Prediction of Remaining Useful Life for Service-Exposed Industrial Turbine Blade

By

Arthit Saengchot A/L Chali

Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (HONS)

(Mechanical Engineering)

SEPTEMBER 2011

Universiti Teknologi Petronas

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Prediction of Remaining Useful Life for Service-Exposed Industrial Turbine Blade

by

Arthit Saengchot A/L Chali

A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

Approved by,

____

(Dr Aklilu Tesfamicael Baheta)

Project Supervisor

Universiti Teknologi PETRONAS

Tronoh, Perak

September 2011

CERTIFICATION OF ORIGINALITY

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

ARTHIT SAENGCHOT A/L CHALI

ABSTRACT

The project aims to determine the remaining useful life of service-exposed gas turbine blades by conducting an experiment to calculate the creep life. Common practice in the industries is to replace the turbine blade after its useful life has expired which is typically specified by the manufacturers. This practice is very costly and may be considered as a waste of capital if the blade can still be used. By determining the remaining useful life of a gas turbine blade, we can prolong the service life of the blade. Conducting the project will require extensive studies on the basic principle of creep deformation in metal and creep life prediction methods. Larson-Miller Parameter, which is a mean of predicting the lifetime of a material versus time and temperature using a correlative approach based on the Arrhenius rate equation, is used to extrapolate the change in rupture life with test temperature at a given stress level after the accelerated testing for creep rupture is done on the turbine blades samples. Accelerated testing needs to be done by extremely increasing the testing temperature and applied stress, thus, shortening the rupture time because the creep rate for the specimens at low temperature and stress might take a longer time frame than provided by the project time limit. A High Temperature Creep Testing Machine should be used to perform the experiment to provide reliable results and the data gathered from the experiment will be tabulated accordingly to ease the process of determining remaining useful life of the sample. Conclusion of the project will be made after the experiment data is thoroughly analyzed.

ACKNOWLEDGEMENT

This thesis would not have been possible without the support of my supervisor, Dr Aklilu Tesfamicael Baheta. I am grateful for his guidance, encouragement and support from the beginning to the end of the project. I owe my deepest gratitude also to Mr. Shahrizal Jasmani, whose passion for the oil and gas industry has always inspired me and for his kind support all the way from Kerteh. Numerous difficulties was faced during the two semesters, however, these two men has gave me unwavering attention and encouragement. Also, Mr. Zamil who has assisted me in fabricating my samples.

I would like to my family members for providing me unsurpassed support in every form especially when there were nobody to turn to. This project was initially planned to be done in Johor which is a great distance from UTP and a visit to Johor was necessary to determine the condition of the machines involved. I would not have made if not for the financial aid from my parents.

I am also indebted to many of my colleagues for supporting me along the way. Nurul Najat and Hafiz Abu Talib, their expertise and knowledge in material science have assisted me tremendously. Thank you to all who were helping me directly and indirectly throughout the rough period of the project.

Contents

CHAPTER 1: INTRODUCTION

1.1 Background of Study

Utilization of turbines is not uncommon in the engineering industry and has become one of the most essential energy equipment. It is used everywhere to convert energy extracted from a fluid, gas or water, into useful work. At the moment, there are many types of turbine that generates energy from different kinds of fluid such as steam, gas, water and wind. One of the most common is the gas turbine, also known as the combustion turbine which is a type of internal combustion engine. Such turbines typically comprise of a few main components, namely a fan, a compressor, a combustor, an inlet and outlet with nozzle or other possible assemblies. It can be seen on a commercial jet, helicopters, power plants, refineries and even on a surface vehicle. With such a wide utilization, many ideas and research works were initiated to improve to the advancement in technology of gas turbine in every part of its mechanism. Customarily operating under extremely high temperature and stress, the blade of a gas turbine will be subjected to creep, resulting in permanent deformation of the blade. With that, this project will determine a method to predict the creep life of service-exposed industrial turbine blades.

1.2 Problem Statement

Commonly, the manufacturer of all gas turbines will specify the expected useful life of the turbine blades. As a natural consequence of operating at high temperatures and stresses, all turbine blades are subjected to creep which is in time the life-limiting process for all blades exposed. Once the turbine blades have surpassed its expected useful life, replacement would be required. This may be costly for the consumer. Other alternative includes stripping down of the turbine, re-using some parts and maybe even refurbishment. Most metal blades would be melted for recast.

However, not all blades are deformed or broken at the end of its specified useful life. If these blades are still capable of operating under the normal condition for an extended period, replacing them will be a waste of capital.

Presently in PETRONAS refineries, replacing the turbine blades after its specified useful life is a common practice. If it is possible to determine or predict the remaining life of used or service-exposed blades, we can extend its service-life, saving PETRONAS the cost of wasting capital on new replacement blades.

1.3 Objective and Scope of Study

The objectives of this project is to investigate whether turbine blades with expired useful-life can still be used by determining methods to predict its remaining creep life and to determine the duration of the remaining creep life.

The scope of study for this project covers a detailed and thorough study on creep life prediction methods and basic principle of creep deformation in metal. Investigation should also be done on the microstructure changes of metal exposed to creep.

This project will be relevance to the study of turbine blade performance for gas turbine in refineries. It is also relevance to turbine blade manufacturers to determine the most optimum pre-determined service life of a blade. PETRONAS is using numerous gas turbines in its operation and hopefully this project will be beneficial financially for the company.

The feasibility of the project depends highly on the method choose to determine the blade creep life as there will be testing machines or equipments involved. Therefore, extensive studies must be done on the methods available.

CHAPTER 2: LITERATURE REVIEW/THEORY

2.1 Creep

Creep is a type of deformation which causes a solid material to gradually deform permanently under the constant exposure to stress and temperature. It is very much dependent on the surroundings including temperature and ambient conditions. Creep may be described as a time-dependent deformation at absolute temperature greater than half the absolute melting point. This relationship, $\frac{T_{abs}}{T_{mp(abs)}}$, is known as the homologous temperate. Examples to illustrate this point include:

a) Ice melts at 273K and creep at 223K. The homologous temperature can be calculated by dividing 223 with 273 resulting in 0.82 which is greater than 0.50 and is consistent with the definition of creep.

b) Lead or tin melts at 473K and creep at 293K. The homologous temperature results in 0.62 which is still consistent with the definition of creep as it is more than 0.50.

When a material is subjected to high levels of stress below its yield strength for a very long time, creep will occur. It is determined to be more critical in materials that are exposed to high temperature nearing the melting for long term and has always increases as the temperature increases.

The rate of creep deformation is related to the properties of the material, exposure time and temperature and the applied load. As the scale of stress and period increases, the creep might be very large that a component fails to execute its purpose, e.g. a severely deformed turbine blade touches the casing, causing failure in its operation.

It is common for engineers to account for creep when assessing components or equipments operating under conditions of high stresses or temperatures or both. Although the mechanism of creep may or may not be a failure mode, in this project, we will consider creep as a failure that shortens the useful life of the turbine blades [1, 2].

2.2 Effect of Creep on Turbine Blades

The blades of a gas turbine are the component which is accountable for extracting energy from the high temperature, high pressure gas from the combustor. The main limitation of a gas turbine is normally the blades. Naturally as they are operating under extreme conditions, the blades are subjected to creep, which eventually limits the service-life.

In a typical gas turbine service, creep causes the blade to stretch or elongates as a form of permanent deformation. This, in turns will cause the tip of the blade to contact the casing or the non-rotating shroud. This observable fact is known as the “tip rub” and will make it necessary to disassemble the gas turbine for repair or replacement of both the shroud and the blades. To counter this, inspections are done routinely to measure the stretching of the blade to determine if it needs length trimming to refurbish the allowable tip clearance and the blades will be dispose of when the stretch reaches a maximum level.

Provided that the gas turbine is operated within its normal limiting condition, creep failures can be prevented by following the inspection procedure mentioned above. However, if the operating temperatures of the gas turbine are exceeded often, blades will fail by creep [3-5]. Figure 1 shows the findings in a routine inspection of turbine blades.

The service life of a turbine blade is limited by fracture and the increasing accumulation of creep damage [9]. Most materials used at elevated temperature service most probably show evidence of time-dependant deformation and temperature-caused changes in its microstructure. The degradation occurrence consists of either physical deformation or metallurgical damage, severely decreasing the service life of the blades which are located directly in the area of the hot gas inlet [6-8]. Issues concerning the remaining service life have always arisen under assumed further operating conditions [10]. Therefore, an accurate prediction method of the remaining life becomes essential to avoid the occurrence of failure in case a change of operating conditions is necessary or happened by accident. This will provide ample time to come up with an action plan and to avoid unnecessary spending. Other than that, turbine blades are costly to be replaced, giving another important reason to predict the service life [9].

2.3 Creep Life Prediction Methods

The aim in creep designing is to calculate and forecast the behavior over a long term or period. At present, there are three key essential methods which are the stress-rupture, minimum strain rate versus time to failure, and temperature-compensated time [2]. There are two vital rules or assumptions that must be followed, no matter which method is used: 1) test time should be at least 10% of design time and 2) creep and/or failure mechanism must not change with time, temperature or stress. The life fraction rule is used to extrapolate the results obtained from accelerated tests on the actual test conditions [14].

2.3.1 Stress-Rupture Test (SRT)

The SRT measures time to failure at specified stress and temperature. It is the sudden and complete failure of a material held under a definite constant load for a given period of time at a specific temperature. It is also known as the 'brute force method' and the results obtained will be plotted on an applied stress versus time to failure as shown in Figure 2. Although plotting these curves is easy, extrapolation of data can be difficult when the failure mechanism changes as a function of time or stress as shown by the 'bend' in Figure 2 [2, 11, 12].

2.3.2 Minimum Strain Rate versus Time to Failure

This is also known as the creep testing. It measures the dimensional changes of a component subjected to constant elevated temperature and stress. Creep testing is practical for long term applications which are strain limited, i.e. turbine blades. A typical creep testing curve can be seen in Diagram 3. This kind of relation (strain-time) is based on the observation that strain is the deformation caused by accumulated creep damage. Therefore, it can be said that failure will occur when the damage in the material has reaches a critical level which can be predicted using the minimum strain rate and the time to failure using this Equation 1:

$$\dot{\varepsilon} t_f = C \approx \varepsilon_f \quad (1)$$

Equation 1 is known as the Monkman-Grant relation. If a log-log plot of $\dot{\varepsilon}_{min}$ versus t_f is done, we should get a slope of -1 no matter the temperatures or applied stresses for a certain material. We can then predict a time of failure by either measuring the minimum strain at a given stress and temperature or by predicting the minimum strain rate from Equation 2 for the given temperature and stress once the A and Q are determined.

$$\dot{\varepsilon}_{ss} = \dot{\varepsilon}_{min} = A\sigma^n \exp(\frac{-Q}{RT}) \quad (2)$$

Where n is the stress component, Q is the activation energy for creep, R is the universal gas constant and T is the absolute temperature. After finding the minimum strain rate, the time to failure can be found by the Monkman-Grant plot for that particular material. Monkman and Grant proposed technique using extrapolation for high temperature-high stress creep-rupture data based on the connection between steady-state creep rate and rupture life [2, 13].

2.3.3 Temperature-Compensated Time

Gas turbines operating at high temperatures and stress are vulnerable to creep damage, and it will most likely be the main life limiting factor. Because of that, numerous life prediction methods focusing on the correlation between rupture life and creep characteristics have been developed and enhanced. Two of the most well known temperature-compensated time relations are Sherby-Dorn and Larson-Miller parameter.

For the Sherby-Dorn parameter with θ as the temperature compensated time, it is given as:

$$P_{SD} = log\theta = logt_f - \frac{\log e}{R}\frac{Q}{T} \quad (3)$$

Where P_{SD} is the Sherby-Dorn parameter and Q is assumed to be constant independent of temperature and stress. The Sherby-Dorn method is based on a temperature adjusted time parameter and it is derived by considering the expression for the secondary creep strain rate at constant stress. Experiments were done at various temperatures and stresses to determine the times to rupture or failure and activation energy. The result is then plotted as Figure 4 with the stress as a function of P_{SD}. From the graph, the allowable stress for a combination of time to failure and temperature can be determined [2, 15].

As for the Larson-Miller parameter, θ is also the temperature compensated time and is given as:

$$P_{LM} = \frac{\log e}{R} Q = T(logt_f + (log\theta = C)) \quad (4)$$

Where P_{LM} is the Larson-Miller parameter while Q is assumed to be a function of stress only and C is a constant with a value about 20 for most materials. Aside from the different assumptions made in its derivation, the Larson-Miller parameter is very similar to the Sherby-Dorn parameter. It has been shown to give reliable predictions as long as the material microstructure is stable with no changes during the extended exposure of high temperature. However, if microstructure changes occur, the actual test result will be lower than the extrapolated values. The result of the Larson-Miller method can also be plotted to be as Figure 5 with the stress as a function of P_{LM}. The allowable stress can also be found from the curve [2, 16, 17, 18]

CHAPTER 3: METHODOLOGY

The flow chart of the project is shown in Figure 6.

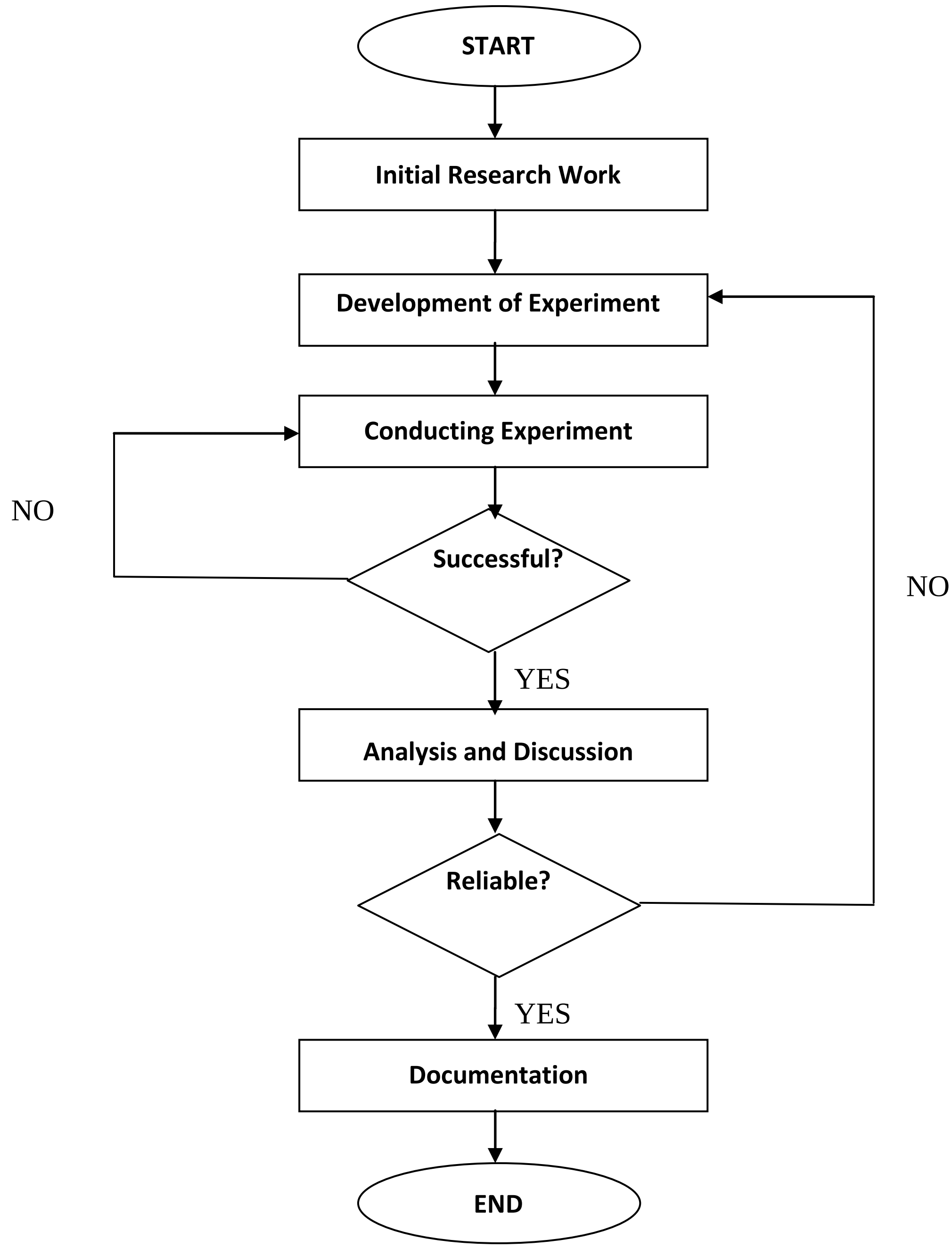

Figure 6: Flow chart of project

3.1 Research Methodology and Project Activities

The research methodology of this project was planned to comprise of five stages with their respective activities. The first stage is the preliminary research works for the projects followed the development of the experiment method. The third stage was planned to be the experiment itself. After the experiment has been done, the results should be analyze and discussed. The last stage of this project is the documentation of every works that has been done.

3.1.1 Initial Research Works

In this first stage, the activities included researching and decision making. Research was done thoroughly on available books and journals relevant to the project. Information needed was recorded in this stage for reference while completing the project. The objective is to fully understand the problem which is shortened service life of turbine blades as a result of creep and the available methods to predict the remaining useful life of industrial turbine blades. From the understanding of the problem, decision was made on the best and most feasible method to be performed for the project.

3.1.2 Project Development

For the second stage, the activities includes deciding the variables after the method of predicting remaining useful life of the turbine blades has been selected. There are many variables to account for the experiment such the material and service-life of blades, temperatures and stress loads. The modus operandi of the experiment should was designed systematically. The tools and machineries needed were identified to be High Temperature Creep Testing Machine (HTCTM) for the creep testing and various machines capable of cutting the turbine blades to prepare the samples. This was also approved by the project supervisor. To proceed with the experiment, a visit to Universiti Teknologi Malaysia in Skudai, Johor was required where the only available

HTCTM is located there.

3.1.2.1 Turbine Blades Received

A few sets of 501-KB7S Rolls-Royce turbine blades were received from Mr. Shahrizal Jasmani, the engineer of PETRONAS Carigali Sdn. Bhd (PCSB). Each set consist of three blades with different dimension according to their stages. The first stage blade is located near the hot air inlet, thus experiences the most damage and is usually shorter than the second and third stage blades. These are used turbine blades that have reached their useful life in the industry and were disassembled from the turbine. With these turbine blades, the author is supposed to investigate how much longer they can actually be used in the industry.

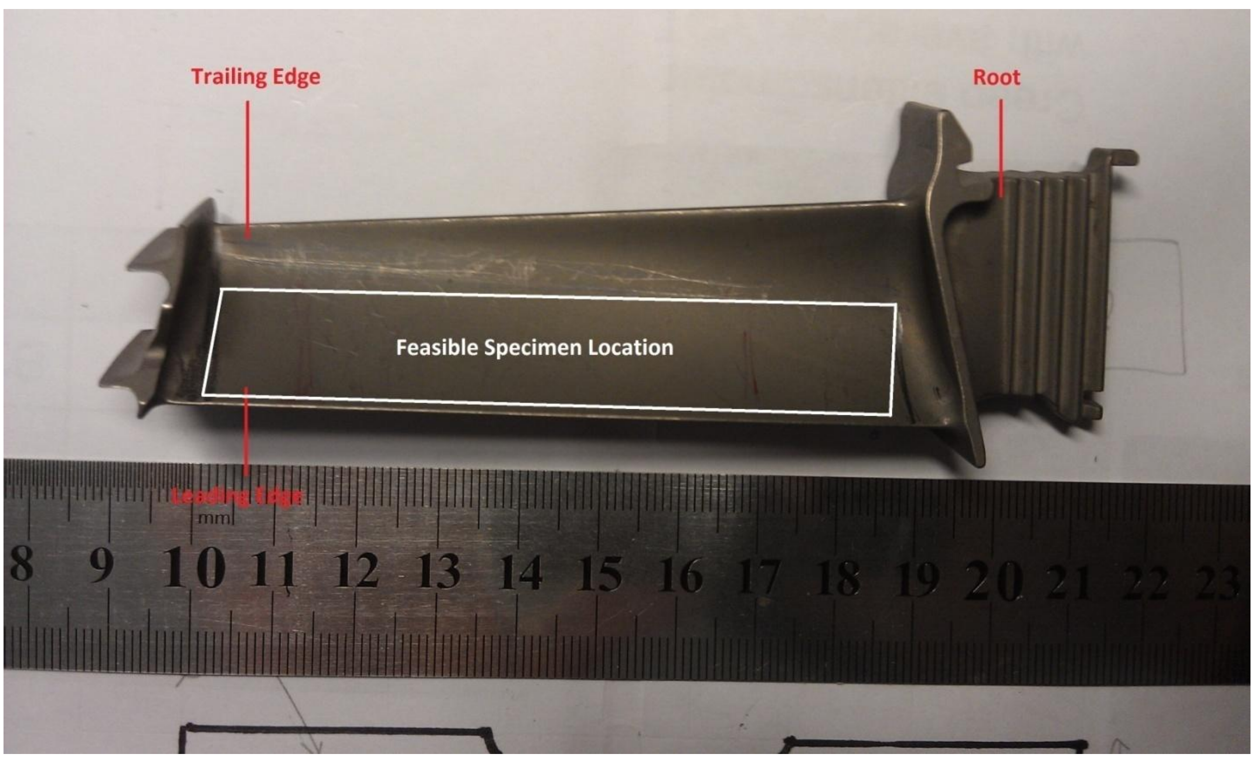

Figure 7: Photograph of third stage 501-KB7S turbine blades

As one can see, each blade consist of three parts namely the root, trailing and leading edge. The overall length is around 125 mm. However, the blade is curvy near the trailing edge. This limits the feasible area for sample preparation where the maximum length of sample that can be prepared from a single blade is only 80 mm.

3.1.2.2 High Temperature Creep Testing Machine (HTCTM)

On the 4th of November, the author has visited Universiti Teknologi Malaysia (UTM) in Skudai, Johor to survey the condition of the high temperature creep testing machine that will be used in this experiment. This machine is the only one available in Malaysia which is still functioning. The purpose of the visit is to learn the capabilities and constraints of the machine before preparing the samples for the experiment.

Figure 8: Photograph of high temperature creep testing machine

The machine consists of five main components which are vital in creep testing experiment. Creep test are usually made at constant load and constant temperature. The load lever allows the user to apply load to the specimens. The machine load lever supports up to approximately 850 MPa. The furnace provides the heat necessary to elevate the temperature of the creep test. The furnace on this machine can reach more than 1000 degree Celsius. This is very excellent and essential in an accelerated creep testing as it reduces the time it takes for the sample to rupture. The grips hold the sample in place in the furnace. They are manufactured to withstand high temperature and to hold standard-sized specimens. The controllers allow the author to calibrate the machine and select the preferred temperature. Another component not included in the photograph above is the extensometer. An extensometer is a device for sensing strain. The extensometer system on this machine senses extension of a gage length that is defined by the specimen feature which is notches. The gage length is the original length of that portion of the specimen over which strain or change in length is determined.

3.1.2.3 Sample Preparation

From the visit to UTM, the required dimension of the samples was determined. There are two types of samples that are suitable for the machine.

Figure 9: Types of specimen; Left side: Dog-bone shape (flat), Right side: Rounded specimen

As the turbine blades available are not very thick, the author is left only with the dog-bone shape option. The dimension of the sample depends heavily on the grip capability. Since, UTM only has one standard set of grips; the sample has to be prepared accordingly. It follows the standard shown in ASTM E8, E139 and also E83. If the specifications in the standards cannot be met, using a sub-standard sized sample will require a custom made set of grips as well. The dimension agreed during the visit was as the photograph below. All samples preparation is done in UTP using the EDM Wire Cut Machine.

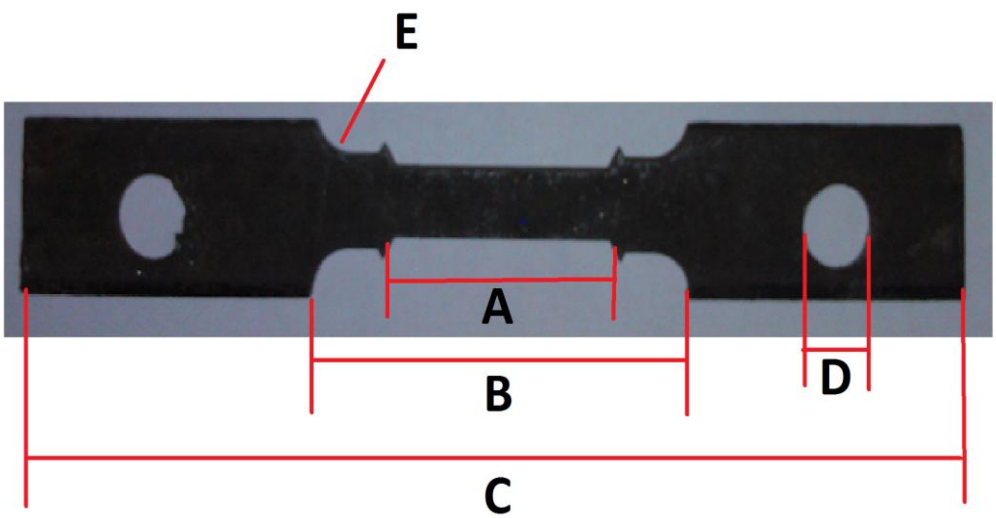

Figure 10: Sample Dimension Guidelines

A: Gage Length = minimum 10 mm

B: Length Between Collars = A + 12.7 mm

C: Total Length = minimum 100 mm

D: Diameter of hole = maximum 8 mm

E: Groove radius = 6.35 mm

Note: The notches for the gage length are made at 60 degree angle to fit the extensometer

The steps taken to prepare the samples are as the following:

1. Glue a flat metal base to the root of the blade. This is to ensure the angle of the blade is 90 degree to the wire that will be cutting it. Cyanoacrylate Acid Eser Type CA 1494 was used.

2. When the glue dried and the position of the blade is fixed, the same metal base was welded to the root of the blade. This strengthens the blade position to avoid disconnection during the vibration of the wire cutting machine.

3. After the weld has cooled off, the wire cutting can be done. The dimension of the final product has to be drawn using AutoCad and loaded into the EDM Wire Cut machine to create code of instructions.

4. Next the grip holes have to be fabricated using the EDM Drilling machine available in the same lab. The machine uses an electrode to penetrate the surface of the blade. Proper marking on the blade has to be done as the machine is operated manually. This leaves a margin for error.

5. Once the hole big enough for a wire to go through was penetrated on the blade surface, the EDM Wire Cut machine is once again used to create accurate 8mm grip holes.

6. All steps were repeated to produce 3 samples.

3.1.2.4 Microstructure Analysis

To study the microstructure of the used blades, a sample for microstructure analysis was also prepared using the remaining of the blades from preparing the dog-bone sample. One sample was fabricated to be analyzed using a Field Emission Scanning Electron Microscope (FESEM). FESEM produces clear microstructure images of the sample using a field-emission cathode in the electron gun of a scanning electron microscope. The objective is to detect the elements present in the used turbine blade besides investigating its material. The result can also be compared to a new blade or even the ruptured blade after creep testing to see the differences or changes.

One sample was prepared for FESEM with the following steps:

1. A 5mm x 5mm square was cut from the remaining of the turbine blade from the previous sample preparation.

2. The square specimen was place inside an Auto Mounting Press machine and mounting powders were added and the machine was operated. This mounting process is important to provide a comfortable way to hold the specimen while it is being grinded and polished.

3. Next, the specimen was grinded at different grits until a mirror-like effect was achieved on the specimen. It was started by using a very fine (P240) grits followed by extra fine (P600) and super fine (P1200) and ultra fine (P4000).

4. Once the mirror effect was achieved, the sandpaper was replaced with polishing cloth and diamond polishing was conducted. Polishing was done to remove the damage introduced by previous steps. Diamond powder was used as an abrasive to achieve the fastest material removal and the best possible flatness.

5. The last step is etching. This is to cut into the unprotected parts of the metal surface. This will allow FESEM to achieve the best image. The etchant used was marble solution.

3.1.3 Conducting the Project Experiment

The process of the experiment may be described as the following:

1. Receive turbine blades sample from PETRONAS.

2. Prepare and shape three (3) samples from the blade to be suitable for the experiment. The turbine blade will be shaped into roughly 16x80 mm overall dimension.

3. Obtain permission to use the HTCTM in UTM Skudai, Johor.

4. Conduct experiment for three (3) samples with different temperature and constant stress. Value of temperature and stress has to be set according to the capability of the machine. However, the values must be set as high as possible to promote accelerated testing.

5. Using a minimum of two results, constant C can be calculated by using this formula:

$$C = \frac{T_2 log t_2 - T_1 log t_1}{T_1 - T_2} \tag{5}$$

6. The value of C can be used to complete the Larson-Miller Equation:

$$P = T(C + \log t_R) \tag{6}$$

7. The last step is to plot the stress rupture test graph for all the six samples and converting the graph into stress versus Larson-Miller Parameter, P plot. Therefore, the change in rupture life with test temperature at a given stress level can be evaluated using the Larson-Miller parameter.

3.1.4 Analysis of Project Results and Discussion

Due to incompatibility between the blades received and the specification of the only creep testing machine available, the experiment cannot proceed. The HTCTM is a machine that allows the user to conduct creep testing at high temperature and stress. This is in line with the condition of the experiment and therefore it is needed to complete the project. In Malaysia, the machine is only available in Universiti Teknologi Malaysia (UTM) in Skudai, Johor.

As shown in the dog-bone sample guidelines provided by the staff in UTM, the minimum total length of the sample has to 100 mm. However, the turbine blade that was provided to the author is a tad bit too short. The maximum total length that can be fabricated using the turbine blade is only 80 mm.

Therefore, the author can only explain in details how the Larson-Miller parameter can be used to predict the remaining life of the used turbine blade under a few necessary assumptions. The discussion on this matter can be found later in the expected results and discussion section.

3.1.5 Documentation of Result

The thesis was produced after all works and activities along the project was documented in an orderly fashioned. They will be the references in concluding the project.

3.2 Machines and Hardware/Raw Material Used

Table 1: Components and hardware table

Components or hardware	Functions/purposes
HTCTM	Used to perform creep testing on the turbine blades under high temperature and stress.
Extensometer	Used to measure small or big changes in the length or strain of the sample.
EDM Wire Cut	Used to cut the strong turbine blade into the dimension required to prepare the dog-bone sample.
EDM Drilling Machine	Used to penetrates the surface of the sample, allowing the Wire Cut machine to fabricate a circle or hole
Cyanoacrylate Acid Ester	Used to temporarily position the turbine blade on a metal base before welding
Welding Machine	Used to fix the position of the blade on the metal base
FESEM	Used to provide microstructure images of the sample and providing the elements present in the blade

Auto Mounting Press	Used to mount the square metal piece on another material to allow comfortable grip on the specimen while grinding and polishing
Grinding/Polishing Machine	Used to perform mechanical preparation of microstructure analysis samples for microscopic examination. Provides the necessary finish for FESEM reading.
Marble Etchant	Used to cut into the unprotected parts of the metal surface to provide the best surface for FESEM reading

CHAPTER 4: DISCUSSION AND EXPECTED RESULTS

This section will discuss the result of the FESEM readings and explain the use of Larson-Miller parameter in predicting the remaining life of the turbine blades. Assumptions will be made to ease understanding in the creep testing analysis.

4.1 FESEM Results

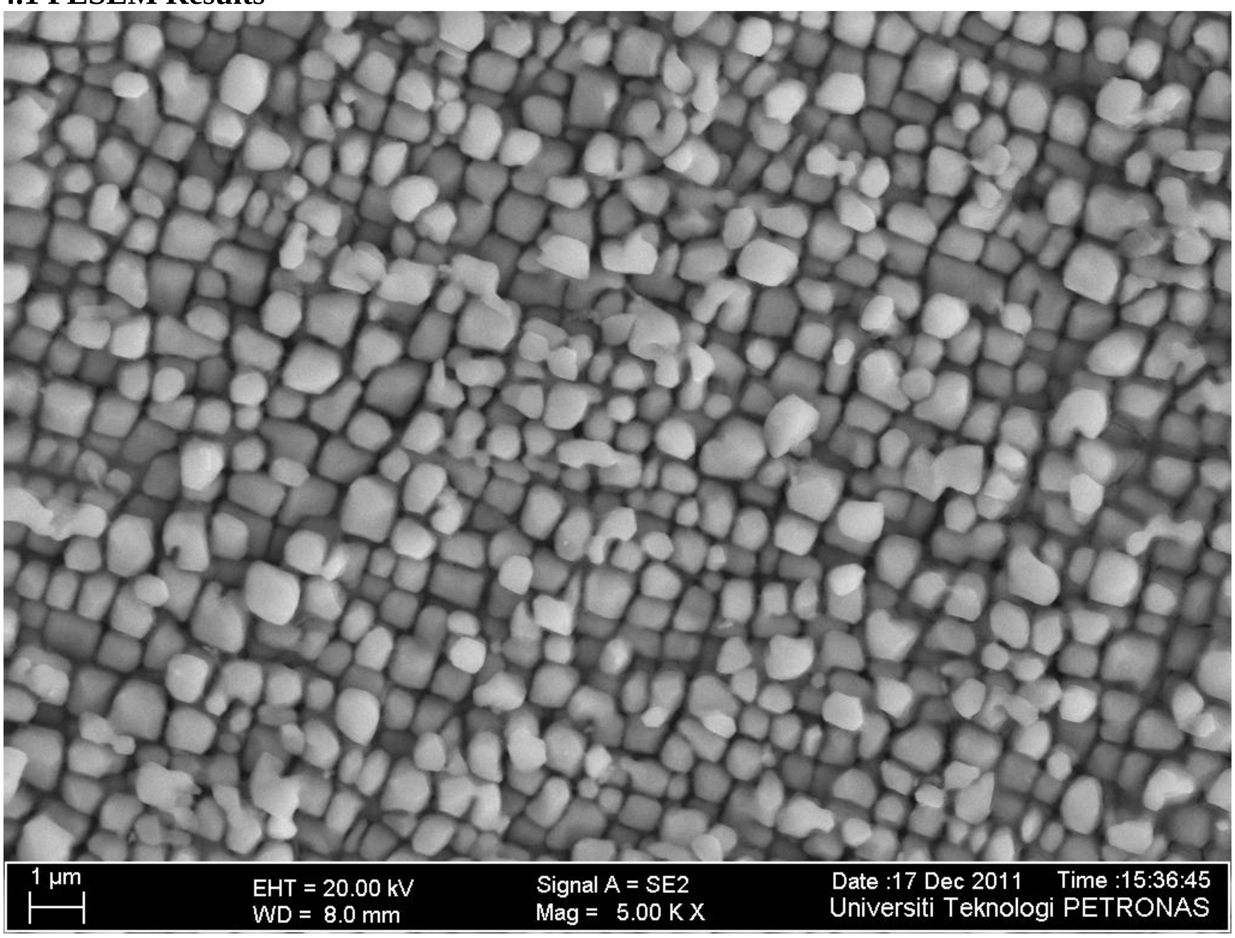

Figure 11: FESEM Microstructure Image

Table 2: FESEM Elements distributions in blade

Element	Weight %	Atomic %
C K	-0.30	-1.22
O K	8.32	25.11
Al K	4.60	8.23
Cl K	1.84	2.50
Ti K	0.84	0.84
Cr K	8.49	7.88
Co K	8.87	7.26
Ni K	53.63	44.10
Cu K	3.40	2.58
W M	10.31	2.71
Totals	100	

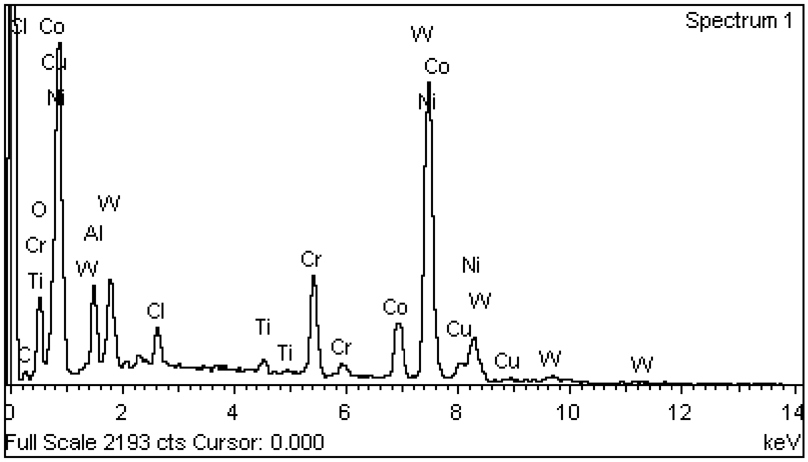

Figure 12: FESEM Elements distribution on a plane

The table shows that more than 50 percent of elements in the blade are Nickel, giving the author an idea that the blade is made of Nickel-based super alloy. After investigation by comparing the result of FESEM with journals, it was concluded that the type of alloy used to manufacture the blade is PWA 1480 or also known as Alloy 454 or Inconel 617 [19]. It is a type of first-generation single-crystal alloys. It is suitable to be used in high temperature and high pressure environment because its corrosion and oxidation resistant is very high. Inconel 617 is preferred over aluminum or steel for high temperature service because it maintains its strength over a wide range of temperature, which retards the creep rate. The table below shows the tensile properties of Inconel 617:

Table 3: Tensile Properties of Inconel 617 [20]

Property	Inconel 617
Elastic Modulus (GPa)	120
Yield Strength (MPa)	1020
Ultimate Tensile Strength (MPa)	1110

4.2 Creep Testing Analysis

The Larson-Miller parameter equation is given as equation (6) such that:

$$P = T(C + logt_R) \tag{6}$$

P is the Larson-Miller parameter for a particular material. T is the temperature in Kelvin. t_R is the creep rupture life in hours. C is a coefficient and the value is dependent on the material used for creep testing. However, in a Larson-Miller study done, data for some 40 materials was evaluated and it was found that the value of constant C was very close to 20 for all materials [21]. Therefore, we can assume C to be 20 and equation (6) can be rewritten as:

$$P = T(20 + logt_R) \tag{7}$$

The temperature used in the equation must be equal to the operating temperature of the turbine. We can estimate temperature using the data given in the figure below:

		Power (ISO)	PT Speed	Fuel Rate	Thermal Efficiency %	Overall Weight (GG & GT)	GG Compression Ratio	GG Compressor Stages	GG Turbine Stages	Exhaust Mass Flow	Stack Temp
		bhp kw	rpm	Btu/hph kJ/kWh		lb kg				lb/sec kg/sec	°F °C
Mechanical Drive	501-KC5	5,500 4,100	13,600	8,495 12,170	29.6	25,000 11,400	9.4:1	14	2	31.2 15.5	1060 571
	501-KC7	7,400 5,500	13,600	7,902 11,340	31.7	26,000 11,800	13.5:1	1+14	2	46.2 20.9	968 520
Electrical Generation	501-KB5	– 3,938(e)	14,600	11,626 12,266		35,000 15,875	9.4:1	14	2	33.9 15.4	1040 560
	501-KB7	– 5,300(e)	14,600	10,787 11,380		36,000 16,329	13.5:1	1+14	2	46.6 21.1	934 501
	501-KH5*	– 6,420(e)	14,600	8,559 9,037		36,000 16,329	9.4:1	14	2	40.5 18.3	986 530

*steam injected

Figure 13: Specifications of 501-KB7 gas turbines [22]

$$Q = c_p \times \dot{m} \times (T_i - T_s) \tag{8}$$

Where Q is the power of the turbine in Kilowatts and C_p is the air specific heat capacity which equals to 1.006 kJ/kg^{o}C. $\dot{m}$ is the mass flow rate of the air entering the gas turbine. T_s is the stack temperature, given in the figure above which equals to 501^{o}C. We can calculate T_i, the operating temperature of the turbine.

$$5300\ kW = 1.006 \frac{\text{kJ}}{\text{kg°C}} \times 21.1\ \frac{\text{kg}}{\text{s}} \times (\text{T}_\text{i} - 501\text{℃})$$

$$T_i = \frac{5300\ kW}{1.006 \frac{\text{kJ}}{\text{kg°C}} \times 21.1\ \frac{\text{kg}}{\text{s}}} + 501\text{℃}$$

$$T_i = 750\text{℃}$$

Next, we have to find the stress value or the load on the blade while it is operating. Turbine blades are subjected to high stress from centrifugal force. Thus, to account for stress, we must first determine the centrifugal force.

$$F_c = \frac{mv^2}{r} = \frac{m(\omega r)^2}{r} = m\omega^2 r \tag{9}$$

where F_c is centrifugal force in N

m is mass of the blade in Kg

v is speed of the blade in m/s

ω is rotational speed of the blade in rad/s

r is radius from the hub to the tip of the blade in meter

From the formula we can observe that the smaller the radius, the bigger value of centrifugal force. Meanwhile, stress is equals to force over the area of the blade. This means that the stress is highest at the root section of the blade. On another note, the centrifugal can be calculated if the author has the mass, speed and radius of the blade. Speed can be calculated as well if the rotational speed of the blade is available.

$$\sigma = \frac{F_c}{A} \tag{10}$$

where $\boldsymbol{\sigma}$ is stress in MPa

Fc is centrifugal force in N

A is section area of the blade in m^2

Using the Larson-Miller parameter plot versus stress of Inconel 617, we can compute the time of failure of the turbine blade for different stresses. The figure below shows the Larson-Miller parameter data for Inconel 617 with comparison to other types of materials.

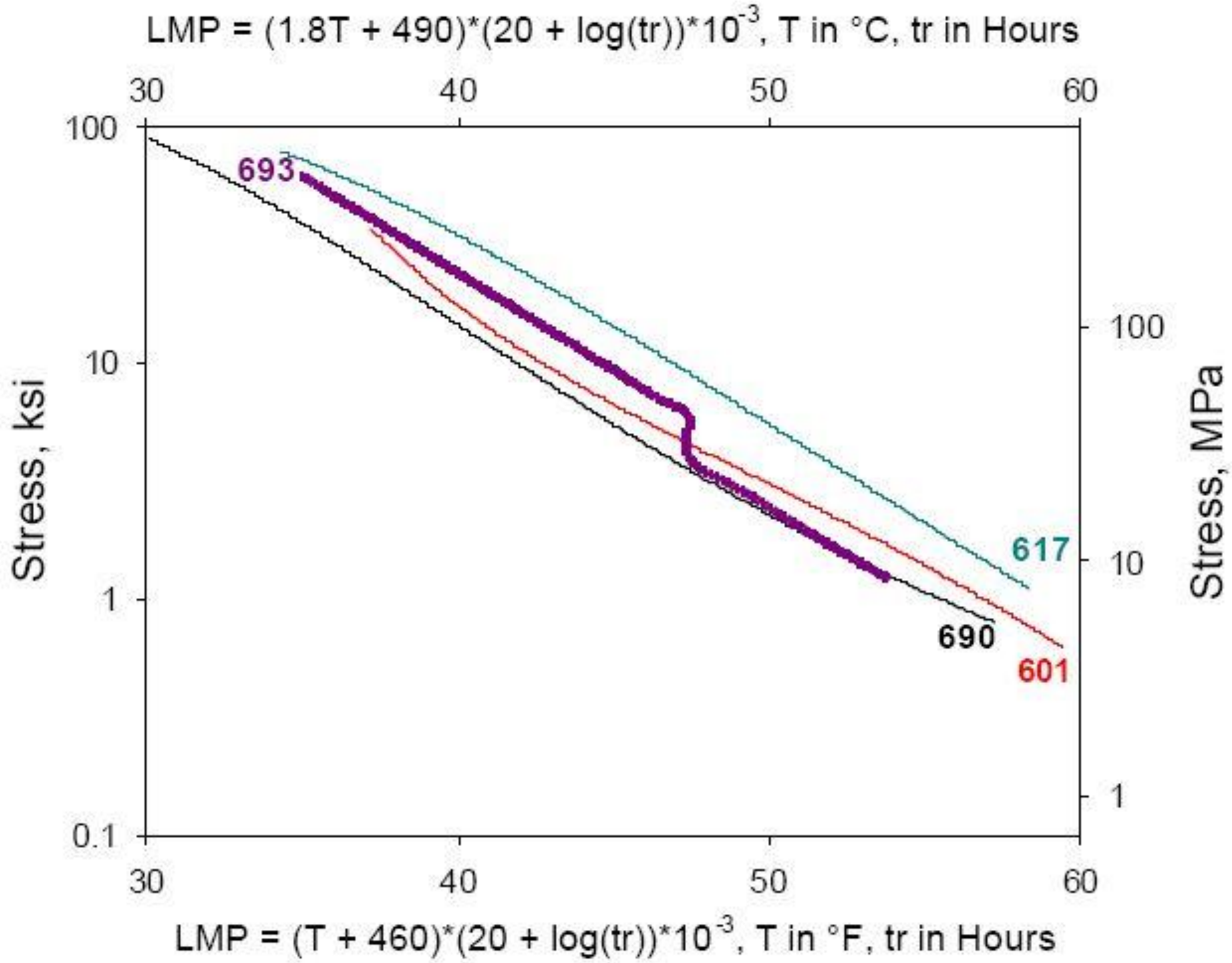

Figure 14: Creep rupture property comparison using the Larson-Miller parameter [19]

Using the Figure 14, we can calculate the rupture time of turbine blade by using the Larson-Miller parameter equation. As an example, the LMP value at stress equals to 100 MPa is approximately 44.8. Taking T to be equal to 750 ^{o}C as we calculated earlier, we can fill in the data in the equation to compute time of rupture. The result will yield approximately 22054 hours. This means that the turbine blade will take almost two and a half years before breaking when it is creep tested at 750 ^{o}C while 100 MPa load is applied to it. Times to rupture for different level of stresses were calculated and are shown in the table below.

Table 4: Time to rupture calculated according to stress value

Stress, σ, MPa	100	200	300	400	500	600	700
Time to rupture, t_r, hours	22054.00	652.60	42.27	10.07	3.10	0.44	0.07

We see from the Table 4 that the time to rupture decreased rapidly as we steadily increase the stress applied on the blade. The results obtained above can be used to predict the remaining useful life of a turbine blade by knowing the hours it has spent on service, $t_{serviced}$ by using the equation below:

$$Remaining\ Useful\ Life = t_r - t_{serviced} \tag{11}$$

It must be noticed that the results obtained in this project is preliminary. A stress-rupture creep testing should be done to obtain a more reliable results. From a stress-rupture test, a plot of stress versus time to rupture can be used to plot a Larson-Miller parameter data such as Figure 14 and the remaining useful life of the turbine blade can be computed using the Larson-Miller equation.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The turbine blade is expensive but strong equipment. It was design to withstand high heat and stress. Replacement of turbine blade can be wasteful if the blade can still be used. By conducting the experiment, it is expected that we can plot the temperature-rupture testing results before changing it into stress versus Larson-Miller Parameter plot. The most important variables are the stress and temperature and the initial condition of the blade, in term of hours-of-service.

With the application of Larson-Miller Parameter, it is expected that the parameter can be used to extrapolate results obtained from the temperature-rupture test to allow us to predict the remaining useful life of a turbine blade. The results should give us the value of Larson-Miller Parameter which can be used to calculate the predicted rupture time if the temperature is known. The rupture time of the blade samples should decrease with increasing load of stress and temperature. With increment in the blade service life, it is likely that the rupture time of the blade decrease. It is the author's belief that if the experiment can be conducted with reliable source of data, the remaining life of a turbine blade can be predicted. Thus, allowing it to be used until its optimum lifespan to avoid wasting.

5.2 Recommendations

In the future if the experiment was conducted, microstructure analysis of the blade samples after creep testing should be included as well. Since the chemical composition of materials of the blades was already examined before the creep test has been done, we can compare the differences in term of microstructure between before and after creep testing. Other than that, if it is feasible, a sample of new turbine blade can be prepared for both creep testing and microstructure studies. This will act as a baseline data for comparison and more accurate data.

Since there is only one high temperature creep testing machine available, we should use a suitable blade to conduct the experiment to avoid complication in fabricating the dog-bone sample. Longer and bigger sized blades are preferred over the current blade that was used.

Besides using the Larson-Miller parameter method, there are also many other time compensated method to predict the remaining life of a turbine blade. Perhaps, these methods can be utilized to predict a better result than Larson-Miller or just for comparison.

Creep testing is known to take a lot of time. Even if accelerated testing is done, it can take weeks or more than a month before a sample rupture under a certain conditions. And fabricating the sample takes time as well. So, it highly advised that the creep testing be started in the first half of FYP as the duration of the project is shorter compared to previous semester due to the shorter semester break that can be used as experiment time as well.

REFERENCES

[1] Creep (Deformation), http://en.wikipedia.org/wiki/Creep_%28deformation%29#Applications

[2] Paul E. Labossiere, "Mechanics of Materials Laboratory, Chapter 8, Time Dependent Behavior: Creep", http://courses.washington.edu/me354a/chap8.pdf

[3] Boyce, Meherwan P. (2006), "Chapter 9: Axial Flow Turbines and Chapter 11: Materials Gas Turbine Engineering Handbook (3rd Edition)". Oxford: Elsevier. ISBN 9780750678469.

[4] Turbine Blade, http://en.wikipedia.org/wiki/Turbine_blade

[5] ScienceDirect, "Engineering Failure Analysis, Volume 12, Issue 2, April 2005, Pages 237-247. Tim J.Carter, Common failures in gas turbine blades".

[6] T.M. Maccagno, A.K. Koul, J.P. Immarigeon, L. Cutler, R. Allem and G. Lesperance, "Microstructure, Creep Properties and Rejuvenation of Service-Exposed Alloy 713C Turbine Blades", Metall. Trans. A

[7] J.A. Brown, R. Freer and A.T. Rowley, "Reconditioning of Gas Turbine Components by Heat Treatment", ASME J. Eng. Gas Turbine Power

[8] R. Viswanathan, "Damage Mechanisms and Life Assessment of High-Temperature Components", ASM International

[9] B. Walser, "Heat and Mass Transfer in Metallurgical System", p.673

[10] R. Castillo, Nickel Metallurgy, vol. 1, p.261

[11] Creep and Stress Rupture, http://www.materialsengineer.com/CA-Creep-Stress-Rupture.htm

[12] Stress Rupture Testing and Creep Testing, http://www.storksmt.com/Stork/18103/Stress_Rupture_Testing_Creep.html

[13] Dieter, G.E., Mechanical Metallurgy, 1988, SI Metric Edition, McGraw-Hill

[14] R. Castillo, A.K. Koul, E.H. Toscano, J. Eng. Gas Turbines Power 109

[15] R. Orr, O.D. Sherby and J.E. Dorn, Correlation of Rupture Data for Metals at Elevated Temperatures, Trans. ASME

[16] A.K. Koul and R. Castillo, Assesment of Service Induced Microstructural Damage and Its Rejuvenation in Turbine Blades, Metall. Trans. A, p 2049-2066

[17] G. Marahleh, A.R.I. Kheder and H.F. Ahmad, Creep-Life Prediction of Service-Exposed Turbine Blades, Mater. Sci. Eng. A, 2006, p 305-309

[18] R. Castillo, Proceedings of Conference on Nickel Metallurgy, vol.1, p.261

[19] B. A. Baker, V. W. Hartmann, "A New Nickel-Based Alloy for Resisting Metal Dusting Attack"

[20] Michael R. Mitchell, "Cyclic Deformation, Fracture and Nondestructive Evaluation of Advanced Materials", ASTM International, 1992

[21] Mohammad Vaezi, Masoud Soleymani, "Creep Life Prediction of Inconel 738 Gas Turbine Blade", Journal of Applied Sciences 9(10): 1950-1995, 2009

[22] Rolls-Royce, Fact Sheet, 501-K Gas Turbines for Oil & Gas Application

APPENDICES

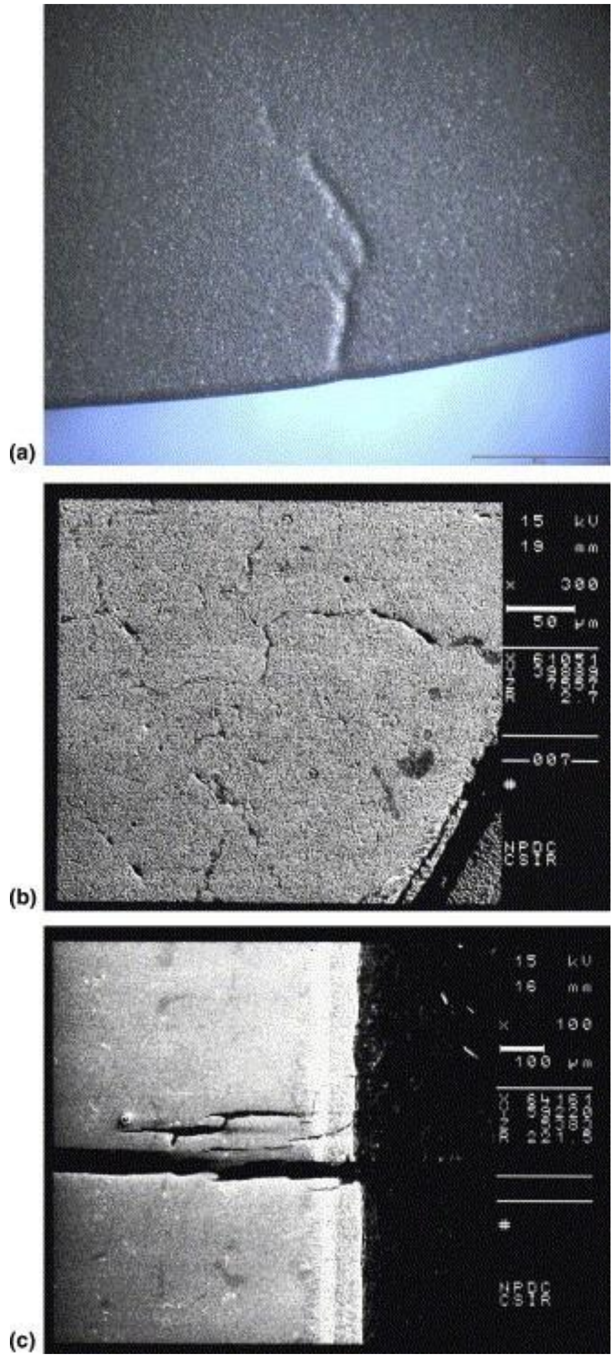

Figure 1 (a) Creep damage observed during routine inspection; (b) grain boundary separation found on metallographic examination of the same blade; (c) appearance of creep cracking in a directionally solidified blade material [5].

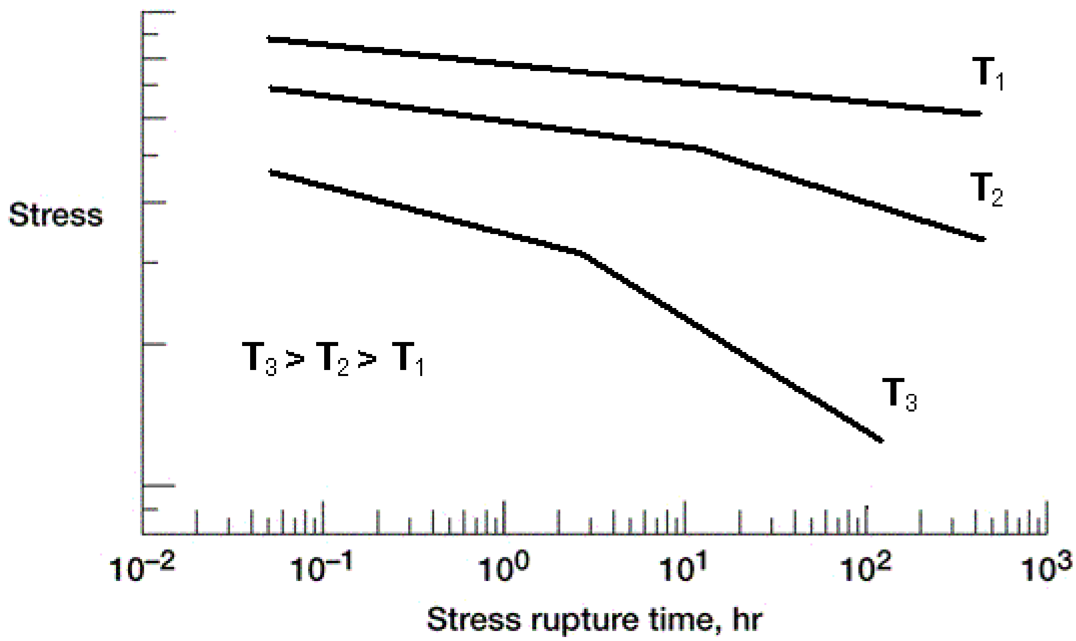

Figure 2: Stress versus rupture time plot [11]

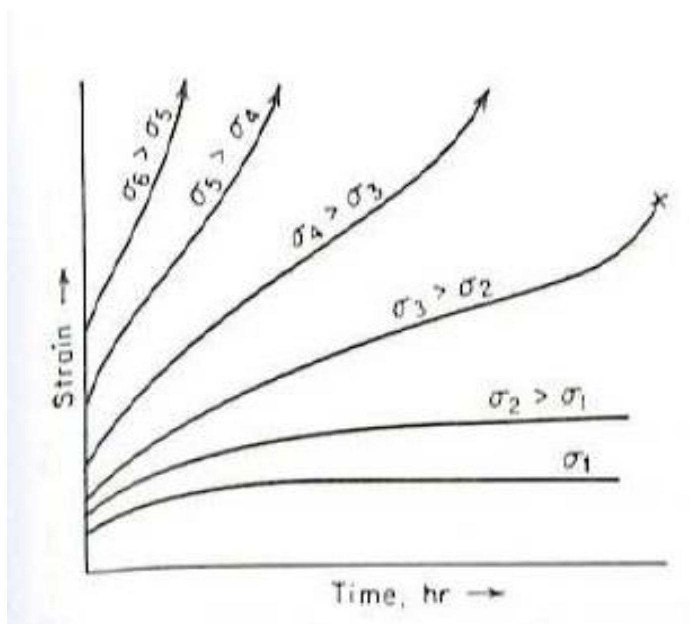

Figure 3: Creep Testing Curve

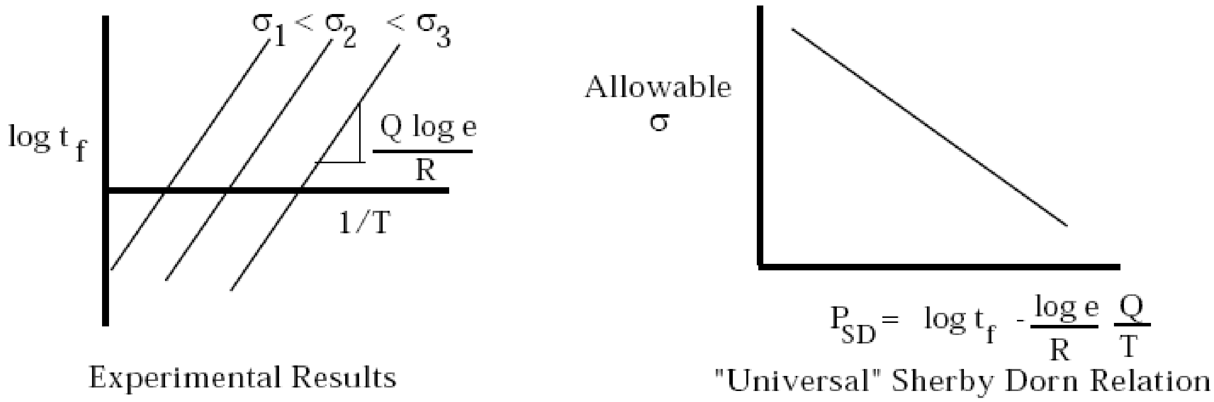

Figure 4: Sherby-Dorn Relation [2]

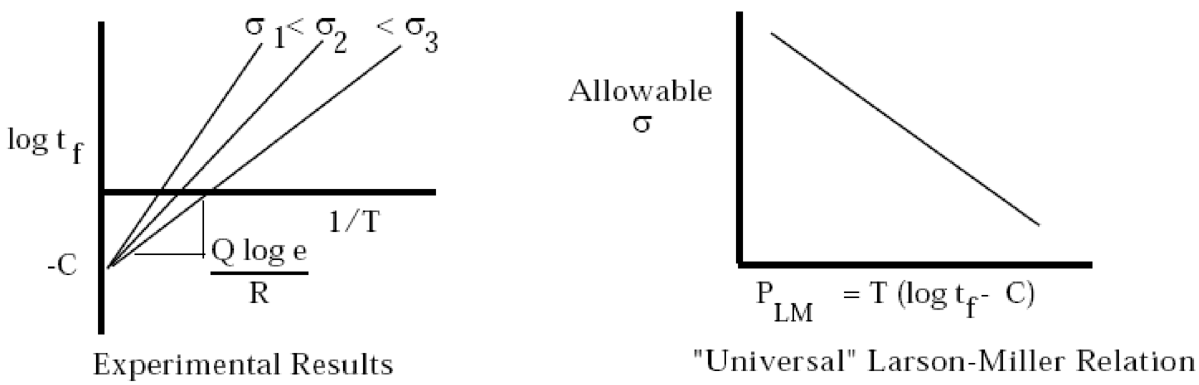

Figure 5: Larson-Miller Relation [2]

Figure 14: Turbine blade glued to a metal cube using cyanoacrylate acid ester

Figure 15: Welding of the blade to the metal cube in progress

Figure 16: EDM Wire Cut machine

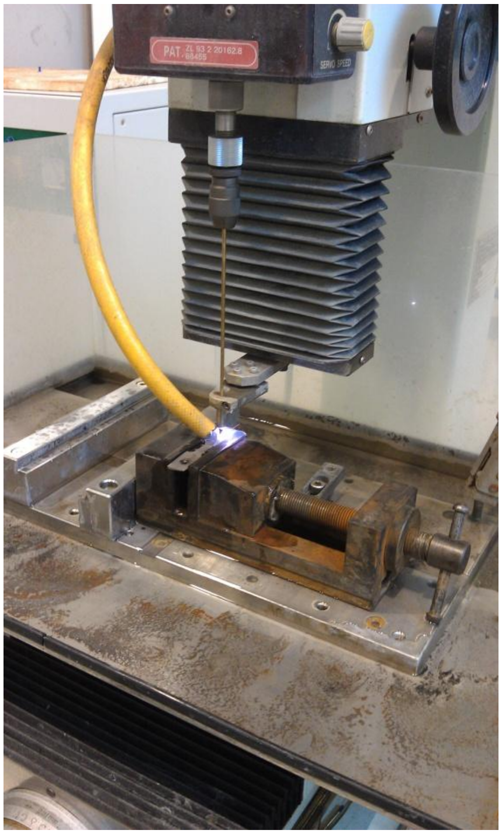

Figure 17: EDM Drilling machine

Figure 18: Auto Mounting Press machine

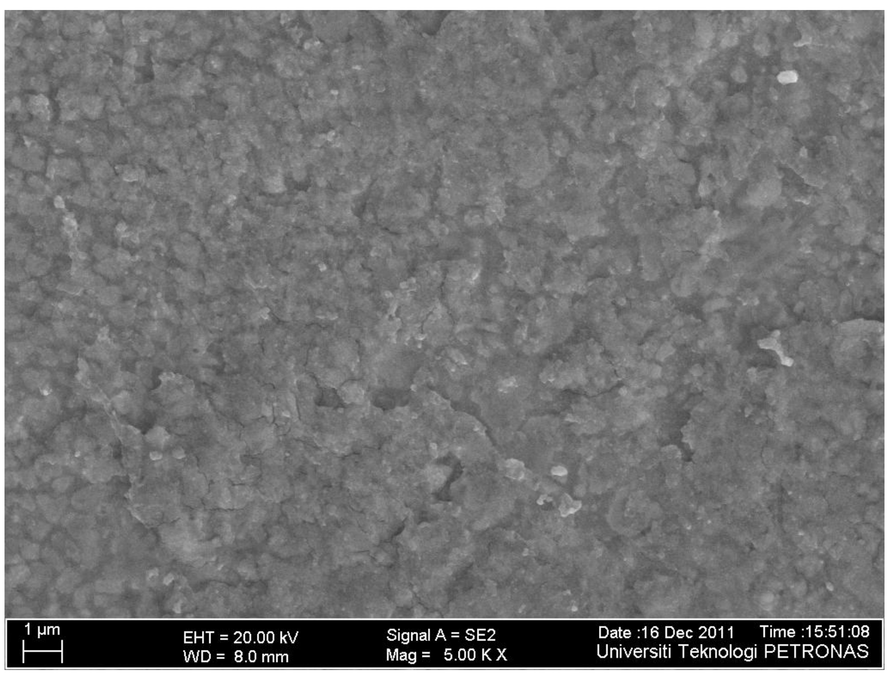

Figure 19: Over-etched FESEM image

Alloy	Ni	Cr	Fe	Si	Al	Other
INCONEL alloy 693	62	29	4	-	3.1	Nb, Zr, Ti
INCONEL alloy 601	60.5	23	13	0.2	1.4	-
INCONEL alloy 690	59	29	9	0.1	0.3	-
INCONEL alloy 617	55	22	1	0.1	1.2	12.5 Co, 9.7 Mo
INCOLOY® alloy 800/800HT	32	21	45	0.1	0.4	0.4 Ti
INCOLOY alloy MA956	-	20	75	-	4.5	0.5 Y_2O_3, 0.5 Ti
INCONEL® filler metal 82	73	20	1	-	-	2.5 Nb, 3 Mn
INCONEL filler metal 52	59	29	9	0.1	0.8	0.5 Ti
INCONEL filler metal 72	56	43	0.3	-	0.1	0.6 Ti

Figure 20: Nominal Composition (Weight %) for Commercial Alloys