FATIGUE LIFE PREDICTION METHODS IN AN ENGINE MATERIAL

by

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SUPERVISOR'S DECLARATION

I hereby declare that I have checked this project and in my opinion this project is satisfactory in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering with Oil and Gas Upstream Engineering.

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CERTIFICATION OF ORIGINALITY

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

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Executive Summary

This report explains some details about the project of "Fatigue-Life Prediction Method in an Engine Material". This report is divided into five (5) main chapters; Introduction, Literature Review, Methodology, Result & Discussion, and Conclusion.

Chapter 1, Introduction consists of problem statement that will be used to extract the problem for this project and act as a premier guideline to solve and complete this project. The objective and scope of study within this task will also be included in this report. In Chapter 2, which is the Literature Review, the author will give a brief explanation about fatigue in metal, fatigue-life prediction methods that have already been done and crankshaft material and manufacturing process. Gantt chart, flow chart and work procedure will be included in the Methodology part in Chapter 3 to show the progress and how this final year project is been carried out. The procedure and steps taken in order to complete this project will be explained.

In Chapter 4, the author will include all the findings and result for this final year project as well as the simulation of the crankshaft. The optimization of the crankshaft will also be included. The result will be discussed and analyzed. Last but not least, the author will conclude this research in the Chapter 5 which is the Conclusion.

The author will include the all the references used upon the completion of this report.

Abstract

Often, machine members are found to have failed due to the action of repeated or fluctuating stresses; yet the most careful analysis revealed that the actual maximum stresses were well below the ultimate strength of the material, and quite frequently even below the yield strength. The most distinguish characteristic of this failures is that the stresses have been repeated a very large number of times. Hence, the failure is called a *fatigue failure*. In this study, crankshaft has been used as a component to analyze and evaluate its fatigue performance. Fatigue is the primary cause of failure in internal combustion engines due to the cyclic loading conditions and the stress concentrations in the crank pin fillet. There are a lot of methods used to predict the fatigue life. However, for this project, only the most common method to predict the fatigue life will be focused, namely Stress Life Method and Strain Life Method. These two methods will be compared and one method will be selected to be used in fatigue life estimation of the crankshaft. Finite Element Analysis (FEA) will be done using ANSYS to obtain variation of stress magnitude at critical locations. In addition, the effect of different manufacturing process and material will be investigated to determine the fatigue performance of the crankshaft.

Acknowledgment

In the name of Allah, the Most Benevolent, the Most Merciful. Alhamdulillah, all praise to the al mighty god, Allah SWT for the countless goodness that are given to me and all the required necessity to complete this project.

First and foremost, I would like to express my deep appreciation to my Final Year Project supervisor, Dr. Rao for all the guidance and supports by giving advices and concerns throughout the completion of this final year project despite of his busy schedule. His kindness is so much well valuable to me as it helps me in becoming more reliable and self-motivated student. I have also learned a lot of valuable knowledge and information from this project. His compliments and critics had helped me most in keeping me focused on my project and to finish in time. Special thanks to him for reviewing the final draft of this report to ensure the cohesiveness and coherence of contents for this final report.

My next recognition is given to my colleagues for his assistance in helping me doing the simulation of my crankshaft using ANSYS. Without his help, I would not be able to get the desired result and will have some difficulties to complete this project. Their sharing and information throughout this project are really meaningful for me as I gained a lot of knowledge including technical skills to complete this final year project successfully.

Special thanks to my beloved parents for all their loves and encouragement to excel in this project. Thanks for their continuous support through all the hard time and for their trust in me.

Last but not least, I would like to thank Universiti Teknologi Petronas (UTP) for all the internet facility to assist me in finding useful literatures for my project. Other than that, the lab facilities provided by the university are proved to be very useful to me especially in the ANSYS software for simulation purposes.

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CHAPTER 1

INTRODUCTION

1.1 Problem Statement

Engine parts are subjected to repeated and variable stresses during their operation. Fatigue failure gives no indication and warning before it actually occurs. It is sudden and total, and hence dangerous. It is relatively simple to design against a static failure, because our knowledge is comprehensive. Fatigue is much more complicated phenomenon, only partially understood, and the engineer seeking competence must acquire as much knowledge of the subject as possible. Therefore, method of predicting fatigue-life on an engine material is important in order to take any necessary action to avoid the failure happens.

1.2 Objective

1) To study, compare and select the most appropriate method in predicting the fatigue-life of a crankshaft.
2) To study the effect of material and manufacturing process towards crankshaft fatigue performance
3) To identify the critical location of the crankshaft using Finite Element Analysis (FEA).
4) To optimized crankshaft design

1.3 Scope of study

For this project, the crankshafts used were forged steel and ductile cast iron from a one-cylinder gasoline engine. The study will be started from the research about the fatigue-life prediction method that already been done. The method will be compared and evaluated to select the most appropriate to be used in the project. The effect of different material and manufacturing process on fatigue life performance will be included in this study. The modeling and analysis of the selected part of the engine will be done using ANSYS. From this software, Finite Element Analysis (FEA) will be carried out. Finally, the optimization of the crankshaft is will also be done using ANSYS. The result will then be discussed and evaluated.

CHAPTER 2

LITERATURE REVIEW

2.1 Fatigue in metal

In most testing of those properties of materials that relate to the stress-strain diagram, the load is applied gradually, to give sufficient time for the strain to fully develop. Furthermore, the specimen is tested to destruction, and so the stresses are applied only once. Testing of this kind is applicable, to what are known as *static conditions*.

The condition frequently arises, however, in which the stresses vary with time or they fluctuate between different levels. For example, a particular fiber on the surface of a rotating shaft subjected to the action of bending loads undergoes both tension and compression for each revolution of the shaft. In this case, some stress is always present in any one fiber, but now the level of stress is fluctuating. These and other kind of loading occurring in machine members produce stresses that are called *variable, repeated, alternating* or *fluctuating* stresses. Machine members are regularly found to have failed under the action of repeated or fluctuating stresses. However, the analysis showed that the actual maximum stresses were well below the ultimate strength of the material, and even below the yield strength. The most distinguish characteristic of these failure is that the stresses have been repeated a very large number of times. Hence the failure is called a *fatigue failure* [1]. **Figure 1** below show the example of the fatigue failure of a kingpin.

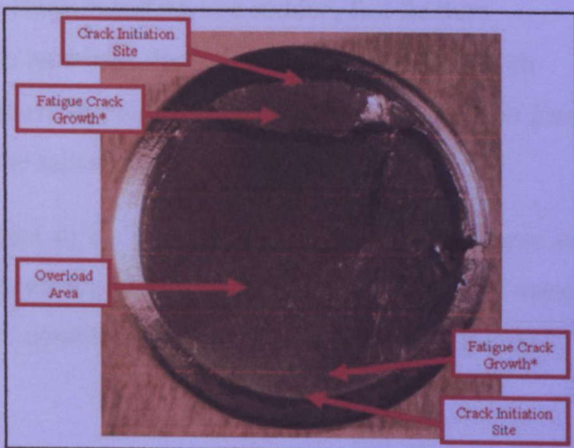


Figure 1: Overview of fatigue fracture of kingpin [1]

A fatigue failure has an appearance similar to brittle fracture, as the fracture surfaces are flat and perpendicular to the stress axis with the absence of necking. The fracture features of a fatigue failure, however, are quite different from a static brittle fracture arising from three stages of development.

Stage I

- Initiation of one or more micro-cracks due to cyclic plastic deformations
- Crystallographic propagation extending from two to five grains about the origin
- Cracks are not normally visible to the naked eye

Stage II

- Progresses from micro-cracks to macro-cracks forming parallel plateau-like fracture surfaces separated by longitudinal ridges
- The surfaces can be wavy dark and light bands referred to as *beach mark* or *clamshell mark*
- During cyclic loading, these cracked surfaces open and close, rubbing together, and the beach mark appearance depends on the charge in the level or frequency of loading and the corrosive nature of the environment.

Stage III

- Occurs during the final stress cycle when the remaining material cannot support the loads, resulting in a sudden, fast fracture
- Fracture can be brittle, ductile, or a combination of both
- Possible pattern in this stage fracture is called *chevron lines*, point toward the origins of the initial cracks

There is a good deal to be learned from the fracture patterns of a fatigue failure. **Figure 2** below shows representations of failure surfaces of various part geometries under different load conditions and level of stress concentration.

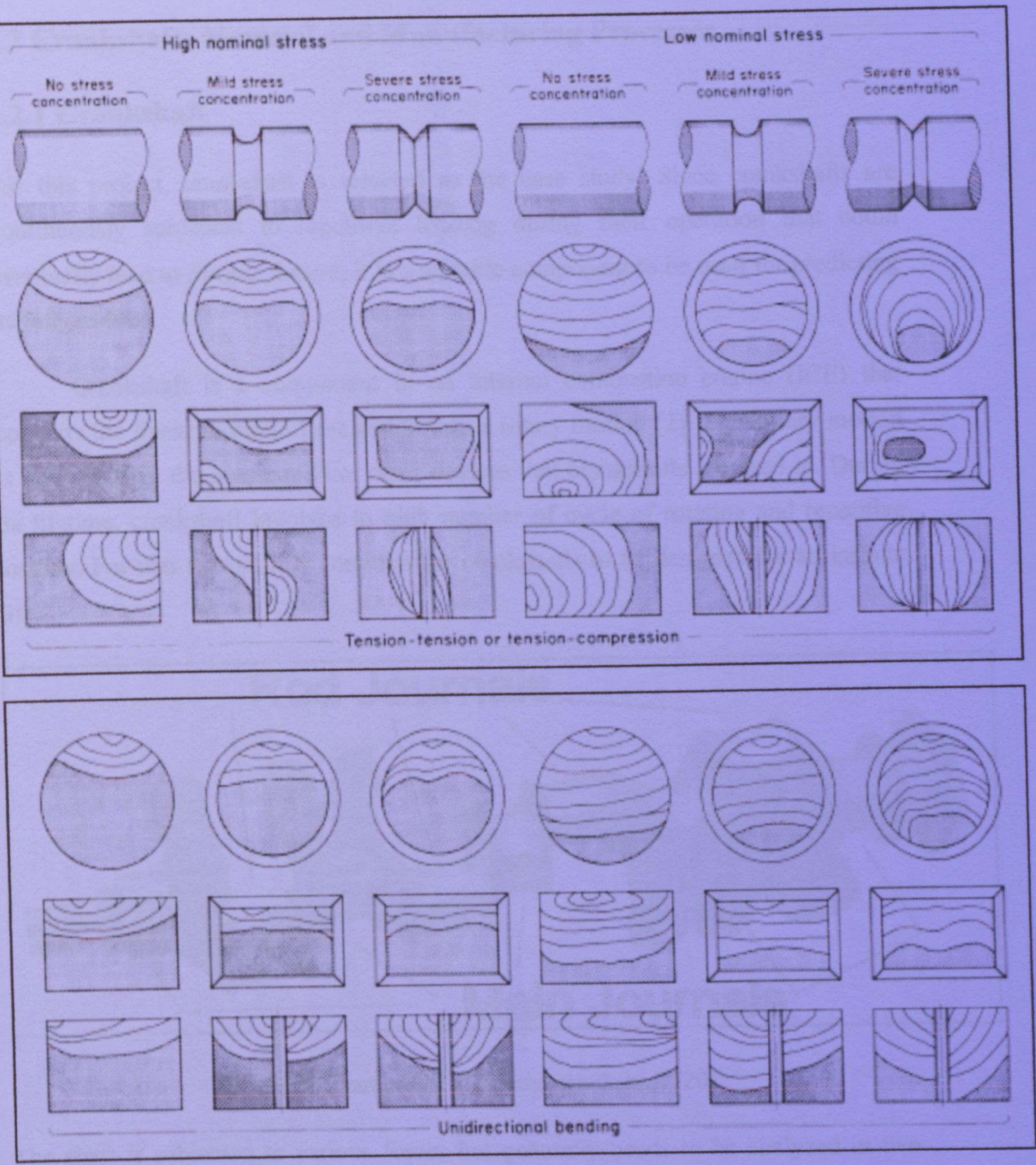


Figure 2: Schematics of fatigue fracture surfaces produced in smooth and notched component with round and rectangular cross sections under various loading conditions and nominal stress levels (*Taken from, Engineering Materials Properties and Selection, Kenneth G. Budinski and Micheal K. Budinski, 9th Ed. Pearson Prentice Hall, 2010*)

2.2 Crankshaft: Material and Manufacturing Processes

2.2.1 Crankshaft

For this project, crankshaft is selected as the case study. Since crankshafts are continuously subjected to repetitive loading during their operation that could eventually lead to *fatigue failure*, it is a suitable component to be used for predicting its fatigue-life.

Crankshaft is a component in an internal combustion engine (ICE) that converts the linear motion of the piston into a rotary motion [2]. This rotary motion is used to drive the automobile or other devices that crankshafts are used in. During its lifetime, crankshaft involves in high number of cycle of rotating and repetitive loading. For that reason, it is common for crankshafts to be designed for an infinite life.

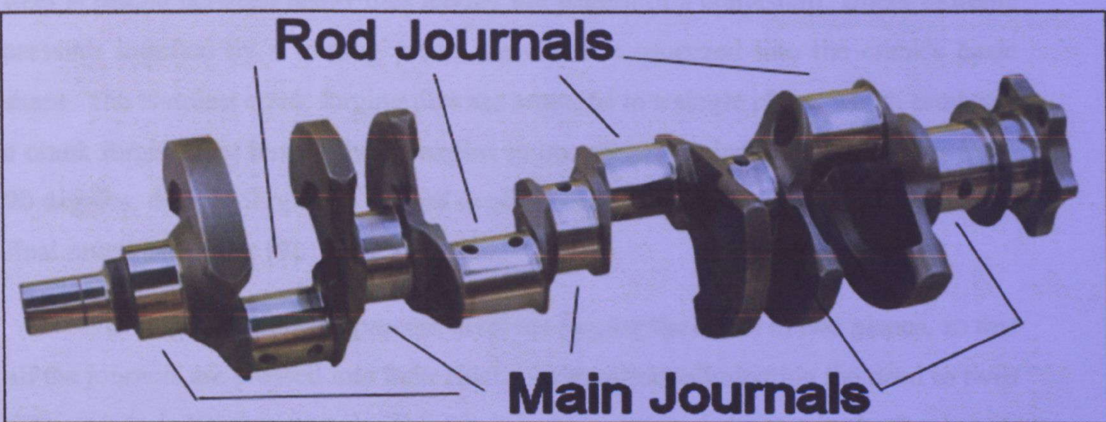


Figure 3: Example of a 2-plane crankshaft [20]

The shaft is subjected to various forces but generally needs to be analyzed in two positions. Firstly, failure may occur at the position of maximum bending; this may be at the center of the crank or at either end. In such a condition the failure is due to bending and the pressure in the cylinder is maximal. Second, the crank may fail due to twisting, so the con-rod needs to be checked for shear at the position of maximal twisting. The pressure at this position is the maximal pressure, but only a fraction of maximal pressure [20].

2.2.2 Crankshafts Manufacturing Processes (Casting versus Forging)

There are a couple of different ways to arrive at the basic shape, and this forms the basis of whether the crank is a forged or cast piece.

In casting, a mold is made and molten crank material, usually cast iron, is simply poured in to create the raw casting. Casting is cheap, the tooling is long lasting, and the raw casting springs from the mold very close to the required final shape, minimizing the final machining requirements. All of these attributes are endearing enough to make cast cranks the overwhelming favorite for OEM and mild performance applications.

In creating a forged crank, an entirely different process of metal forming is used, fittingly referred to as the forging process. In forging, a hot chunk of rolled steel is placed between heavy dies having the pattern of a crankshaft. Under extreme pressure supplied by a forging press, the metal is squeezed into the crank's basic shape. The simplest crank forging dies are arranged in a single plane, which produces a crank forging that has all the crankpins in one plane. To index the crank throws at 90 degrees, the raw forging is twisted to offset the journals in two planes to create the final raw crank blank [9].

An improved forging process involves forging the crank in two planes, so that all the journals are pressed into their final configuration, eliminating the need to twist the crank to index the journals. The result is fewer internal stresses in the forging, as well as an improved grain flow in the metal. Cranks made with this type of tooling are referred to as non-twist forgings. Tooling for a non-twist forging is considerably more complex and less durable than that for a simple flat forging, and there is typically more excess material to be machined from such a blank to create a finished crankshaft. Manufacturers producing crank forgings in huge volumes naturally gravitated to the lower cost and higher tooling life of a flat forging. In the aftermarket, with smaller production runs and an emphasis on durability for high-end cranks, non-twist forgings are available for many popular engines [9].

2.2.3 Crankshaft Materials

Crankshafts materials should be readily shaped, machined and heat-treated, and have adequate strength, toughness, hardness, and high fatigue strength. The crankshafts are manufactured from steel either by forging or casting. Generally automobile crankshafts were forged in past to have all the desirable properties. However, with the evolution of the nodular cast irons and improvements in foundry techniques, cast crankshafts are now preferred for moderate loads. Only for heavy duty applications forged shafts are favored. The summary of crankshaft materials for various applications is tabulated in the **Table 1**.

Table 1: Crankshaft materials and applications

Material	Applications
Manganese-molybdenum Steel	- relatively cheap forging steel and is used for moderate-duty petrol-engine crankshafts - suitable for both tin-aluminum and lead-copper plated bearings
2.5%-Nickel-chromium-molybdenum Steel	- opted for heavy-duty diesel-engine applications - slightly more expensive than manganese-molybdenum , but has improved mechanical properties
Nodular/Ductile Cast Irons	- also known as speroidal-graphite irons or ductile irons - have properties of grey cast iron (i.e., low melting point, good fluidity and cast-ability, excellent machinability, and wear resistance) - have mechanical properties of steel (i.e., relatively high strength, hardness, toughness, workability, and harden ability)

2.2.4 Application of Finite Element Method (FEM) in Fatigue

The use of numerical method such as Finite Element Method now a day commonly used to gives detail information about structure or component. This method predicts the behavior that is difficult to find out by theoretical calculation, because large number of degree of freedom involved in the process. FEM can be used as a tool to study and analyze fatigue life estimation of crankshaft by computer simulation. Thus, it can help to reduce time and costs required for prototyping and to avoid numerous test series when laboratory testing is not available. Various Finite Element analysis tool such as MSC-Fatigue, ANSYS, and FEMFAT are commonly used now a days by automobile companies to check durability of their products [15].

Finite Element Analysis (FEA) was performed by Jonathan Williams and Ali Fatemi [1] on forged steel and cast iron crankshaft to identify critical location and investigate the effect of engine speed as well as torsional load on stresses. Geometries of the two crankshafts were obtained using a digital caliper and a Coordinate Measuring Machine (CMM). Both crankshafts were modeled in IDEAS 12 and imported into ABAQUS which was used for the FEA. For the FE model, a mesh of 122,441 quadratic tetrahedral elements was used with a global mesh length of 5.08 mm and a local mesh length of 0.762 mm at the fillet. In the study, it is showed that the critical locations on the crankshaft geometry are all located on the fillet areas because of high stress gradients in these locations which result in high stress concentration factors.

This study compares the fatigue life prediction methods that have been used in predicting the fatigue life of the crankshafts. One method which is Stress-Life Method is selected to be used in this study for fatigue prediction purpose. Modeling and FE was done using ANSYS to identify and justify the critical location of the crankshaft. The crankshafts analyzed in this study are forged steel and ductile iron crankshaft from one cylinder engine. However, the geometry of these crankshafts will be simpler from the one that have been used by Williams et al [1].

2.3 Fatigue-life prediction methods

Traditionally, fatigue life at variable amplitude is predicted by using material properties from constant amplitude laboratory tests together with the Palmgren-Miner damage accumulation hypothesis [8].

The three major fatigue life method used in design and analysis are the *stress-life method*, the *strain-life method* and the *linear-elastic fracture mechanic* method. These methods attempt to predict the life in number of cycles to failure, N, for a specific level of loading. Life of $1 \leq N \leq 10^3$ cycles is generally classified as low-cycle fatigue, whereas high-cycle fatigue is considered to be $N > 10^3$ cycles.

Jonathan Williams and Ali Fatemi [2] have compared to fatigue behavior of forged steel and ductile cast iron crankshafts from a one-cylinder engine as well estimated the fatigue life of those crankshaft. Monotonic tensile tests as well as strain-controlled fatigue tests were conducted using specimens machined from the crankshafts to obtain the monotonic and cyclic deformation behavior and fatigue properties of the two materials. In their study, the procedures and results from specimen testing are presented and compared, including monotonic tensions, constant amplitude uniaxial fatigue, and Charpy v-notch tests. A description of finite element analysis (FEA) and result also included. Fatigue life prediction for these two crankshafts was compared with the result from the component fatigue test. The study showed that forged steel had higher tensile strength and better fatigue performance than the ductile cast iron. Load controlled component fatigue tests were performed using the forged steel and ductile iron crankshafts. For a given bending moment amplitude, the forged steel crankshaft had a factor of six (6) longer life than the ductile cast iron crankshafts. The fatigue properties from the specimen test were used in life prediction of the crankshafts. The study also showed that forged steel crankshafts life predictions using S-N approach based on material fatigue test data provided reasonable, but non-conservative estimation of the component fatigue lives, as judged by comparison with crankshaft fatigue test data. For the cast iron the S-N approach was less accurate than for forged steel, but provided a conservative life estimate [3].

Chatterly et al. [4] compared the fatigue performance of crankshafts made from ductile iron, austempered ductile iron (ADI), and forged steel. The ductile iron and ADI crankshafts were manufactured to the same dimensions as the forged steel crankshaft. Each crankshaft was clamped at the two main bearings and a bending moment was applied by a moment arm attached to one end of the crankshaft. The crankshafts were tested to 10^7 cycles or failure. A fatigue limit was established at 10^6 cycles for the three materials. The results show that when standard fillet rolling forces are used, ADI had ominously lower fatigue strength than forged steel. Higher rolling forces improved the fatigue strength of ADI, but were still lower to forged steel. However, the study did show that ADI had better fatigue strength than ductile iron.

Rahman et al. [5] performed a study on fatigue life prediction of lower suspension arm using strain-life approach. The main objectives of this study are to predict the fatigue life and identify the critical location and to select the suitable materials for the suspension arm. Aluminum alloys are selected as a suspension arm material. The structural model of the suspension arm was utilizing the Solid Work. The finite element model and analysis were performed utilizing the finite element analysis code. The fatigue life was predicted using the strain-life approach subjected to variable amplitude loading. The study showed that the fillet of the bushing experiences the largest stresses, where the maximum principal stress is maximum. The study also showed that 7075-T6 aluminum alloy is the suitable material compared to others material in the optimization.

Newman et al. [6] investigate the fatigue life prediction of Ti-6Al-4V alloy that subjected under various constant amplitude loading conditions on notched and un-notched specimen. A crack-closure model with a cyclic-plastic-zone-corrected effective stress-intensity factor range and equivalent-initial-flaw-sizes (EIFS) were used to calculate fatigue lives using only crack-growth-rate data. The study showed that for large crack, load-reduction test method caused elevated thresholds and slower crack-growth rates than the compression pre-cracking constant-amplitude (CPCA) test method. The study also conclude that plasticity effect on the effective stress intensity factor range were small, even for very high applied stress levels, but the crack-closure transients become dominator for rapid small-crack growth.

Jensen [7] showed in his study of a V-8 automotive crankshaft that the inertial and gas loads of the engine create a multi-axial stress situation in the form of bending and torsion. This was done through the application of strain gages to the crankshaft to measure bending and torsion. Only the maximum torsion and bending moment were considered and the test was reduced by using the maximum principal stress theory to a constant amplitude bending test. Resonant bending tests were conducted on sections of the crankshafts. The fatigue life of the crankshaft was determined using the S-N approach.

In this project, the focus will be on the stress-life and strain life method since these methods have already be implemented and has many journal and articles established using these techniques. The techniques will be studied and compared to evaluate the suitability of the method in predicting the fatigue life of the crankshaft. The research done by Jonathan Williams and Ali Fatemi will be the main reference for this project.

CHAPTER 3

METHODOLOGY

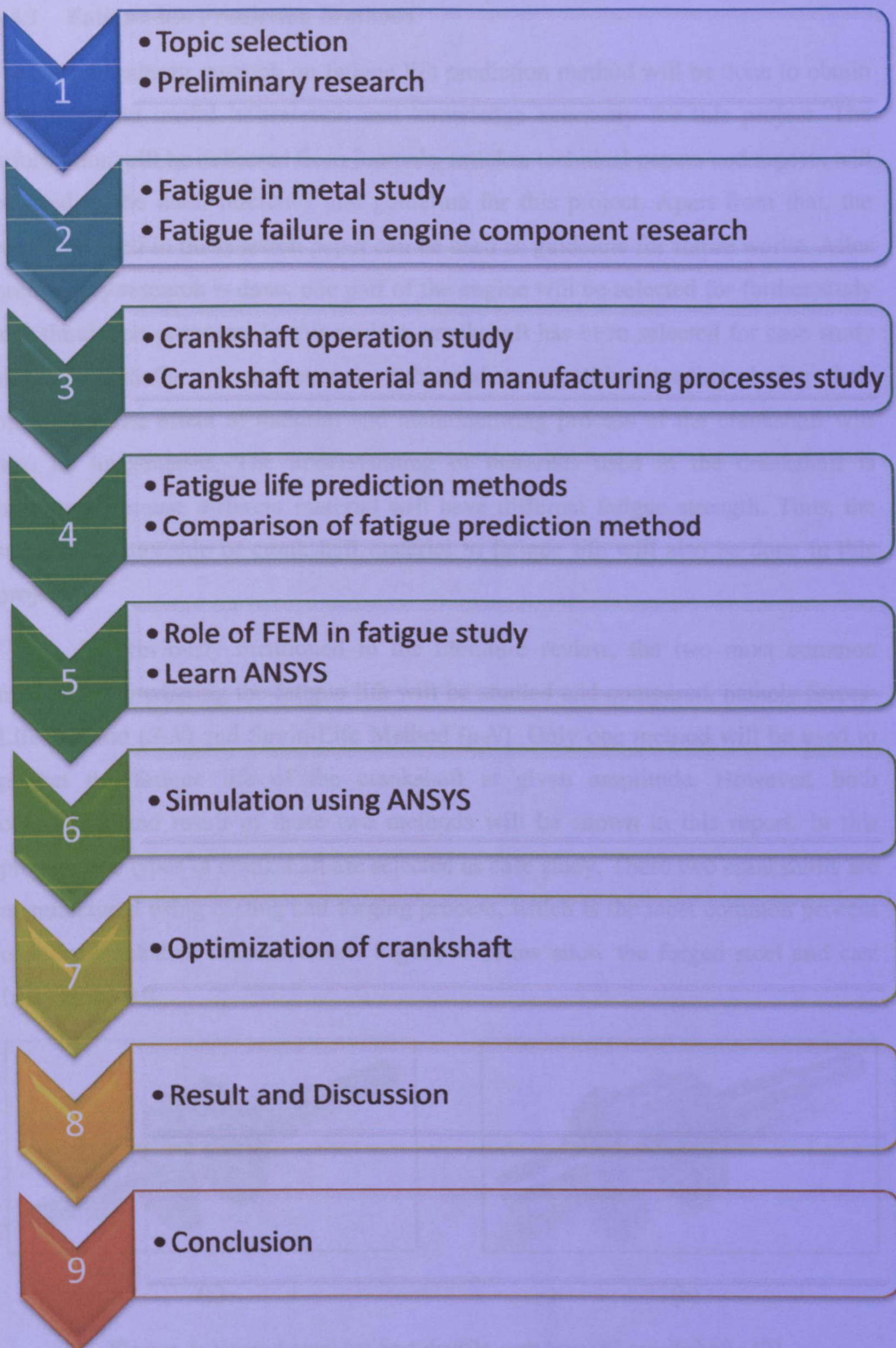
3.1 Gantt chart (FYP I)

No	Detail	Week													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection of project topic								MID SEMESTER BREAK						
2	Preliminary research work														
3	Preliminary report submission														
4	Fatigue-life prediction method study														
5	Crankshaft material and manufacturing process study														
6	Extended proposal report submission														
7	Proposal defense														
8	Reliability engineering study														
10	Learn ANSYS in detail														
11	Interim report draft submission														
12	Seminar														
13	Interim report final draft submission														

3.2 Gantt chart (FYP II)

No	Detail	Week														
		15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
14	Project Work Continues							MID SEMESTER BREAK								
15	Submission of Progress Report															
16	Simulation using ANSYS															
17	Pre-EDX															
18	Submission of Draft Report															
19	Submission of Dissertation (soft bound)															
20	Submission of Technical Paper															
21	Oral Presentation (viva)															
22	Submission of Project Dissertation (hard bound)															

3.3 Flow chart

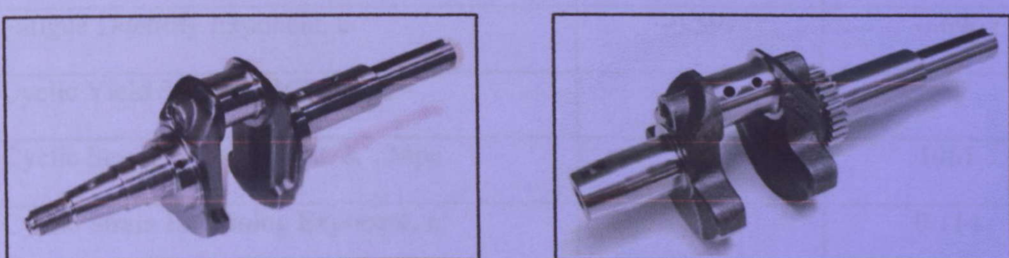


3.4 Work procedures

3.4.1 Fatigue-life Prediction Methods

Firstly, preliminary research on fatigue life prediction method will be done to obtain beneficial and useful information and knowledge necessary for this project. The information will be collected from journals, articles, technical papers and reports will be used as the main reference and guideline for this project. Apart from that, the result obtained in the research paper can be used as guideline for future works. After preliminary research is done, one part of the engine will be selected for further study and simulation purposes. In this project, crankshaft has been selected for case study since crankshafts are continuously subjected to repetitive loading during their operation. The effect of material and manufacturing process of the crankshaft will also be investigated. The understanding of materials used in the crankshaft is important because different material will have different fatigue strength. Thus, the study of relationship of crankshaft material to fatigue life will also be done in this project.

As previously mentioned in the literature review, the two most common methods of predicting the fatigue life will be studied and compared, namely Stress-Life Method (*S-N*) and Strain-Life Method (ε-*N*). Only one method will be used to predict the fatigue life of the crankshaft at given amplitude. However, both calculation and result of these two methods will be shown in this report. In this project, two types of crankshaft are selected as case study. These two crankshafts are manufactured using casting and forging process, which is the most common process used by crankshaft manufacturers. **Figure 4** below show the forged steel and cast iron crankshaft.



(a) (b)

Figure 4: Forged steel (a) and ductile cast iron (b) crankshafts [2]

The material properties of forged steel and ductile cast iron material properties are summarized in the **Table 2** below. These properties will be used to calculate the fatigue life prediction of the crankshafts.

Table 2: Forged steel and ductile cast iron material properties

Monotonic Properties	**Forged Steel**	**Cast Iron**
Average Hardness, HRC	23	18
Average Hardness, HRB	101	97
Modulus of Elasticity, E, GPa	221	178
Yield Strength (0.2% offset), YS, Mpa	625	412
Ultimate Strength, S_u, Mpa	827	658
Percent Elongation, %EL	54%	10%
Percent Reduction in Area, %RA	58%	6%
Strength Coefficient, K, Mpa	1316	1199
Strain Hardening Exponent, n	0.152	0.183
True Fracture Strength, σ_f, Mpa	980	562
True Fracture Ductility, ε_f	87%	6%
Cyclic Properties	**Forged Steel**	**Cast Iron**
Fatigue Strength Coefficient, σ_f', MPa	1124	927
Fatigue Strength Exponent, b	-0.079	-0.087
Fatigue Ductility Coefficient, ε_f'	0.671	0.202
Fatigue Ductility Exponent, c	-0.597	-0.696
Cyclic Yield Strength, YS', Mpa	505	519
Cyclic Strength Coefficient, K', Mpa	1159	1061
Cyclic Strain Hardening Exponent, n'	0.128	0.114

Source [2]

3.4.2 Fatigue-life prediction calculation

Stress Life Method (*S-N*)

The stress-life approach was the first well-develop approach for fatigue analysis. It is suitable to predict fatigue life for applications that involve in a large number of cycles and has been widely used in automotive industry. Fatigue life depends primarily on materials, loads, environmental effects and geometry and it is usually described by S-N curve. The relationship between the nominal stress amplitude life can be expressed in Equation (1)

$$\sigma_a = \sigma_f'(2N_f)^b \tag{1}$$

where σ_a is a stress amplitude, σ'_f is a fatigue coefficient, $2N_f$ is the reveals to failures and b is the fatigue strength component [2].

Strain Life Method (ε-N)

The equation of the plastic-strain is given by

$$\frac{\Delta\varepsilon}{2} = \varepsilon'_f(2N)^c \tag{2}$$

The equation of the elastic strain is

$$\frac{\Delta\varepsilon_e}{2} = \frac{\sigma'_f}{E}(2N)^b \tag{3}$$

Therefore, from the first equation, we have for the total-strain amplitude

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c \tag{4}$$

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. This equation is also known as Manson-Coffin relationship between fatigue life and total strain [1].

These formulas will be used to calculate the fatigue life of forged steel and ductile cast iron crankshafts at given stress or strain amplitude and to obtain fatigue strength at given cycles.

3.4.3 Finite Element Analysis (FEA) of crankshafts using ANSYS

In this project, two crankshafts with different manufacturing methods and materials are used for further studies. These crankshafts, namely forged steel and ductile cast iron will be evaluated and compared regarding their fatigue performance using ANSYS. Finite Element Analysis (FEA) will be performed to identify critical locations and to determine the stress concentration factors for purpose of life prediction. Dynamic load and stress analysis of the forged steel and ductile cast iron crankshafts were also performed. The analysis was done and as a result, critical region on the crankshafts were obtained. The effect of different material used to manufacture crankshaft will be investigated and discussed. The steps taken to do the simulation of the crankshafts are explained below.

1) ***Crankshaft geometry and modeling***

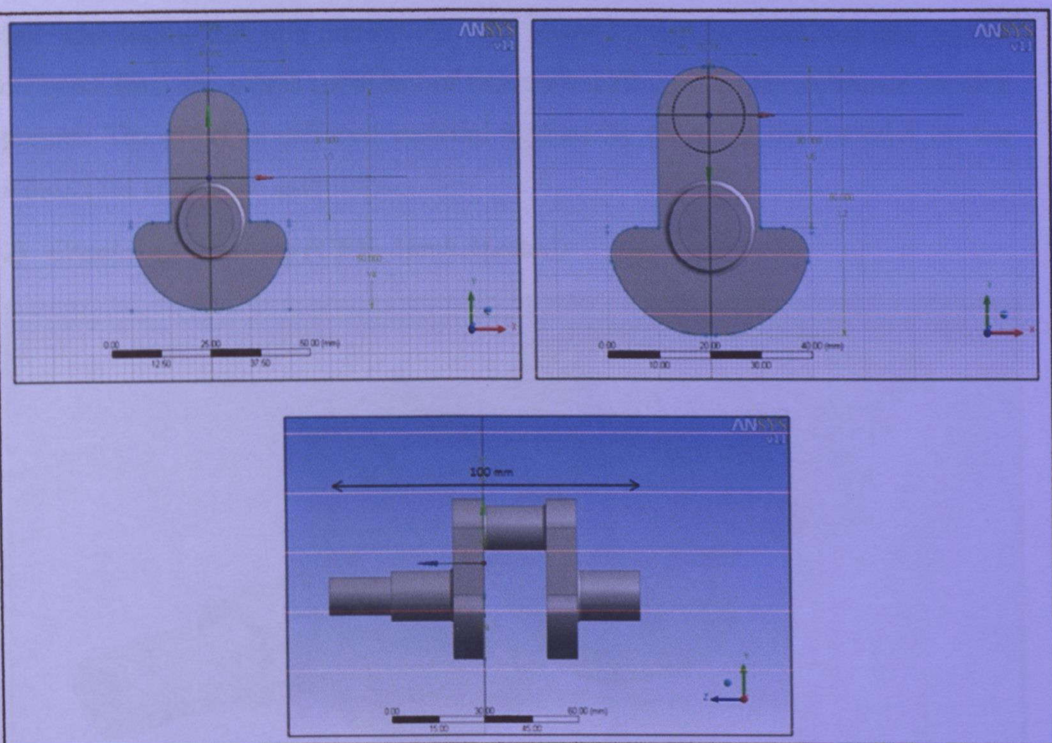


Figure 5: Crankshaft dimensions

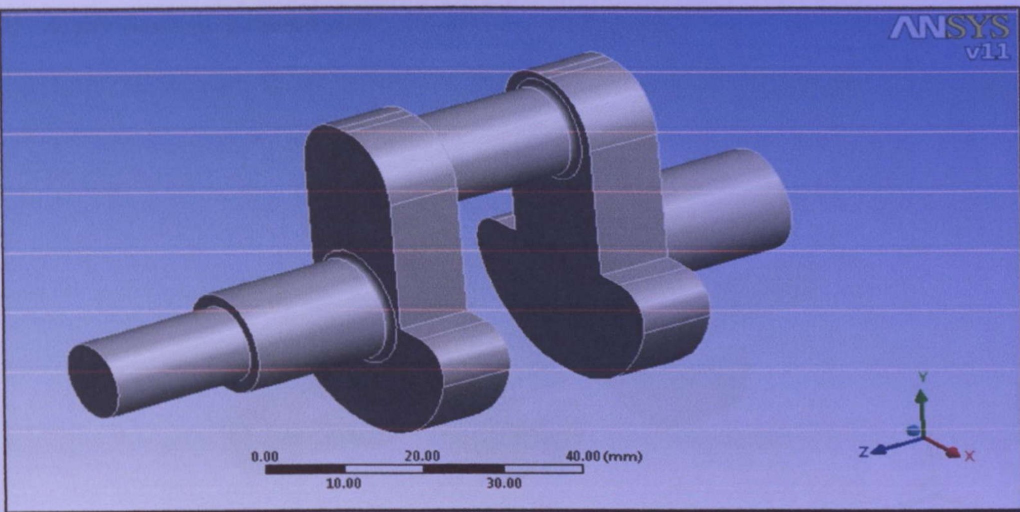


Figure 6: Forged steel and ductile cast iron crankshaft model

Due to time and specialty constraint, the same geometry will be used for both forged steel and ductile cast iron crankshafts. The geometry will be simplified and will be different from the actual geometry of the crankshaft used as the reference for this project. The effect of different material is done by changing the material for the solid of the crankshaft geometry.

2) Crankshaft meshing (CFX- Mesh Method)

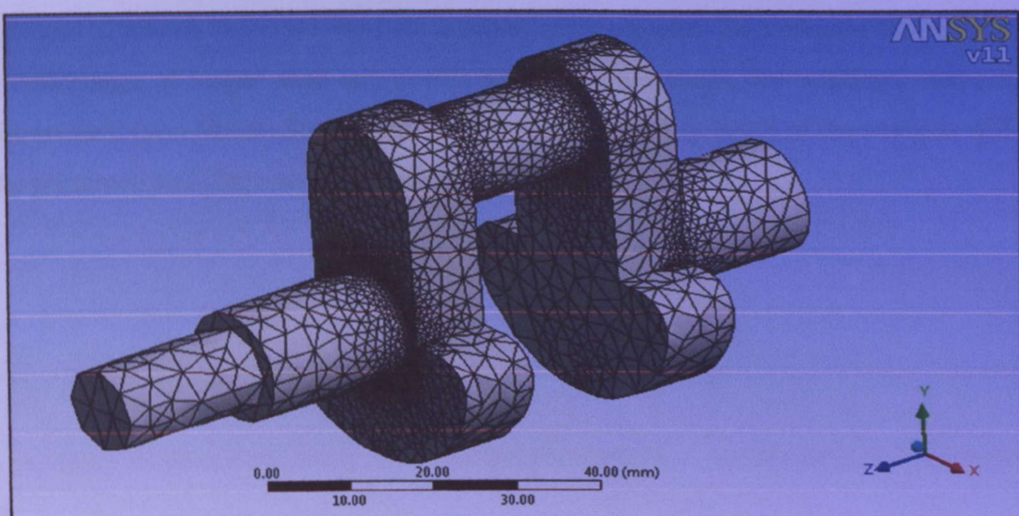


Figure 7: Forged steel and ductile cast iron crankshaft meshing

The element size of this meshing is set to be 5 mm. The meshing resulting in 6193 nodes and 20089 numbers of elements produced.

3) Apply boundary conditions

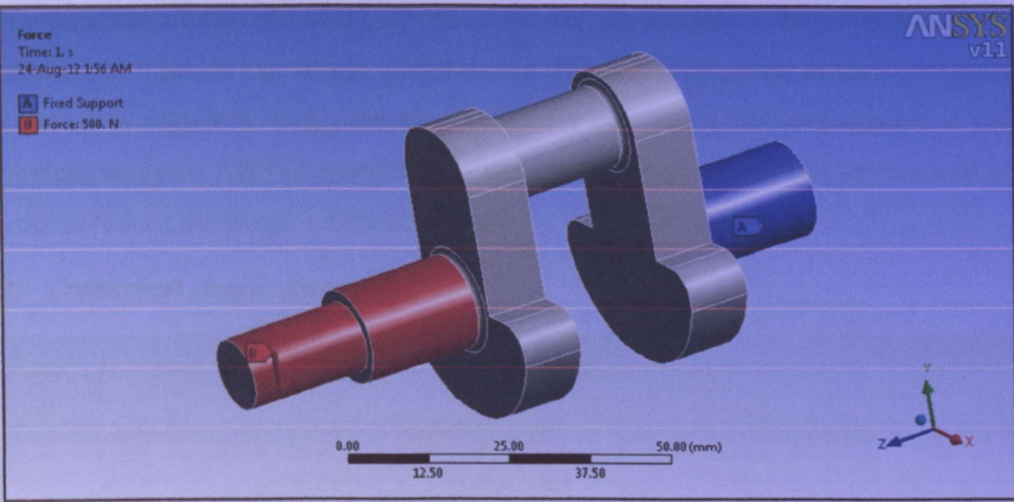


Figure 8: Boundary condition of forged steel and ductile cast iron crankshaft

The boundary condition is applied according to the test set-up done by Montazersadgh and Fatemi [2]. The right side of the crankshaft is being fully constrained. The load was applied either along axis Z or X (as shown is **Figure 8**) resulting in stresses at fillet region.

4) Analysis

Several solutions were selected for comparison purposes. To compare the fatigue performance of forged steel and ductile cast iron crankshafts, the solutions used are Equivalent (von Mises) Stress, and Total Deformation. The result of the analysis will be presented and discussed in Result and Discussion.

3.4.4 Optimization of crankshaft

The purposes of the optimizations are to reduce the weight of the crankshaft, and maintain or improve the fatigue performance. The initial geometry of the crankshaft is shown in **Figure 6**. Using the same boundary conditions and load applied in the previous analysis, ANSYS software can identify which areas that can be removed in order to reduce the weight of the crankshaft.

1) Crankshaft shape removal

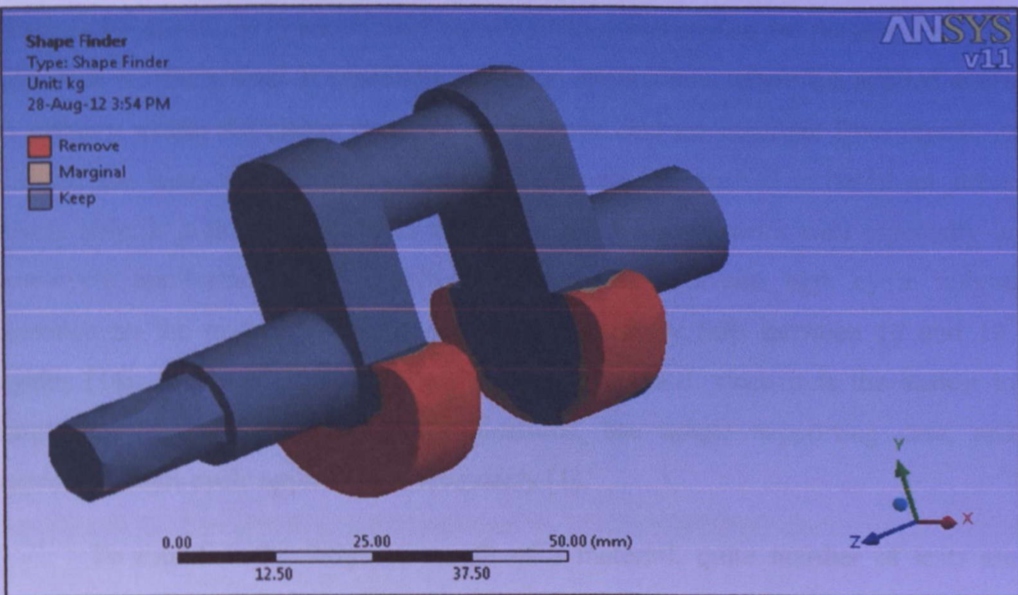


Figure 9: Crankshaft removal areas

Figure 9 shows the area of the crankshaft than can be removed. The removal of these areas will not affect the overall crankshaft operations.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Fatigue Life Prediction Methods

4.1.1 Stress-life method

The stress-life (-N) method was applied over centuries ago and consider nominal elastic stresses and how they relate to life. This method is suitable for fatigue analysis for situations in which only elastic stresses and strains are present. The S-N approach is widely used in especially in design applications where the applied stress is primary within the elastic range of the material and the resultant lives (cyclic to failure) are long, such as crankshaft. Since stress-life method is based on stress levels only, it is the least accurate approach, and does not work well especially in low-cycle applications. The dividing line between low and high cycle fatigue depends on the material being considered, but usually falls between 10 and 10^5 cycles [16]. However, it is the most traditional method, since it is the easiest to implement for a wide range of applications, has ample supporting data, and represents high-cycle applications adequately [1].

To establish the fatigue strength of a material, quite number of tests are necessary because of the statistical nature of fatigue. For rotating-beam test, a constant bending load is applied, and the number of revolutions (stress reversals) of the beam required for failure is recorded. The first test is made at stress that is somewhat under the ultimate strength of the material. The second test is made at a stress that is less than that used in the first. This process is continued and the results are plotted as an S-N diagram [2].

The ordinate of the S-N diagram is called the *fatigue strength* S_f, a statement of this strength value must always be accompanied by a statement of the number of cycles N to which it corresponds. S-N diagram can be determined either for a test specimen or for an actual mechanical element. Even when the material of the test specimen and that of the mechanical element are identical, there will be significant differences between the diagrams for the two [17].

The Stress-Life (S-N) diagram of forged steel and ductile cast iron are shown in the graph below. Equation (1) is used to calculate the fatigue life of the crankshafts. Fatigue limit is defined at 10^6 cycles.

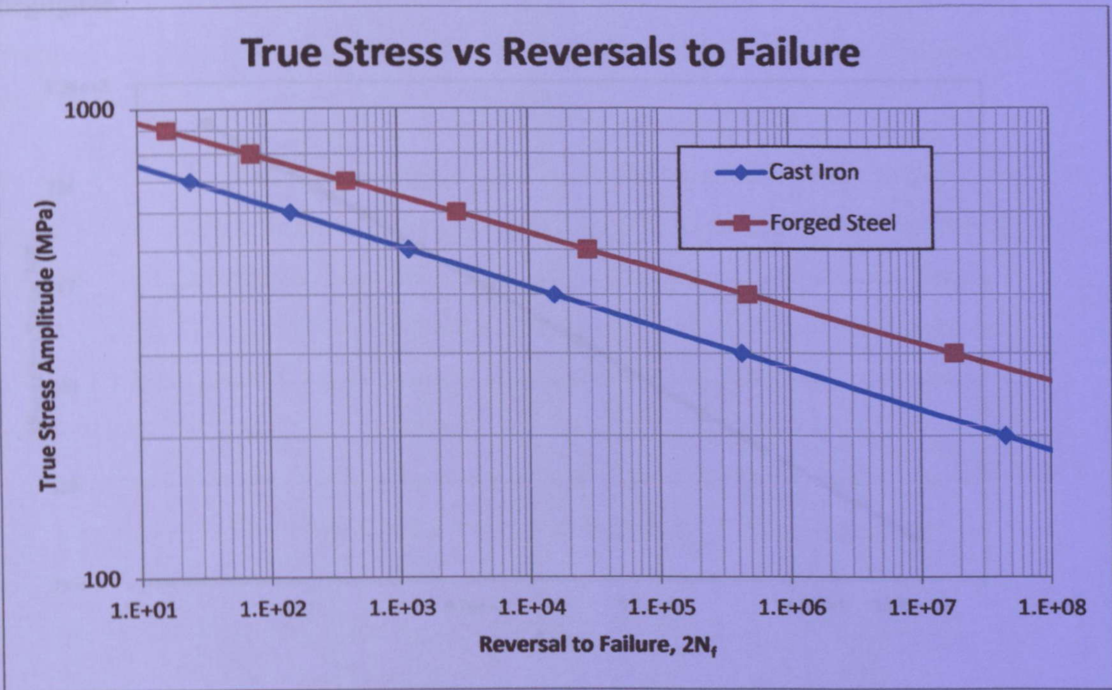


Figure 10: True stress amplitude versus reversals to failure of forged steel and ductile cast iron material

From the figure above, at 10^6 cycles, it indicates that the forged steel has higher fatigue strength compare to ductile cast iron. We can see that the fatigue strength of the ductile cast iron is estimated around 280 MPa and for forged steel are 380 MPa. This shows that the fatigue strength at 10^6 cycles for ductile cast iron is about 75% of the fatigue strength of forged steel.

Using the same data from the calculation of stress-life method, alternating stress versus cycle for cast iron and forged steel are plotted using ANSYS as shown in **Figure 11** and **Figure 12**. The graphs were plotted with log values and mean stress is negligible.

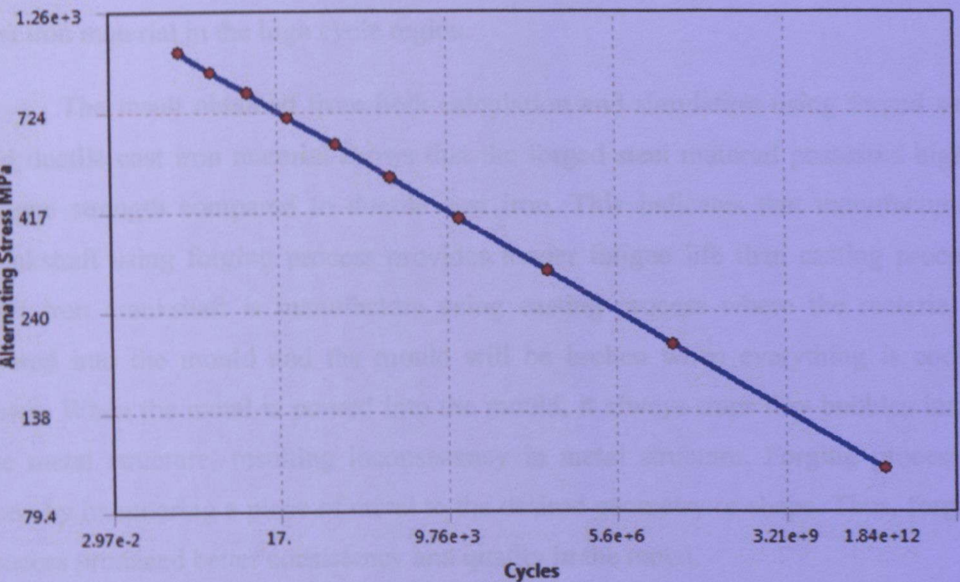


Figure 11: Alternating stress versus cycles for cast iron material

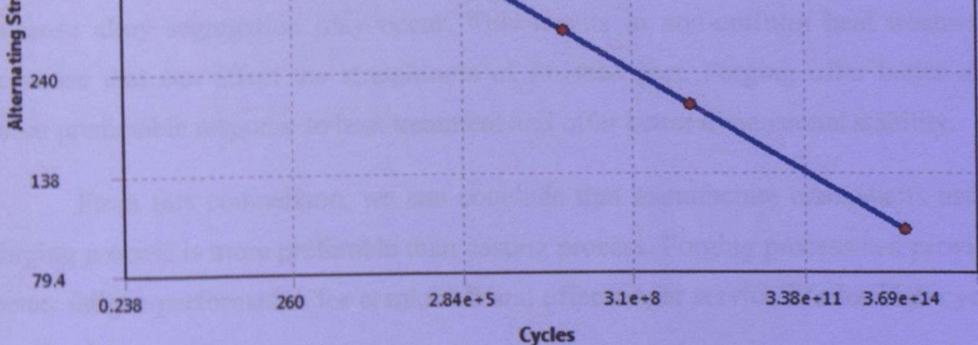


Figure 12: Alternating stress versus cycles for forged steel material

From **Figure 11** and **12**, for any given stress amplitude, forged steel material has higher fatigue strength compare to ductile cast iron. When stress value is set to be at 240 MPa, the number of cycle to failure of ductile cast iron material is 5.6×10^6 cycle while for forged steel material is 3.1×10^8 cycles. At a given stress amplitude, manufacture a crankshaft using forged steel material offers longer life that ductile cast iron material in the high cycle region.

The result obtained from both calculation and simulation using forged steel and ductile cast iron material shows that the forged steel material possesses higher fatigue strength compared to ductile cast iron. This indicates that manufacture a crankshaft using forging process provides longer fatigue life than casting process. Cast iron crankshaft is manufacture using casting process where the material is poured into the mould and the mould will be broken when everything is cooled down. When the metal is poured into the mould, it always traps tiny bubbles inside the metal structure, resulting inconsistency in metal structure. Forging process is done by hammering a piece of metal to the desired geometry or shape. Thus, forging process produced better consistency and quality in the metal.

Forging process is more reliable and less costly. Casting defect occur in a variety of forms. Because hot working refines grain pattern and imparts high strength, ductility and resistance properties, forged product are more reliable. In addition, the parts are manufactured without the added cost for tighter process controls and inspection that are required for casting. Heat treatment plays important role in improving the quality and fatigue performance of the crankshafts. In casting, heat treatment process requires close control of melting and cooling processes because alloy segregation may occur. This results in non-uniform heat treatment response that can affect the straightness of finished part. Forging offer better and more predictable response to heat treatment and offer better dimensional stability.

From this comparison, we can conclude that manufacture crankshafts using forging process is more preferable than casting process. Forging process can provide better fatigue performance for crankshaft and offer longer service life for high cycle applications.

4.1.2 Strain-life method

The strain-life method involves more detailed analysis of the plastic deformation at localized regions where the stresses and strains are considered for life estimates. It is the best approach yet advance to explain the nature of fatigue failure. This method is based on the observation that in many components, the response of the material in critical location is strain dependent. When loads are low, stress and strain are linearly related [1]. In this range, strain-controlled and load-controlled test results are equivalent. For low cycle fatigue, the material behaviors are best model under strain-controlled conditions.

In applying this method, several idealizations must be compounded, and so some uncertainties will exist in the results. A fatigue failure typically begins at a local discontinuity such as notch, crack, or other area of stress concentration. When the stress at the discontinuity exceeds the elastic limit, plastic strain occurs. If a fatigue fracture is to occur, there must exist cycle plastic strains [1]. Thus, the investigation of the material behavior subject to cyclic deformation needs to be done.

Most components may appear to have nominally cyclic elastic stresses but stress concentrations present in the component may result in local cyclic plastic deformation. Under these conditions, the local strain-life method uses the local strain as the governing fatigue parameter. The local strain-life approach is preferred if the loading history is irregular and where the mean stress and the load sequence effects are thought to be of importance [5].

Figure 13 and 14 in the next page shows the true plastic strain, true elastic strain and total strain amplitude versus reversal to failure for the forged steel and ductile cast iron crankshafts. Equation (2) and Equation (3) are used to calculate the true plastic and elastic strain of the crankshafts.

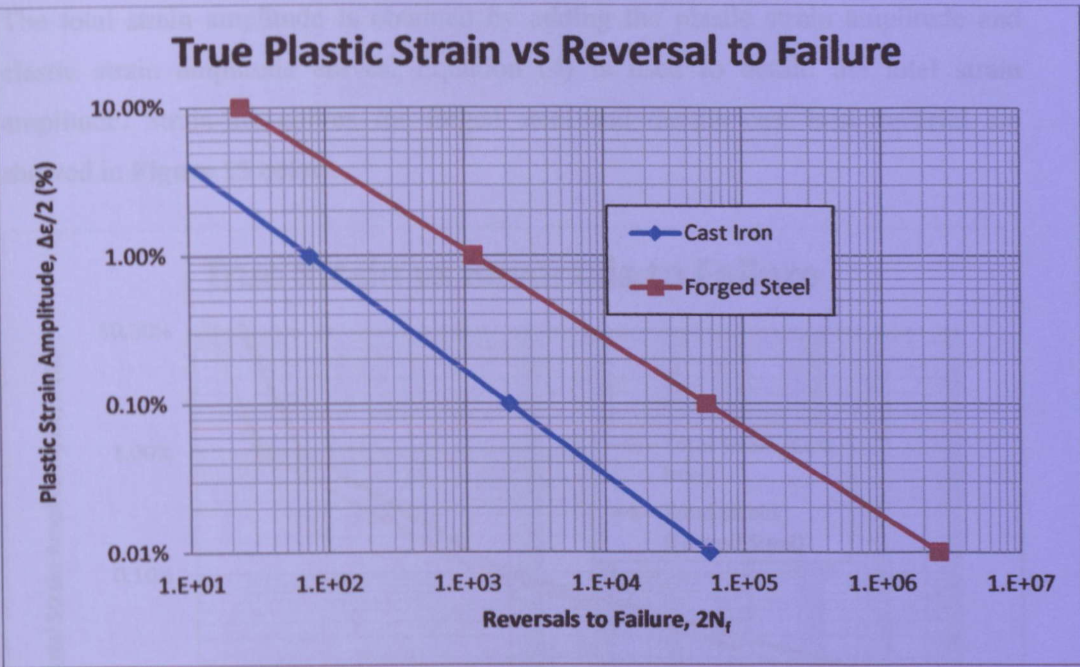


Figure 13: True plastic strain versus reversals to failure for forged steel and ductile cast iron materials.

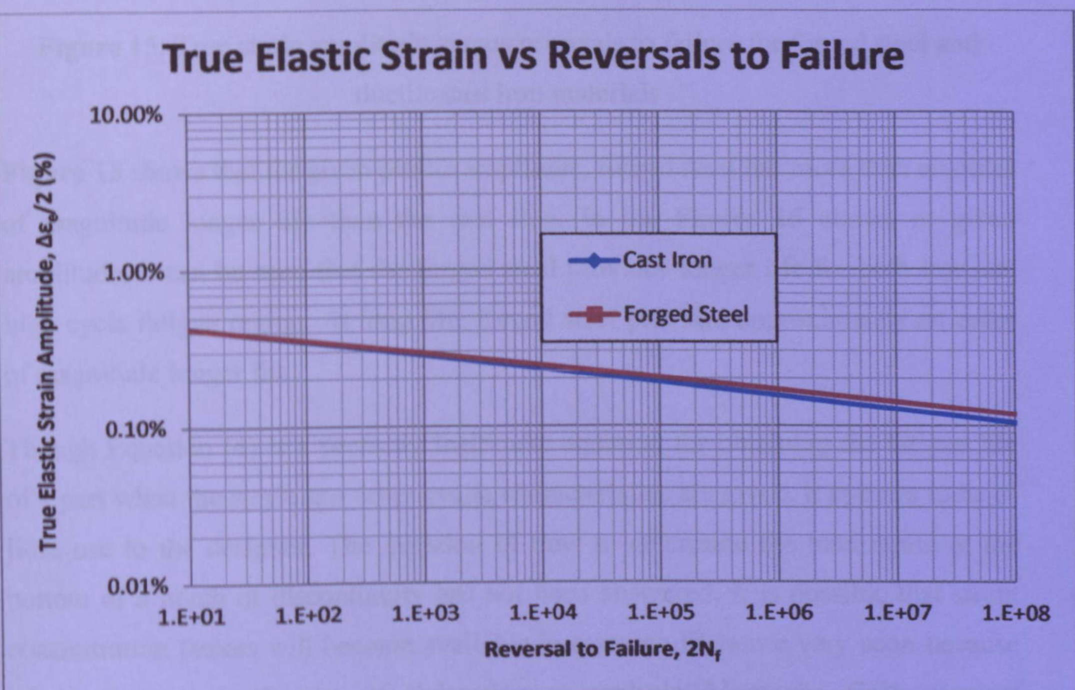


Figure 14: True elastic strain versus reversals to failure for forged steel and ductile cast iron materials

The total strain amplitude is obtained by adding the plastic strain amplitude and elastic strain amplitude curves. Equation (4) is used to obtain the total strain amplitude. Strain-life curves for forged steel and ductile cast iron material are showed in **Figure 15** below.

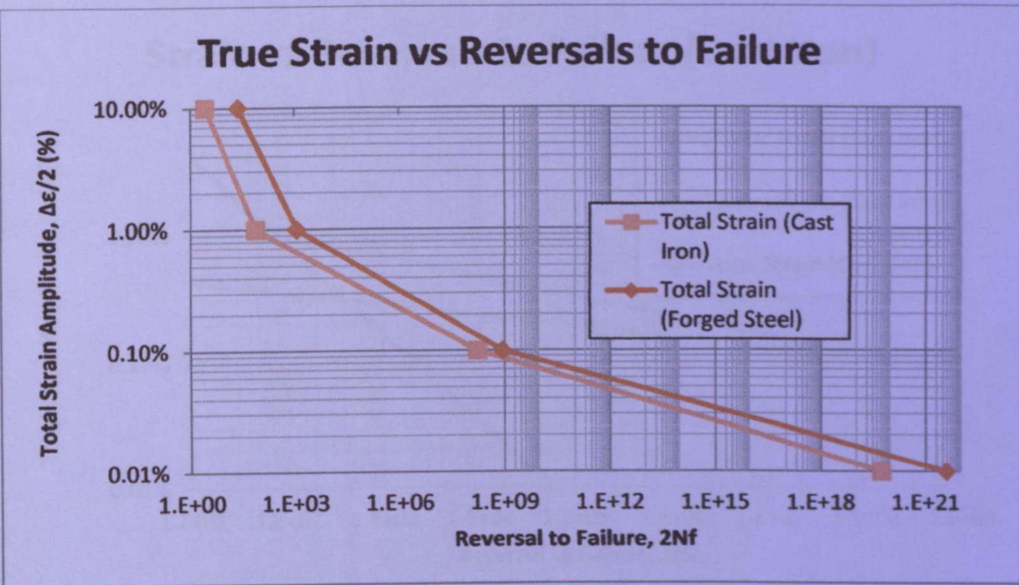


Figure 15: True strain amplitude versus reversals to failure for forged steel and ductile cast iron materials

Figure 13 shows that for given plastic amplitude, forged steel has more than an order of magnitude longer life than the cast iron. In the **Figure 15** above, at given amplitude, it can be seen that the forged steel provides longer life for both low and high cycle fatigue region. At long life, forged steel provides approximately an order of magnitude longer life.

Though Equation (4) is a perfectly legitimate equation for obtaining the fatigue life of a part when the strain and other cyclic characteristics are given, it appears to be of little use to the designer. The question of how to determine the total strain at the bottom of a notch or discontinuity has not been answered. It is possible that strain concentration factors will become available in research literature very soon because of the increase in the use of finite-element analysis. Moreover, finite element analysis can of itself approximate the strains that will occur at all points in the subject structure.

Figure 14 and 15 below show the superimposed strain versus reversal to failure for ductile cast iron and forged steel material. The strain curve for both ductile cast iron and forged steel material are verified using ANSYS. The graphs are shown in Appendix A-4.

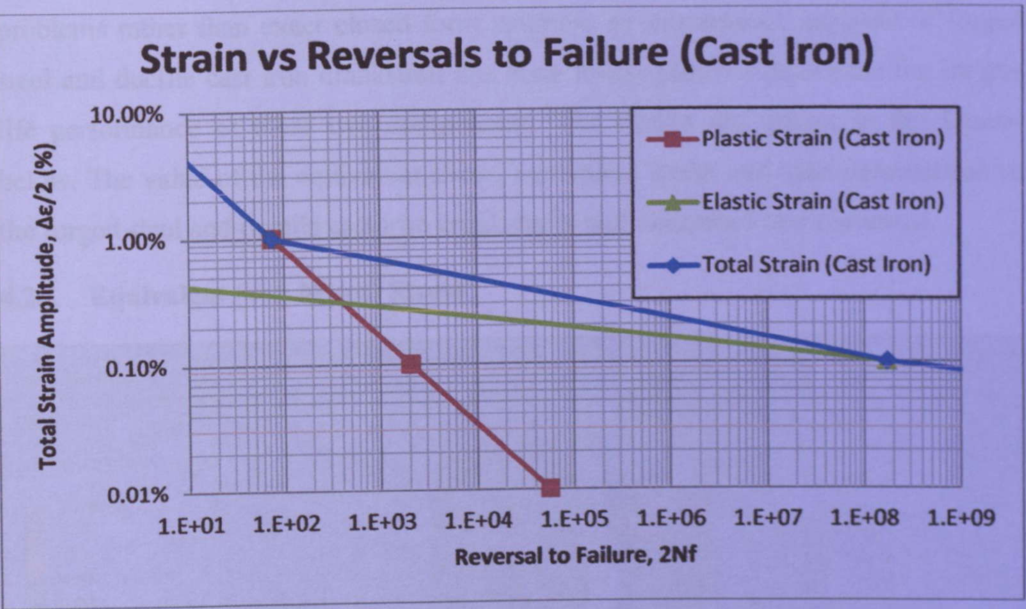


Figure 16: Superimposed strain versus reversal to failure for ductile cast iron

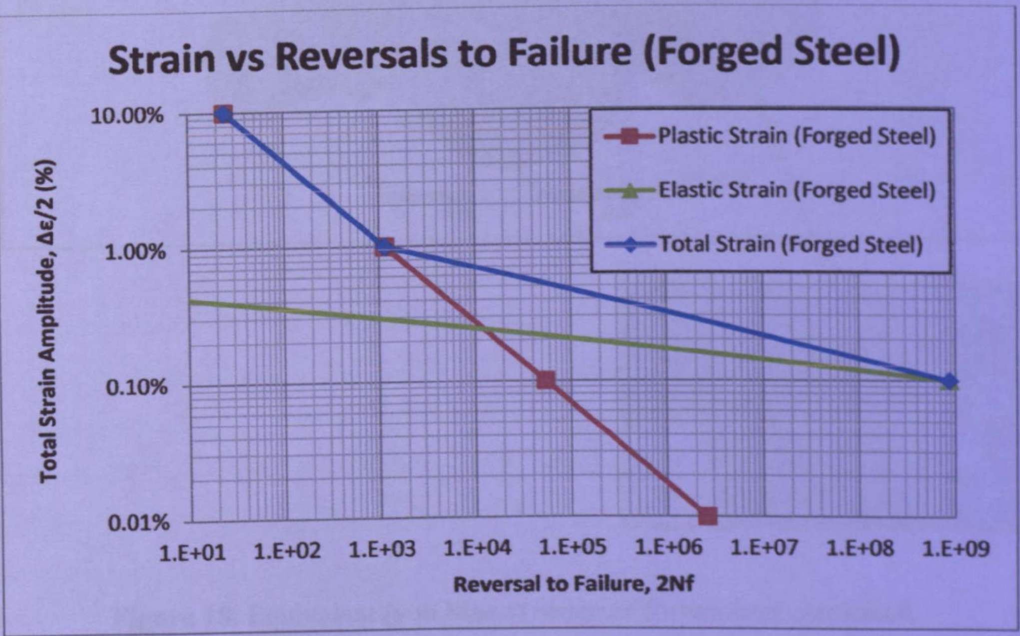


Figure 17: Superimposed strain versus reversal to failure for forged steel

4.2 Finite Element Analysis (FEA) of crankshafts

The finite element method is numerical analysis technique for obtaining approximate solutions to a wide variety of engineering problems. In more and more engineering situations today, we find that it is necessary to obtain approximate solutions to problems rather than exact closed form solution. In this project, analysis of forged steel and ductile cast iron crankshaft has been investigated to determine the fatigue life performance of these two components. The results are shown in the figures below. The value of the equivalent stress, equivalent strain and total deformation of the forged steel and ductile cast iron crankshafts will compared and discussed.

4.2.1 Equivalent (von Mises) Stress

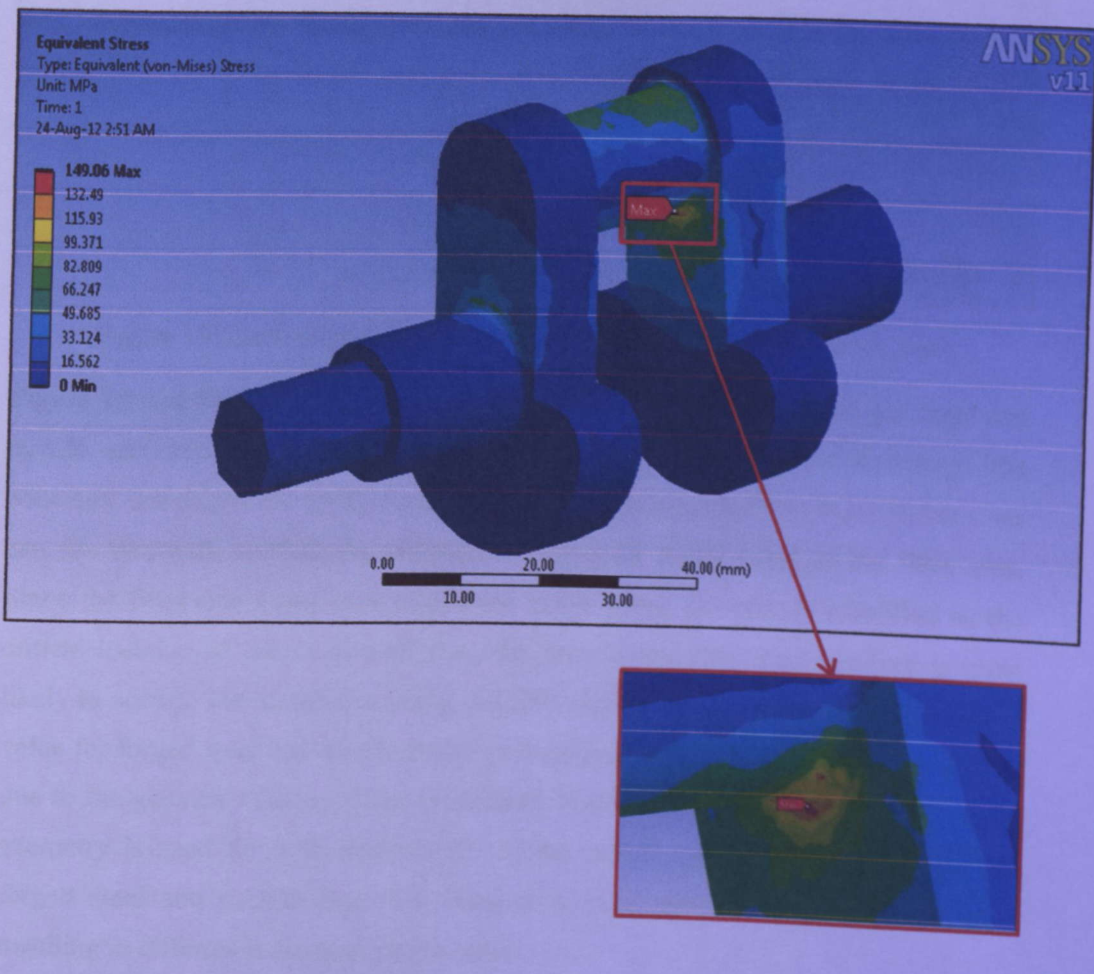


Figure 18: Equivalent (von Mises) Stress of forged steel crankshaft

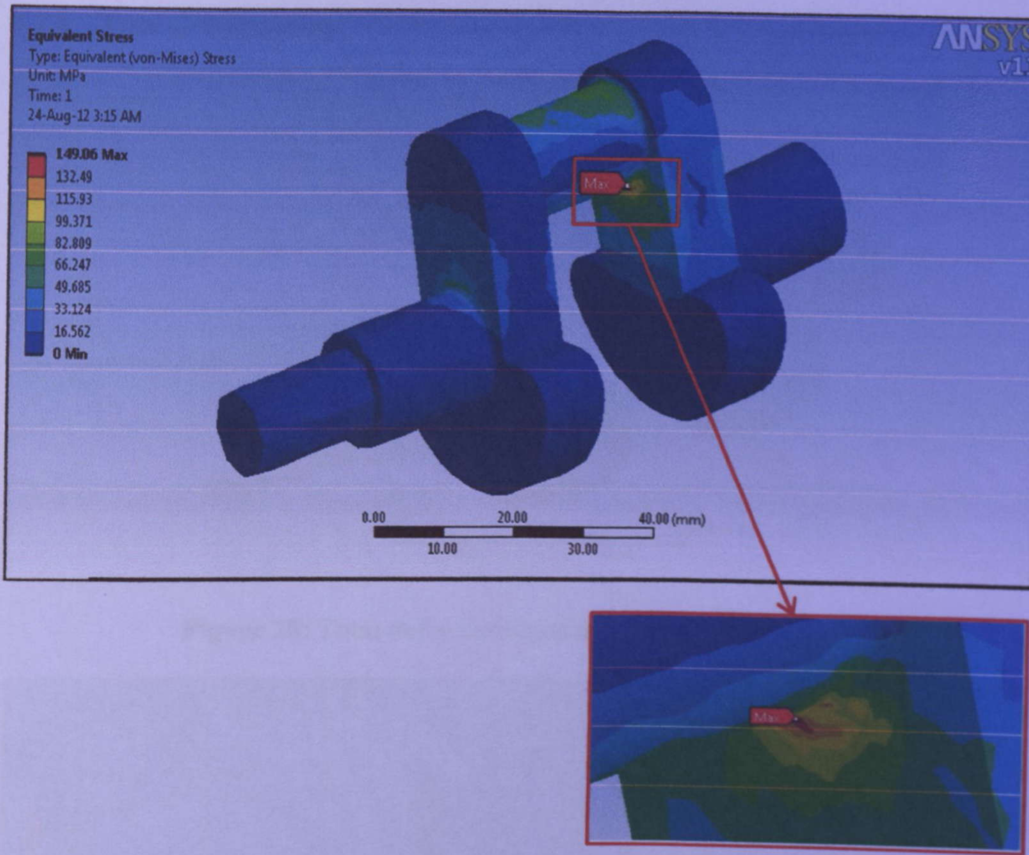


Figure 19: Equivalent (von Mises) Stress of ductile cast iron crankshaft

Figure 18 and **Figure 19** show the variation of stress magnitude at forged steel and ductile cast iron crankshafts. As previously mentioned in the methodology, the boundary conditions are applied according to the test set-up. From those figures, we can see that both crankshafts experience maximum stress value at the fillet area. Since the fillet area experience maximum stress value, the area is classified as the critical location of the crankshaft (i.e., the area where the fatigue failure is most likely to occur). The simulation using ANSYS resulted in the same maximum stress value for forged steel and ductile cast iron crankshafts which is 149.06 MPa. This is due to the geometry factor of the crankshaft. For simplification purposes, the same geometry is used for both crankshafts. In the actual application, the designs for forged steel and ductile cast iron crankshaft have different geometry and thus resulting in different maximum stress value.

4.2.2 Total Deformation

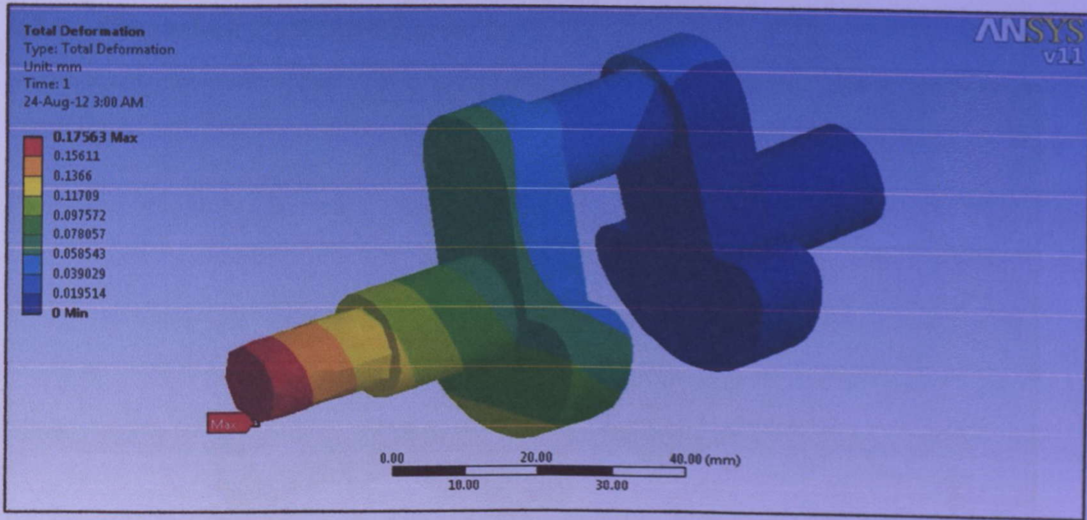


Figure 20: Total deformation of forged steel crankshaft

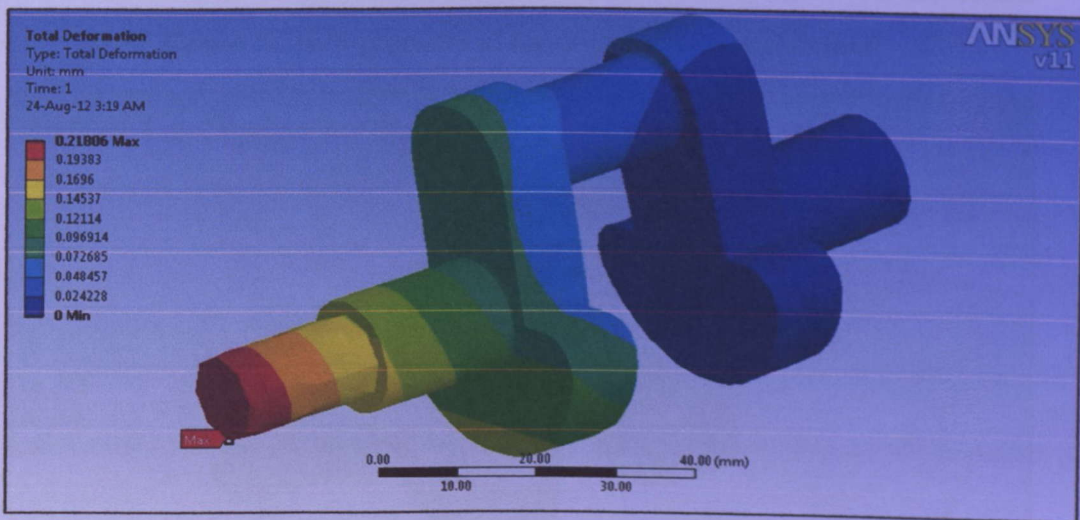


Figure 21: Total deformation of ductile cast iron crankshaft

The value of the maximum deformation for forged steel is 0.17563 mm and for ductile cast iron 0.21806 mm. The result indicates that forged steel will experience lower maximum deformation compare to ductile cast iron crankshaft. Deformation of an engine part will reduce the interaction between the piston and the crankshaft. This will result in worse performance as well as reduce power and less economic of an engine. The deformation will also alter the gaps between the interconnected parts causing the distortion of their original shape and surface as well as changing their relative position [18].

4.3 Optimization of crankshafts

4.3.1 Crankshaft Optimized Geometry

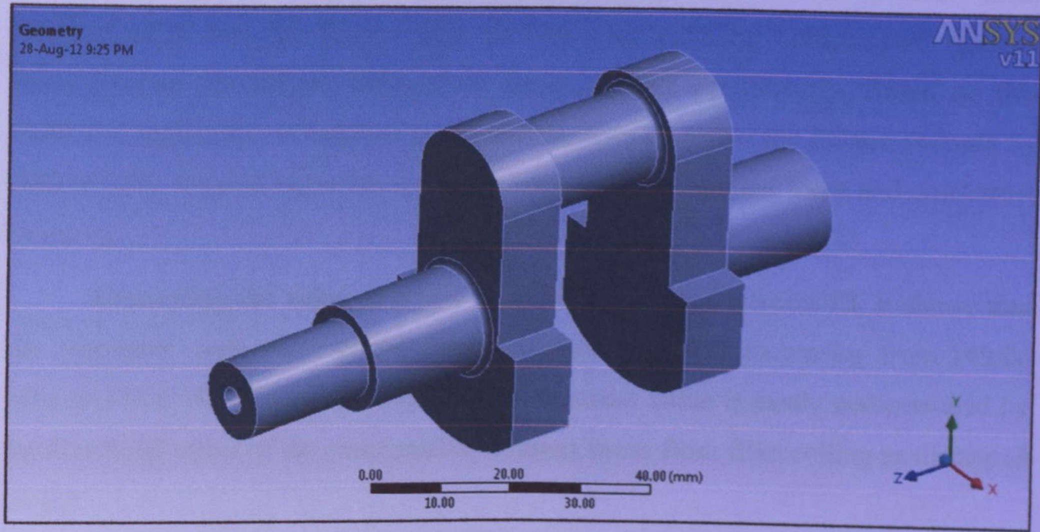


Figure 22: New geometry of crankshaft after shape removal

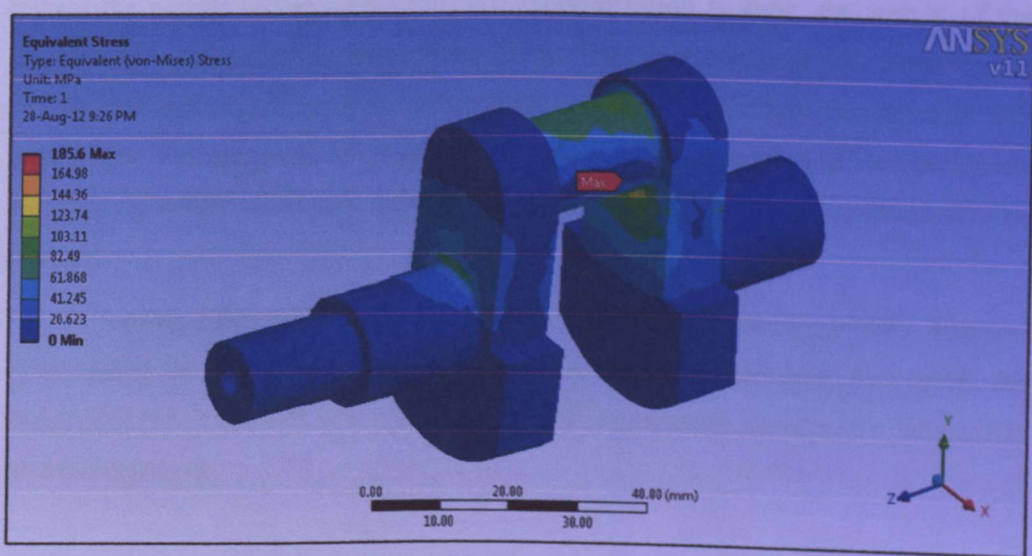


Figure 23: Equivalent (von Mises) Stress of optimized forged steel crankshaft

Figure 22 shows the final optimization of the forged steel crankshaft. From the stress-life estimation and Finite Element Analysis (FEA), the result shows that forged steel crankshaft provides longer fatigue life compared to ductile cast iron. Hence, in this section, only forged steel crankshaft will be considered for optimization purposes.

One of the potential modifications for the improvement and weight reduction of the crankshaft is the addition of compressive residual stress to the fillet area of the crankpin where the stress concentration is maximum and critical area. Montazersadgh and Ali Fatemi [21] showed that inducing compressive residual stress increase the fatigue strength of the crankshaft significantly. Based on this study, the application of residual stress at fillet area increases the fatigue strength by 40% to 80%, depending on the material properties, the applied force and crankshaft geometry.

Comparing the value of stress from **Figure 18** and **Figure 23**, it shows that the maximum stress value of the forged steel crankshaft is increasing from 149.06 MPa to 185.6 MPa. However, this increase in stress value is easily compensated by the beneficial effect of the compressive residual stress from fillet rolling as discussed earlier.

As previously mentioned in Methodology, the objective the optimization is to reduce the weight of the crankshaft. After optimization is done, the weight of the forged steel crankshaft is reduced by 20%. This was achieved by changing the dimensions and geometry of the crankshaft counterweight where the stress in that area is low. The optimization does not change the overall operation of the crankshaft. As the total weight of the crankshaft is reduced by 20%, the overall cost can also be reduced.

Adding fillet rolling was considered in the manufacturing process because fillet rolling can induced compressive residual stress in the fillet area. As a result, the strength of the crankshaft will increase and thus significantly increase the fatigue life of the component.

CHAPTER 5

CONCLUSIONS

1) Crankshaft is used in high cycle performance, thus the stress-life (*S-N*) method is the most appropriate approach in predicting the fatigue-life performance of the crankshafts. This method can be very helpful to test fatigue life but only disadvantage is that the plasticity effect is not considered and provides poor accuracy for low cycle fatigue. However, strain life method provides more detailed analysis involving plastic deformation and useful in low cycle fatigue. Although this stress life (*S-N*) method is the least accurate approach, nevertheless, it is the most traditional method, since it is the easiest to implement for a wide range of applications.

2) Forging process is proved to have better consistency and quality of metal compared to casting process. Casting may be a more economical way to manufacture a crankshaft but the downside of this method is the bubble-trapping problem that may reduce the fatigue strength of the crankshaft.

3) In Finite Element Analysis (FEA) using ANSYS, the critical location is identified to be at the fillet area where it experiences the maximum value of stress. This indicates that fillet area is the area which the failure is likely to occur due to high stress gradient in these locations which result in high stress concentration. Given the same load applied on the forged steel and ductile cast iron crankshaft, the crankshafts with forged steel material shows higher fatigue strength compared to ductile cast iron material and it indicates that forged steel crankshaft offers higher fatigue life.

4) Forged steel crankshaft experience lower maximum deformation compared to ductile cast iron crankshaft at the same applied load. This is preferable because deformation can result in poor engine performance and become less economic.

5) Optimization of the crankshaft reduced the weight of the forged steel crankshaft by 20% and can reduce the overall cost.

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APPENDIX 1: EXAMPLE OF CALCULATIONS

Stress-life method (Cast Iron)

Formula: $\sigma = \sigma_f'(2N_f)^b$

b = -0.087; σ'$_f$ = 927 MPa; σ = 100 MPa;

$$(2N_f)^{-0.087} = \frac{100\ MPa}{927\ MPa}$$

$$= 0.10787$$

$$-0.087 \log 2N_f = \log 0.10787$$

$$\log 2N_f = 11.11586$$

$$2N_f = 1.3057\ X\ 10^{11}\ cycles$$

Strain-life method (Cast Iron - elastic)

Formula: $\frac{\Delta\varepsilon_e}{2} = \frac{\sigma_f'}{E}(2N)^b$

b = -0.087; σ'$_f$ = 927 MPa; E = 178 GPa; $\Delta\varepsilon_e/2$ = 1.00% = 0.01

$$0.01 = \frac{100\ MPa}{178{,}000\ MPa}(2N)^{-0.087}$$

$$(2N)^{-0.087} = 1.9202$$

$$-0.087 \log 2N_f = \log 1.9202$$

$$log\ 2N_f = -3.25678$$

$$2N_f = 5.5363\ X\ 10^{-4}\ cycles$$

APPENDIX 2: STRESS-LIFE DATA

Stress (MPa)	$(2N_f)^b$ (Cast Iron)	$(2N_f)^b$ (Forged Steel)	Log value (Cast Iron)	Log value (Forged Steel)
100	0.107874865	0.08896797	-0.967079734	-1.050766311
200	0.21574973	0.17793594	-0.666049738	-0.749736316
300	0.323624595	0.26690391	-0.489958479	-0.573645057
400	0.431499461	0.35587189	-0.365019743	-0.44870632
500	0.539374326	0.44483986	-0.26810973	-0.351796307
600	0.647249191	0.53380783	-0.188928484	-0.272615061
700	0.755124056	0.6227758	-0.121981694	-0.205668271
800	0.862998921	0.71174377	-0.063989747	-0.147676324
900	0.970873786	0.80071174	-0.012837225	-0.096523802
1000	1.078748652	0.88967972	0.032920266	-0.050766311

Stress (MPa)	Cycle to Failure, $2N_f$ (Cast Iron)	Cycle to Failure, $2N_f$ (Forged Steel)	Log $2N_f$ (Cast Iron)	Log $2N_f$ (Forged Steel)
100	11.11585901	13.30083938	1.30575E+11	1.99912E+13
200	7.65574412	9.490333108	45263081.83	3092666631
300	5.63170666	7.261329829	428259.1592	18252814.04
400	4.195629228	5.679826834	15690.22703	478439.2867
500	3.081721032	4.453117809	1207.038249	28386.88961
600	2.171591767	3.450823555	148.4539533	2823.732517
700	1.402088438	2.603395838	25.23994698	401.2322546
800	0.735514335	1.86932056	5.438940841	74.01513916
900	0.147554307	1.221820276	1.404605313	16.66557398
1000	-0.37839386	0.642611535	0.418413935	4.391486324

APPENDIX 3: STRAIN-LIFE DATA

Plastic Strain

Plastic Strain Amplitude	$(2N_f)^c$ (Cast Iron)	$(2N_f)^c$ (Forged Steel)	Log value (Cast Iron)	Log value (Forged Steel)
0.01 %	0.000495	0.000149	-3.305351369	-3.82672252
0.10%	0.0049505	0.0014903	-2.305351369	-2.82672252
1.00%	0.049505	0.0149031	-1.305351369	-1.82672252
10.00%	0.4950495	0.1490313	-0.305351369	-0.82672252
Plastic Strain Amplitude	**Cycle to Failure, $2N_f$ (Cast Iron)**	**Cycle to Failure, $2N_f$ (Forged Steel)**	**Log $2N_f$ (Cast Iron)**	**Log $2N_f$ (Forged Steel)**
0.01 %	4.74906806	6.409920469	56113.5906	2569925.12
0.10%	3.31228645	4.734878593	2052.51552	54309.8487
1.00%	1.875504841	3.059836717	75.0766423	1147.72203
10.00%	0.438723232	1.384794841	2.74614353	24.2546405

Elastic Strain

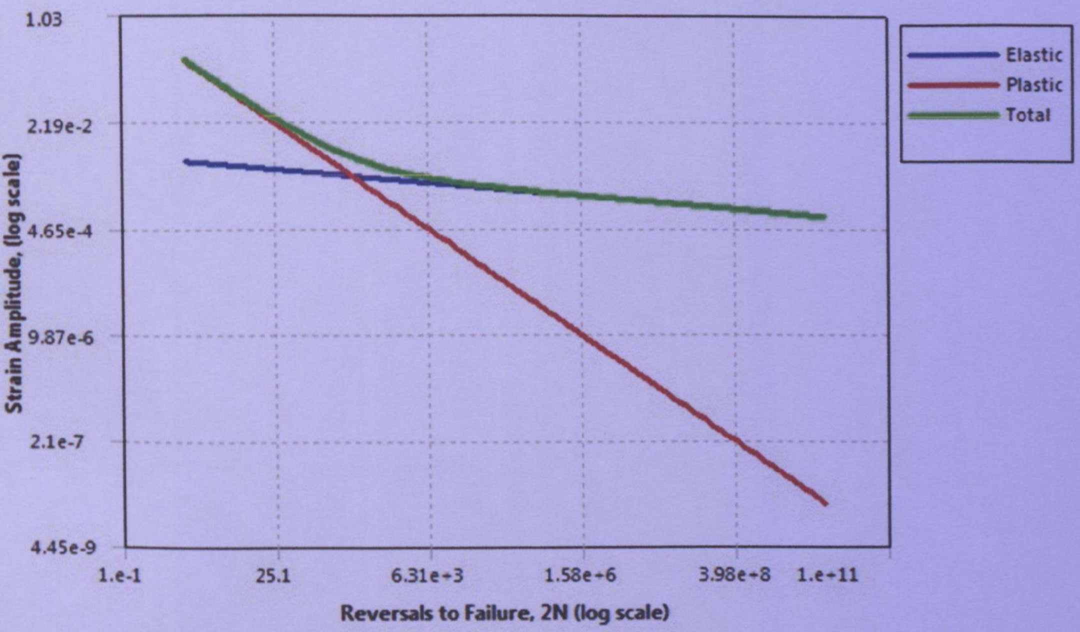
Plastic Strain Amplitude	$(2N_f)^c$ (Cast Iron)	$(2N_f)^c$ (Forged Steel)	Log value (Cast Iron)	Log value (Forged Steel)
0.01 %	0.019201726	0.019661922	-1.717	-1.7064
0.10%	0.19201726	0.196619217	-0.717	-0.7064
1.00%	1.9201726	1.966192171	0.2833	0.2936
10.00%	19.201726	19.66192171	1.2833	1.2936
Plastic Strain Amplitude	**Cycle to Failure, $2N_f$ (Cast Iron)**	**Cycle to Failure, $2N_f$ (Forged Steel)**	**Log $2N_f$ (Cast Iron)**	**Log $2N_f$ (Forged Steel)**
0.01 %	19.73172106	21.59967136	5.39164E+19	3.97806E+21
0.10%	8.237468182	8.941443513	172769939.8	873863325.7
1.00%	-3.25678469	-3.716784335	0.000553625	0.000191962
10.00%	-14.7510375	-16.37501218	1.77404E-15	4.21685E-17

Total Strain

Plastic Strain Amplitude	Total Strain (Cast Iron)	Total Strain (Forged Steel)
0.01 %	5.39164E+19	3.97806E+21
0.10%	172771992.4	873917635.6
1.00%	75.07719592	1147.72222
10.00%	2.746143528	24.25464046

APPENDIX 4: STRAIN-LIFE CURVE OF FORGED STEEL AND DUCTILE CAST IRON MATERIAL USING ANSYS

Cast Iron



Forged Steel