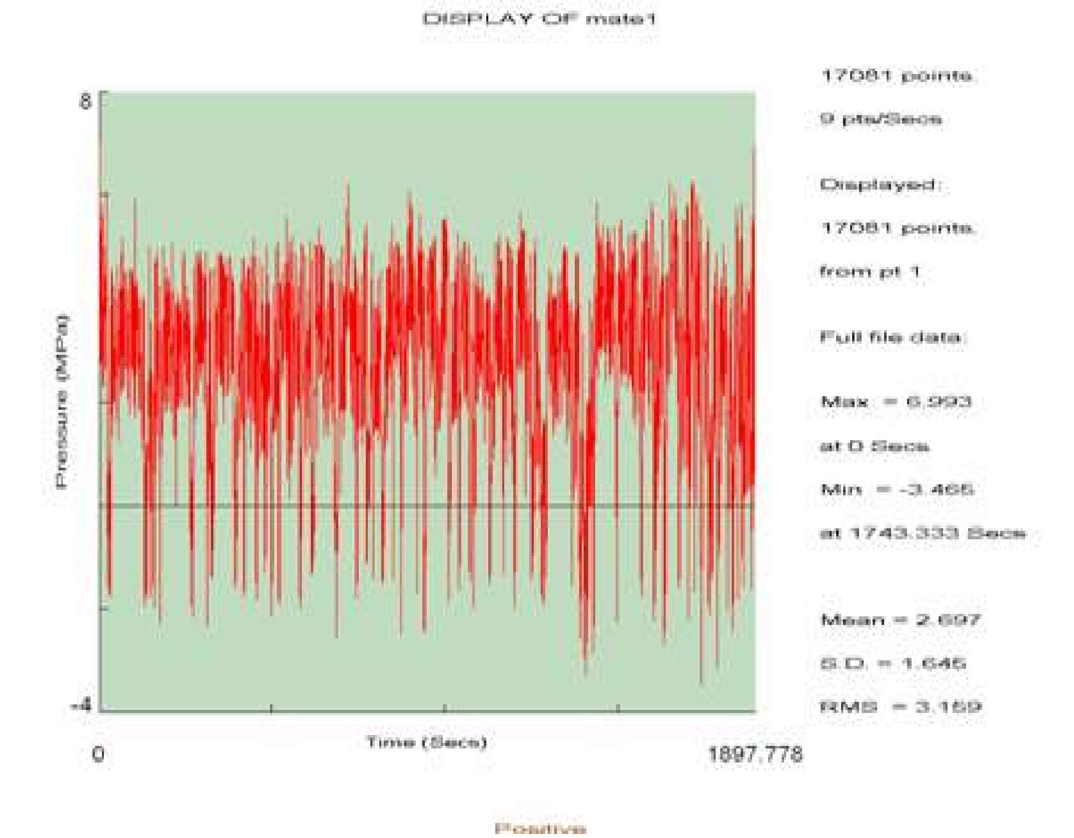
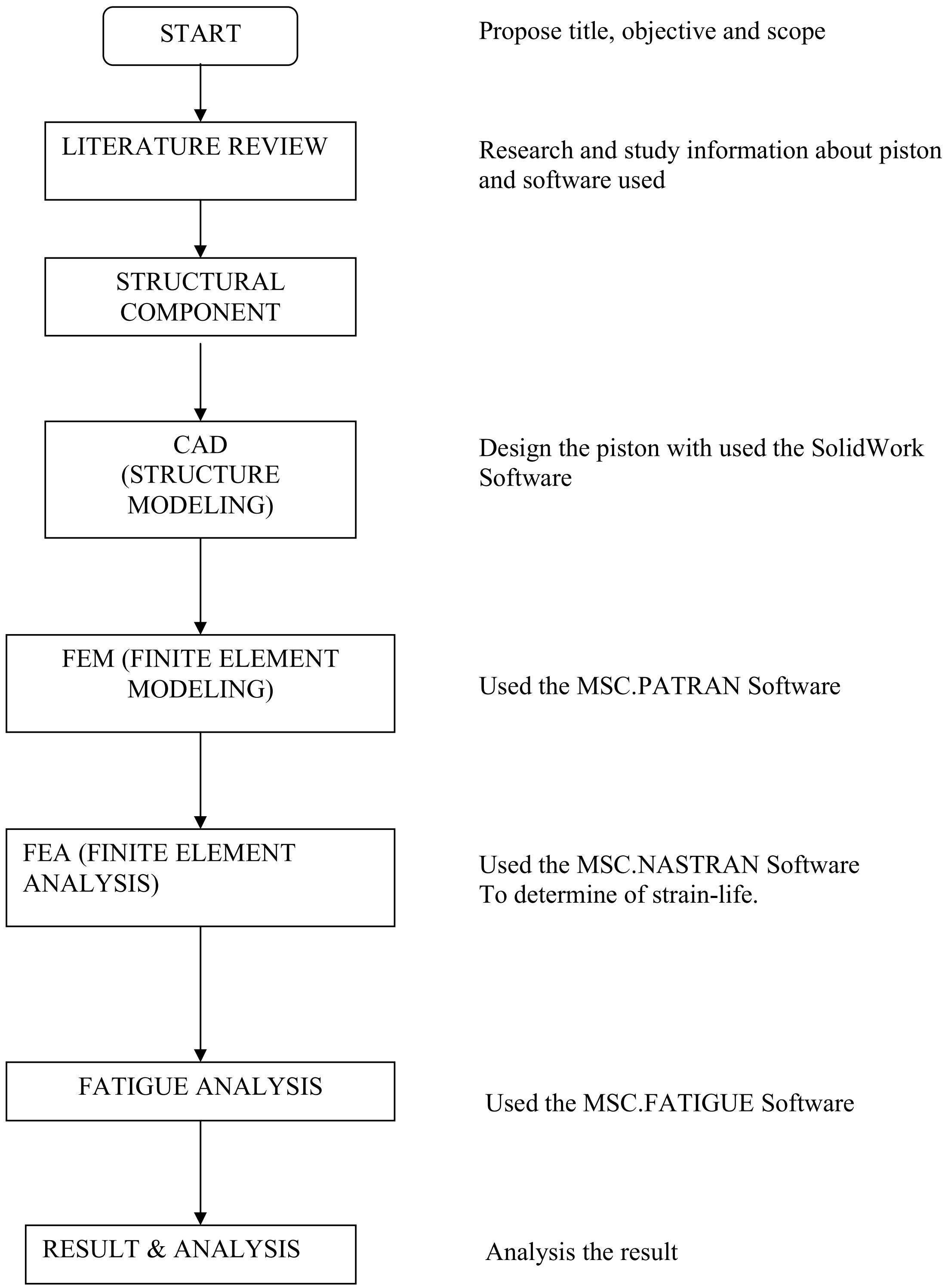


Figure 3.4: Time-Load-History

3.6 Project Methodology



3.7 Structural Modeling

For design the 3D drawing, first step is to sketch the piston with all dimension that take from original parts into rough paper. We take dimension for geometry that important to give a real shape of the reference model by using vernier caliper. After that, transfer it into 3D drawing via Solid Works software to see the probability simulation view.

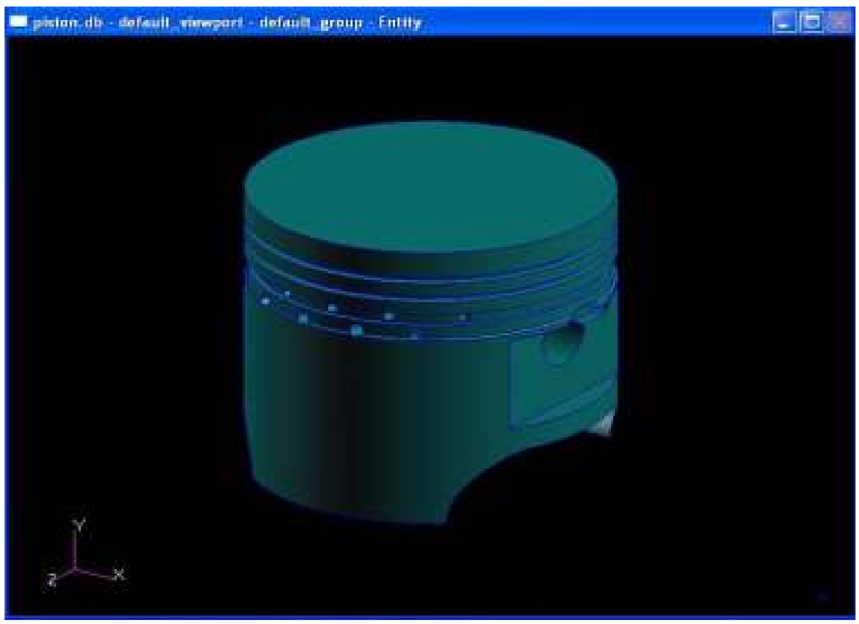


Figure 3.5: 3D Piston Drawing

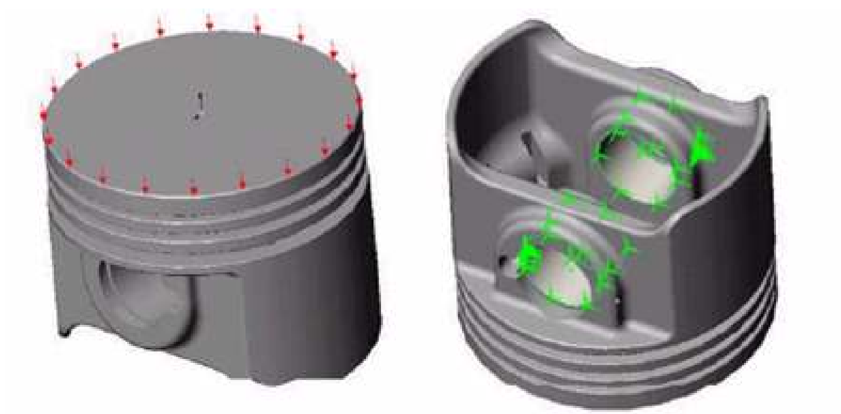
Skill in Solid Works software is needed to make the job run and us easy to design smooth. Design the piston from reference piston model for running the simulation job. After satisfy with the design, draw it into real piston looking to give the view that supposed to be when it going to simulate.

3.8 Finite Element Modeling

After design the piston in SolidWork software, we need to simulate it to see the result when we apply force or load from on top of surface piston direction that we imagine it will be happen in real conditions. Normally we apply compression forces from upper and lower part; bending forces also can apply from either x, y or z-axis. During piston in initial condition, usually area of piston pin must be fixing and on top surface piston area we can apply the pressure about 7 MPa (Rahman et al, 2007).

We also can assume the material that suitable for the design from previous material use to make it better than original during apply the load or force. But, in this case we choose the 6061 T6 Aluminum Alloy as piston material.

In the end of this step, we can conclude either it is better than the original in term of many parameters such as we discuss.



(a) Pressure at the piston head area **(b)** Restraints at the piston pin holes

Figure 3.6: Typical Engine Piston

3.9 Analysis Data

Actually analysis can do after simulation, data and pictures that given from simulation are the result of the model. Using that data, we can analysis in term of prediction parallel with theory that we learn in mechanical study. The prediction may come from stress, displacement, and strain factor and also can see their factor of safety. The colors given in scale show the maximum and minimum value for the result. Which area or nodes is critical also can determine by colors in the model result.

3.10 Conclusion

Fatigue analysis in this study concern on strain life approach under variable amplitude loading. These analyses consist of computational analysis which involve structural modeling, finite element analysis, and fatigue analysis. Structural modeling was built in SOLIDWORK® software while the finite element study continued in PATRAN® and the analysis then will be finalized in NASTRAN® and yields the fatigue life result.

CHPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In this chapter discuss about the finite element modeling, finite element analysis result, fatigue analysis results and lastly optimization. The finite element modeling result consist of choosing either tetrahedral 10 or tetrahedral 4 as a topology, and choosing the best global edge length to get the highest stress result. Then for the finite element analysis consist of choosing either max principal or von misses for the highest stress result. The result consists of to determine critical locations on the piston. These results included strain-life with Mean Stress Correction, strain-life with material comparison and lastly strain life with comparison surface treatment.

4.2 Structural Modeling Result

In this case we take Honda EX-5 motorcycle piston 4- Stoke engine as reference model. At the 3D drawing we put cut plane at center of piston which is sketch that show at Figure 5 below. After that, transfer it into 3D drawing via Solid Works software to see the probability simulation view.

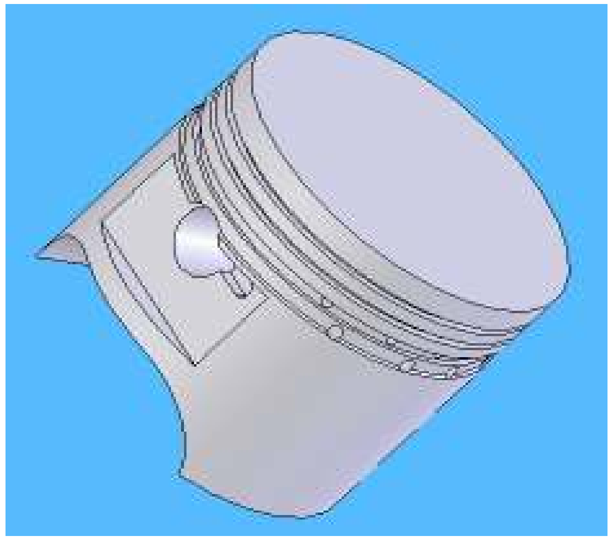


Figure 4.1: 3D Piston Model

Skill in Solid Works software is needed to make the job run and us easy to design smooth. Design the piston from reference piston model for running the simulation job. After satisfy with the design, draw it into real piston looking to give the view that supposed to be when it going to simulate. After that, import this 3D drawing into the MSC Patran software for the next step to Finite Element Modeling and Fatigue Analysis.

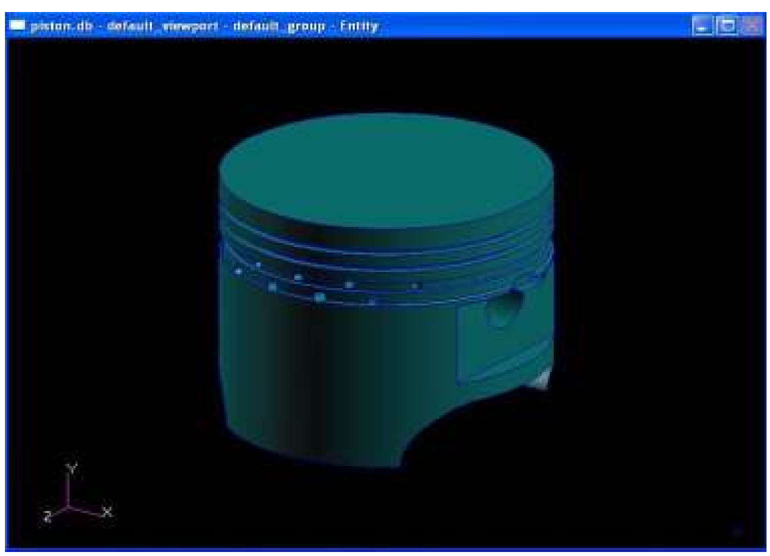


Figure 4.2: 3D Drawing Piston after import to the MSC Patran Software

4.3 Finite Element Method

The three-dimensional model of linear engine cylinder head was developed using SOLIDWORK® software. The 10 nodes tetrahedral were selected to be used for the topology. The sensitivity analysis then was performed to obtain the optimum size of the element. It was performed iteratively at different element length or called global edge length until the solution gave appropriate accuracy value. The mesh size was successively refined as the result showed the highest and convergence stress against the global edge length. In the analysis the final element size of 5mm was considered. A pressure of 7.0 MPa was applied on the top surface of the piston due to compressive pressure of internal combustion. The bolt holes were set to be constraint and fixed. The loading and boundary condition are also indicated in Figure 4.3.

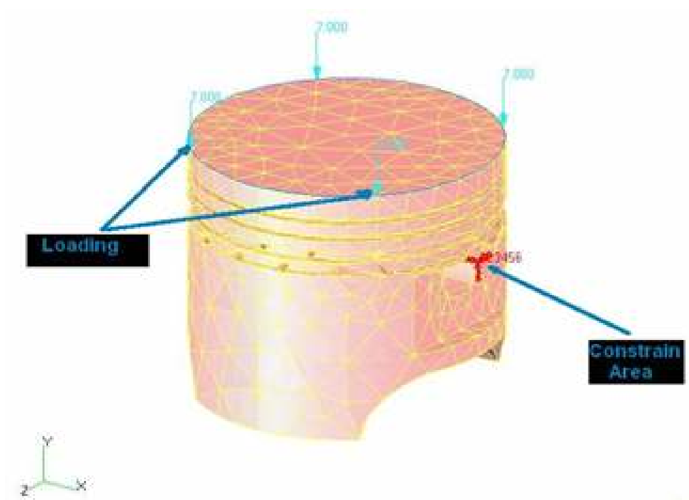


Figure 4.3: Structural and finite element modeling of cylinder head with loading and boundary condition

4.4 Selection of Mesh Type

Mesh study is performed in the FE analysis as a result to obtain the accuracy in calculated data. In this process, specific particular condition is selected and the convergence of the result is monitored using PATRAN® and evaluated using

NASTRAN®. Mesh is selected based on the geometry, model topology, analysis objectives and engineering judgment. Triparametric solids with the topological shape of brick or wedge can be meshed either hexahedral or wedge element. The auto tetrahedral meshing approach is the highly automated technique for meshing solid region of geometry. It produces high quality meshing for boundary representation solid model imported most from CAD systems (Rahman et al. 2007). In the initial analysis, the 4 nodes tetrahedral (TET 4) element of cylinder head was used. The result of the analysis was then compared to 10 nodes tetrahedral (TET 10) element mesh using the same global edge length and the highest pressure of (7.0 MPa). The results showed that TET 10 mesh predicted higher von Mises stresses than TET 4 mesh element. TET 4 used a linear order interpolation function while TET 10 employed quadratic order interpolation function. For the same element size, TET 10 is expected to be able to capture the high stresses concentration associated with the bolt holes. TET 4 and TET 10 element are shown in Figure 4.4.

(a) TET4

(b) TET10

Figure 4.4: Types of meshing element used in finite element method

Table 4.1 shows result of maximum stress between Tet 4, and Tet 10 . From the result obvious that Tet 10 got the highest stress result among the Tet types. The Tet 10 von Mises result was 554MPa, and 187MPa for Tet 4. Figure 4.5 shows graph maximum stress versus type of topology using von Mises and Maximum Principal. It's obvious that result Tet 10 for von Mises was higher than result Tet 10 for Maximum Principal. Because of that, Tet 10 using von Mises was chosen for meshing.

Table 4.1: Maximum stress between TET types

Tet Type	Von Mises (MPa)	Maximum Principle (MPa)
4	1.87E+02	4.62E+01
10	5.54E+02	1.32E+02

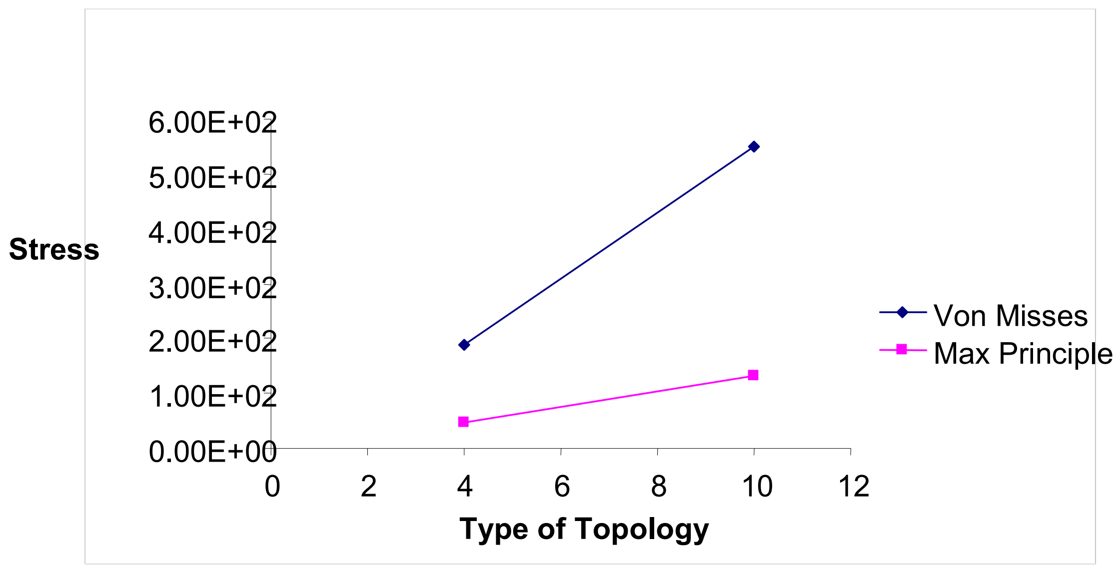


Figure 4.5: Stress versus type of topology

4.4.1 Comparison maximum of stress between global edge lengths for TET10

Figure 4.6 shows the maximum stress versus global edge that is plot from information in Table 4.2. The figure shows that at 0.622272 global edge lengths perform the highest stress either for von Mises or Max Principal. Between von Mises and Maximum Principal, von Mises got the highest pressure about 554MPa and

Maximum Principal just about 132MPa. From that, 0.3 global edges were chosen and von Mises is used to get the highest pressure.

Table 4.2 Maximum of stress between global edge lengths for Tet 10

Global edge length	Von mises (MPa)	Max.principle (MPa)
0.622272	5.54E+02	1.32E+02
0.6	5.49E+02	1.16E+02
0.5	5.33E+02	1.01E+02
0.4	3.70E+02	1.19E+02
0.3	3.65E+02	1.17E+02

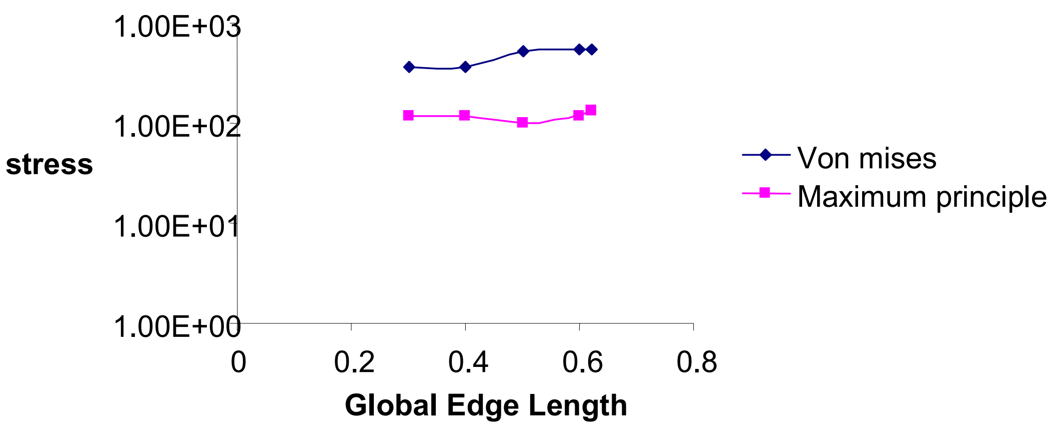


Figure 4.6: Graph maximum stress versus global edge length

4.5 Result for Finite Element Analysis

4.5.1 Material Information

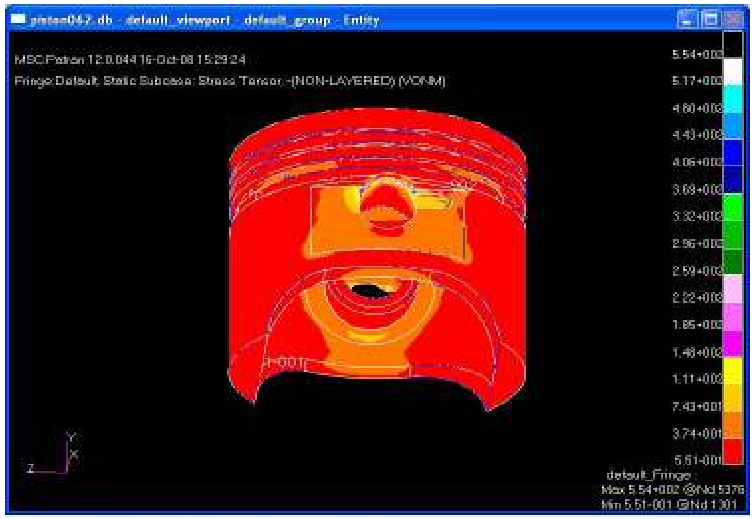
Material used in the analysis was 6061-T6 aluminum alloy. This material is in 2000 series aluminum alloy. Furthermore it is nonferrous metal. It has good machinability and surface finish capabilities. In addition it has high strength material of adequate workability. 6061-T6 has largely superceded 2017 for structural applications. The common uses of 6061-T6 are in aircraft fittings, gears and shafts, bolts, clock parts, computer parts, couplings, fuse parts, hydraulic valve bodies, missile parts, munitions, nuts, pistons, rectifier parts, worm gears, fastening devices, veterinary and orthopedic equipment, structures. The monotonic and cyclic properties of AA6061-T6 are listed in Table 4.3 here.

Table 4.3: Material Information of Aluminum Alloy 6061 T6

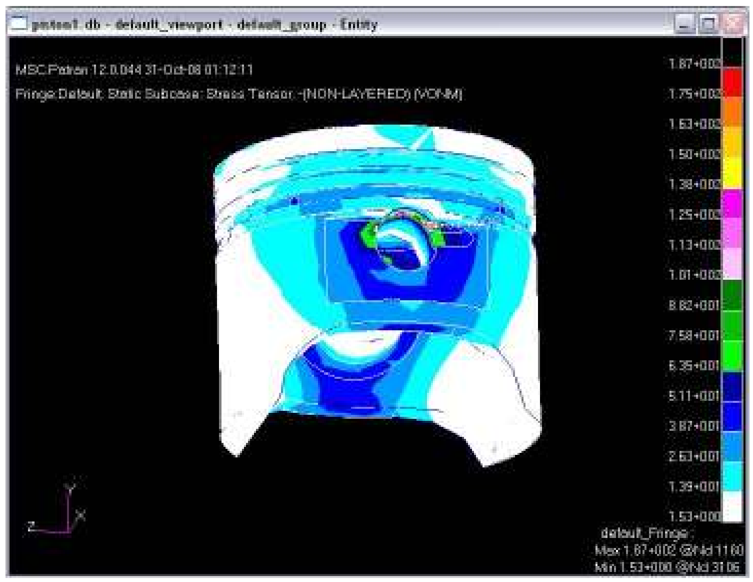
Materials properties	**Value**
Young's modulus, E, GPa	68.9
Ultimate tensile strength, S_u , MPa	290
Tensile Yield Strength	255
Shear strength, MPa	186
Density	2.7
Poisson ratio	0.33
Cyclic and Fatigue Properties	
Fatigue strength coefficient, σ'_f , MPa	1100
Fatigue strength exponent, *b*	-0.124
Fatigue ductility coefficient , ε'_f	0.22
Fatigue ductility exponent, *c*	-0.59
Fatigue strength, S_f @ 10^8 cycles, MPa	138
Cyclic strength coefficient, K' , MPa	655
Cyclic strain hardening exponent, n'	0.065

4.5.2 Result for Finite Element Analysis

Figure 4.7 shows von Mises stresses contours (a) TET4 and (b) TET10 at high load level. From the result shows both of the TET4 and TET10 can exactly show the stress state of piston for a 7 MPa load condition. The result for using TET4 is 187 MPa while for TET10 is 554 MPa. Even though TET4 mesh is still capable of identifying critical areas, among these result obvious that TET10 mesh predict higher von Mises stresses than the TET4. So TET10 mesh was chosen for the fatigue analysis.



(a)



(b)

Figure 4.7 Von-Misses stress contours (a) TET4 and (b) TET10 at high load level

4.6 Result of Fatigue Analysis

Figure 4.8 shows that predicted fatigue life contours plotted for TET10 using Strain method. It's obvious that pin piston hole found to experience the critical locations (Rahman et al, 2007).

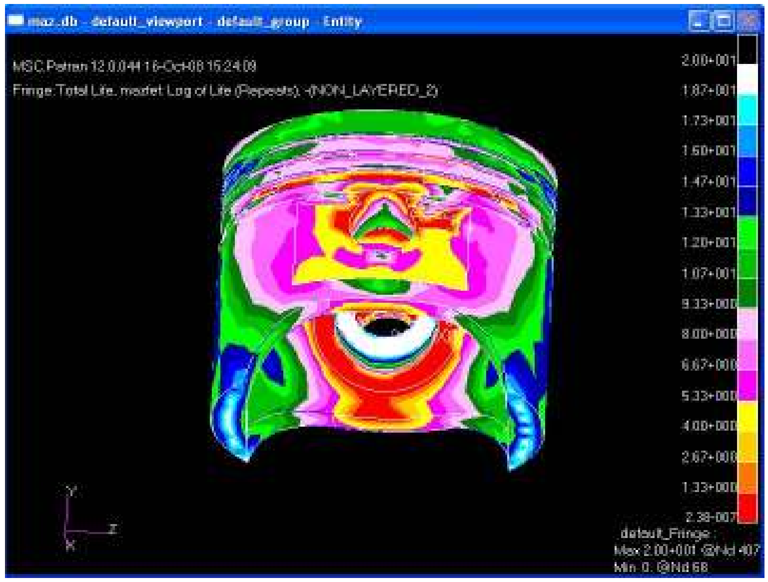


Figure 4.8 Predicted fatigue life contours plotted for TET10 using Strain method

4.7 Optimization

4.7.1 Strain-Life with Mean Stress Correction

This section is about to discuss about optimization from the fatigue analysis result. Strain-life mean stress correction is consisting of Morrow and Smith-Watson-Topper method. Figure 4.9 below shows the Strain method, Morrow and Smith-Watson-Topper method results for fatigue life.

Figure 4.9 shows that graph life (repeats) versus pressure using Coffin Manson method, Smith-Watson-Topper and Morrow method. From that graph show that Smith-Watson-Topper method is the best among Coffin Manson and Morrow method. From the graph show Coffin Manson and Morrow method had broken at 3.85 MPa. But it’s different with Coffin Manson method where the piston broke at 4.55 MPa.

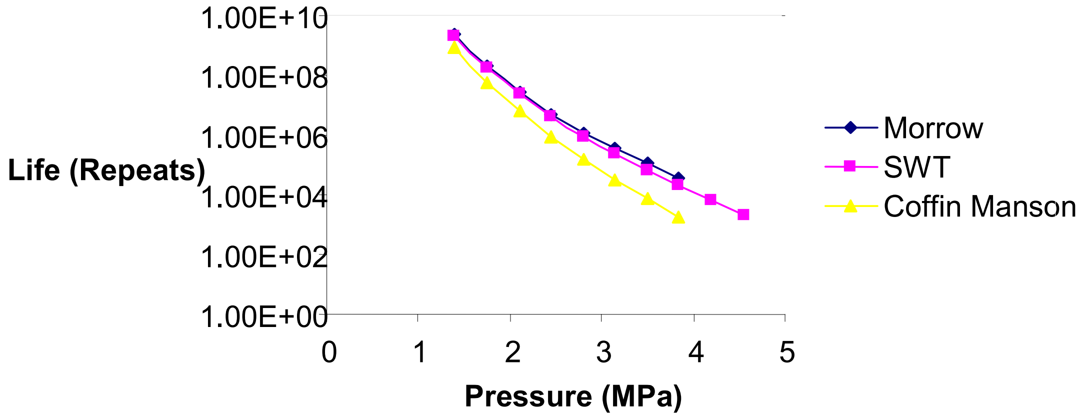


Figure 4.9 Life (repeats) versus pressure

4.7.2 Strain-life with Comparison of Surface Treatment

Figure 4.10 shows that life (repeats) versus pressure of surface treatments. From the graph, it's obvious that nitriding was the best surface treatment than cold rolling and shot peening. From the graph, it seems that all of the surface treatment broke at 3.85 MPa but only nitriding can fully protect the life of the piston because Life cycle of nitriding is higher than other treatment about 4.22E+12 Life (repeats).

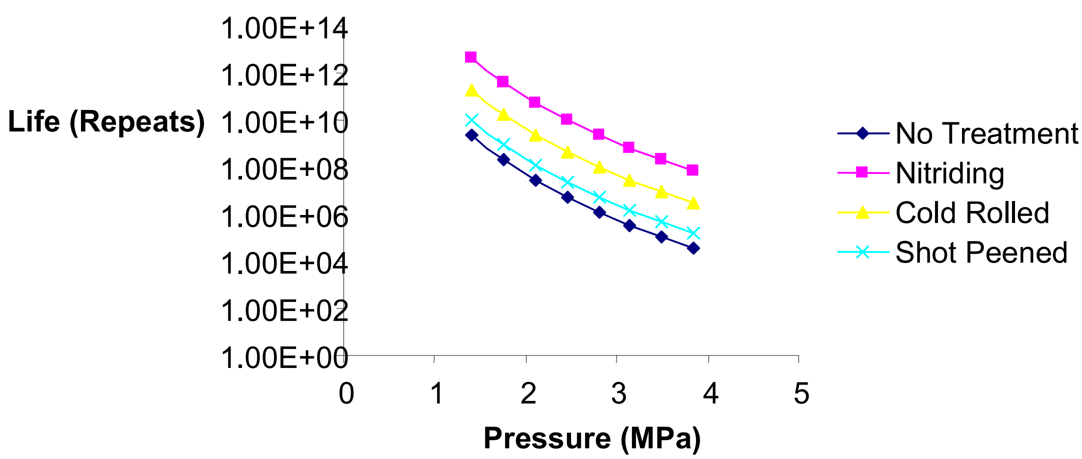


Figure 4.10 Life (repeats) versus pressure of surface treatments

4.7.3 Strain-life with Material Comparison

This section is about to discuss about optimization with material comparison. Material comparison is consisting six materials. The aluminum alloy materials are 6061 HV T6, 7075 HV T6, 2024 HV T3, 2219 HV T87, 2014 HV T6 and 7175 T73 None HF. Figure 4.11 below shows the fatigue life results for every material.

Figure 4.11 shows life (repeats) versus pressure of six materials. The graph shows that 7075 HV T6 was the best among the six aluminum alloy materials. The graph shows that for 7075 HV T6 broke at 7 MPa and second was 2024 HV T3. This means 7075 HV T6 suitable for produce piston to longer its fatigue life.

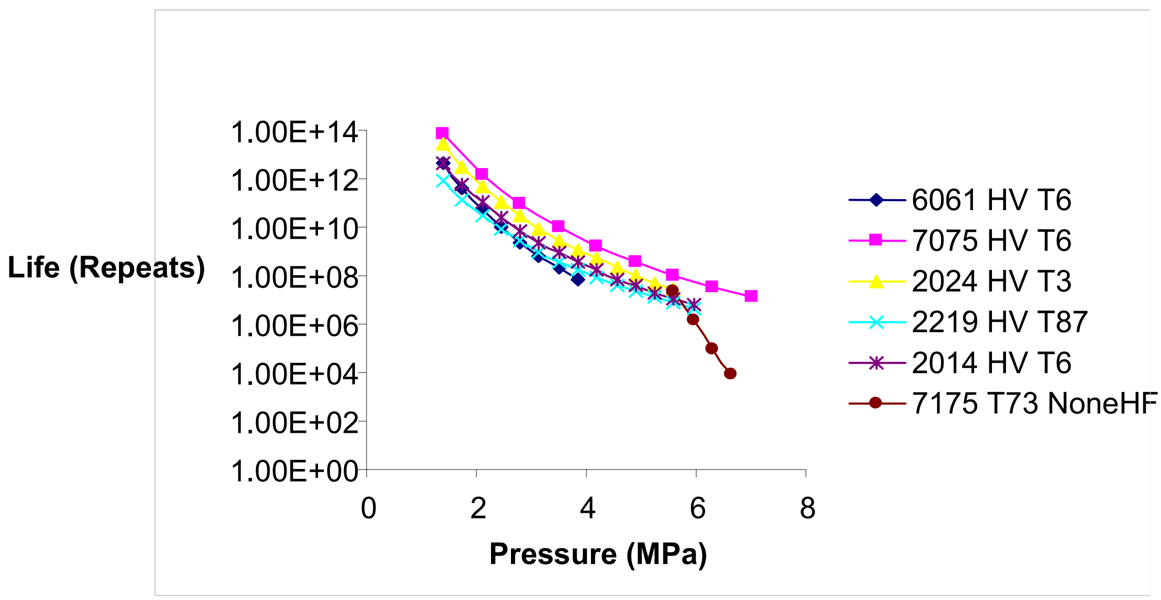


Figure 4.11 Life (repeats) versus pressure of materials

CHAPTER 5

CONCLUSIONS

5.1 Introduction

The purpose of this project is to observe probability of creating design that can see result for piston 4-stroke engine fatigue life using strain-Life method on aluminum alloy material. Many criteria must take place to achieve the objective. Whole criteria must combine in one to make sure the result is shown in fair and realistic condition.

As a conclusion from the result, fatigue life of the piston can be predicted using the Strain method. From the result it shows that this piston will break at 4.20MPa without using any surface treatment. When using nitriding as a surface treatment, the fatigue life of piston can be longer than before. When using nitriding, the piston broken still at 4.20 MPa but the Life (cycle) is higher than other surface treatment. This also shows that nitriding treatment exponentially improves the fatigue life of the piston.

For material comparison, after optimization the material 7075-T6 is the superior material among the others for both cases. The 7075-T6 is the best aluminum alloy material that can be use for improve life of piston. The material broken at 7.70MPa while the other material generally will broke at 6.65MPa below.

5.2 Recommendation

The recommendation of this project is made for future research. It's suggested to enhance the design geometry with fully design of piston and more treatment to use for give more life of piston so they can fulfill are demanded for modern automotive systems.

This project should not just about computer analysis but also should use the analysis data to test in experimental test. Maybe someday the life of the piston can be much longer than today.

REFERENCES

Crouse- Anglin 1993 *Automotive Mechanics*. New York, USA: International Edition

Glancey, C.D. and Stephens, R.R. 2005. Fatigue crack growth and life predictions under variable amplitude loading for a cast and wrought aluminum alloy. *International Journal of Fatigue*. 29(3): 587-588.

Kalpakjian, S. (2006) *Manufacturing Engineering and Techonology* USA: Prentice Hall

Lee, K.S. and Song, J.H. 2005. Estimation methods for strain-life fatigue properties from hardness. *International Journal of Fatigue.* 28(4): 386-400.

Pulkrabek, W.W 1997 *Engineering Fundamentals of the Internal Combustion Engine* USA: International Edition

Raman, S.G.S. and Radhakrishnan, V. M. 2002. On cyclic stress–strain behaviour and low cycle fatigue life. *Materials & Design.* 23(3): 249-254.

Rahman M.M., Ariffin, A.K., Abdullah, S. and Jamaludin, N. 2007. *Finite element based Durability Assessment of a free Piston Linear Engine Component.* SDHM 3, 1-13.

Rahman M. M., Ariffin A. K. 2005. *Effects of surface finish and treatment on the fatigue behaviors of vibrating cylinder block using frequency response approach*. J2US 7(3):352-360

Shen, C.L., 1994. *The statistical analysis of fatigue data*, Ph. D thesis, Department of Aerospace and Mechanical Engineering, University of Arizona.

Wirshing, P.H., 1983. *Statistical summaries of fatigue data for design purpose* NASA contract report 3697, N83-29731.