INVESTIGATION OF REMAINING USEFUL LIFE OF GAS TURBINE BLADE

by

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14760

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
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Approved by,

(Dr Mior Azman bin Meor Said @ Mior Said)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
January 2015

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.

MUHAMMAD HAFIZUDDIN BIN OSMAN

ABSTRACT

The aim of this research is to investigate the remaining useful life of gas turbine blade. This investigation was done by predicting the turbine blades service life using Stress Rupture Test (SRT) under accelerated test conditions where the applied stresses to the specimen is between 400 MPa to 600 MPa and the test temperature is 850^{o}C. The study will focus on the creep behaviour of the 52000 hours service-exposed blades. The test specimens - made up of Ni-based superalloy of the first stage turbine blades - are machined based on International Standard (ISO) 204. The results from the SRT will be further analyzed using these two main equations – Larson-Miller Parameter and Life Fraction Rule for remaining useful life analysis. Based on the results of the remaining useful life analysis, the 52000 hours service-exposed blade has the condition to operate until up to another 11911 hours.

ACKNOWLEDGEMENTS

First of all, I would like to thank Allah SWT (The Almighty), for His countless guidance and blessing throughout this period. In addition to that, I would like to thank to my family, friends and supervisor for the encouragement, support and making me believe that I can complete the tasks within the given time.

Certainly, my Final Year Project (FYP) could not has been successful without UTP Supervisor, Dr Mior Azman bin Meor Said @ Mior Said who contributed a lot to my FYP progress. He has not only served as my supervisor but also patiently guided me throughout the project, never accepted less than my best efforts.

Besides, a special gratitude to Mr Azwan, Research/Test Engineer at TNB Research in Bangi who helped me a lot to conduct the experiment at TNB Research due to unavailability of the SRT Machines in UTP. I am also indebted to Mr Luthfi, the staff of Alta Precision Engineering Sdn Bhd who helped me to prepare the sample specimens for conducting the SRT by using Wire Cut Machine. Lastly, thank you to all who helped me directly or indirectly throughout the rough period of the project.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

Turbine is a type of rotary mechanical equipment that is essential especially in the engineering industry and has become one of the main energy equipment for the power generation. There are many types of turbine that generates energy from different kinds of moving fluid such as gas, steam or water. Nowadays, gas turbine, also known as combustion engine, is one of the most widely used power generating technologies [1]. Gas turbine is widely used in oil and gas industry, power plant, and even in surface vehicles, such as cars, trains, tanks and marine application [2]. As a reason of wide utilization of the gas turbine, especially in oil and gas industry, there are many studies and research works were initiated in order to improve the advancement of existing technologies of gas turbine.

One of the critical mechanisms of gas turbine is gas turbine blades, as shown in Figure 1.1. Boyce said that the turbine blades are commonly became the limiting component of gas turbine [3]. The environment inside the gas turbine is very strenuous. So, the turbine blades are exposed to high temperature, high stresses and a potentially high vibration environment inside the gas turbine. All of these three factors may expose the turbine blades from creep, that resulting in permanent deformation of the blades. Therefore, this research will investigate and predict the remaining useful life of gas turbine blade based on its creep service life.

FIGURE 1.1: Picture of Gas Turbine Blades [4]

1.2 PROBLEM STATEMENT

Gas turbine blade is made up of exotic materials like superalloys to withstand in the difficult environment inside the gas turbine. As a consequence of operating the gas turbine at high temperature and high stresses, the turbine blades are subjected to certain deformation (creep). Commonly, the used turbine blades are replaced with the new once based on the manufacturer's expected useful life. The replacements of the turbine blades may be costly and need to plan for the schedule, manpower, tools and equipment needed.

Presently in PETRONAS Company, replacing of the gas turbine or known as engine change-out after its specified useful life is a common practice. However, not all the blades are creep or deformed at the end of its expected useful life period. Question always rises about the remaining useful life of gas turbine blade under its operating conditions. If it is possible to predict and determine the remaining useful life of gas turbine blades, we can reuse and extend its service life thus saving all the cost of replacing the turbine blade.

1.3 OBJECTIVES OF STUDY

The main **objectives** of this research are:

- Investigate the creep life of gas turbine blade by using stress rupture test (SRT) or known as creep rupture test.
- Predict the remaining useful life (duration) of gas turbine blade by using relationship equation of Larson-Miller Parameter and Life Fraction Rule.

1.4 SCOPES OF STUDY

The **scopes of study** of this research are:

- Sample preparation of the gas turbine blade by referring to the ISO Standard.
- Study on creep life of gas turbine blade and basic principle of creep deformation.
- Predict the remaining creep useful life of gas turbine blade by using relationship equation of Larson-Miller Parameter and Life Fraction Rule.

1.5 RELEVANCY OF THE PROJECT

This project is **relevant** to Mechanical Engineering studies, as it is related to some of the completed courses such as Thermodynamics, Heat Transfer and Engineering Materials. The study on the service life of Gas Turbine blade is very useful to PETRONAS Company especially. This research will help the company to estimate the remaining useful life of the gas turbine blade after its specified operating life.

1.6 FEASIBILITY OF THE PROJECT

The **feasibility** of the project is depends on the method and availability of tools and equipment to perform stress-rupture test. Two semesters of studies are allocated to complete the Final Year Project, which almost eight month of study. The planning of schedule is very important to ensure that this research can finish within the allocated time. During Final Year Project I, the author spent most of the time to do some research on the journal related to the topic and ensure the availability of tools and equipments to conduct the experiment. The practical on conducting experiments continue during Final Year Project II. The data obtained from the experiment will be analyzed based on all the theories and knowledge to provide a conclusion as the result of this research.

CHAPTER 2

LITERATURE REVIEW / THEORY

2.1 GAS TURBINE AND ITS SYSTEM

Nowadays, gas turbine is the most versatile equipment of turbomachinery. It can be used in various different modes in critical industries, such as power generation, oil and gas, process plant, aviation and also in domestic and smaller related industries. Rolls-Royce is one of the famous companies in industrial gas turbine systems. They have been supplied the gas turbine to the worldwide oil and gas and power generation industries for almost five decades. Based on the information from Rolls Royce company, nearly 4,000 Rolls-Royce gas turbines have been sold and over 200 million hours operation to date [4].

In an ideal gas turbine, gases will undergo three thermodynamic processes, which are an isentropic compression, an isobaric combustion and an isentropic expansion. Theoretically, a gas turbine essentially brings along air that already compressed in its compressor module and also fuel, which are then ignited for combustion and resulting the gases expands through the turbine [5]. That turbine's shaft continues to rotate and drive the compressor unit which is on the same shaft and this operation continues. In the simplest word, these processes are explained by the Brayton cycle.

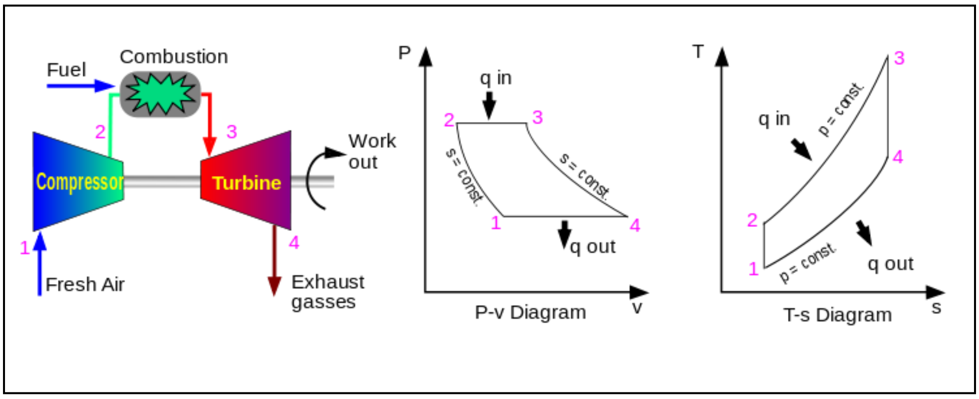


FIGURE 2.1: Brayton Cycle Processes [2] [6]

Based on Figure 2.1, from State 1 to State 2 the gas undergoes an isentropic and adiabatic compression. This process will increase the temperature, pressure and density of the gas. The process continues from State 2 to State 3, where heat is added at constant pressure through a combustion process. From State 3 to State 4 the gas passes through an adiabatic isentropic turbine which decreases the temperature and pressure of the gas. Heat is removed from the gas between State 4 and State 1 to close the Brayton cycle via a heat exchanger [6].

2.2 GAS TURBINE BLADE AND ITS MATERIAL

A turbine blade is one of the important components which make up the turbine section of a gas turbine. The function of the blades is to extract the energy from the high temperature and high pressure gas from the combustor. The turbine blades face high stress from centrifugal force and fluid force that can cause fracture, yielding or creep. In addition, the blades also face high temperature that weaken the blades and can cause creep failure. Finally, vibrations available from the engine itself can cause fatigue failure. All of these major factors (high stress, high temperature and vibrations) can lead to the blade failure that destroy the turbine and the turbine blades need to be carefully designed to overcome those problems [7].

In the earliest development of gas turbine blade, the material used was Nimonic alloy [8]. Further research on superalloys was made in the 1940's to improve the performance of the blade. Advancement made in the field of materials lead in development of gas turbines with higher power ratings and efficiency levels. Xijia Wu said that nowadays, mostly the gas turbine blades are made up of single crystal Nickel-base superalloys, which are the composition of intermetallic γ' Nickel aluminide (Ni_3Al) precipitates in a solution-strengthened γ matrix, solidified in the crystallographic direction [9]. This material used for application at high temperature of hot gas in the gas turbine. Figure 2.2 shows the development of Nickel-based superalloy to single crystal. Table 2.1 shows the type of materials and chemical compositions of industrial gas turbine (IGT) blades that available in the industry.

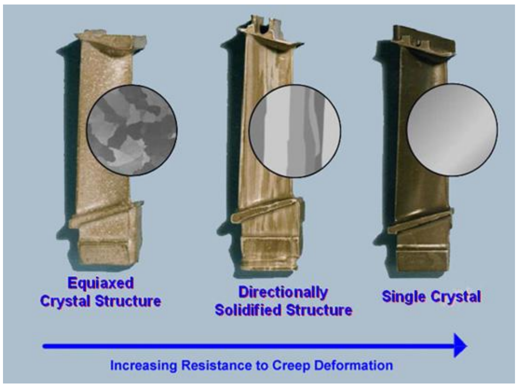


FIGURE 2.2: Grain Structure Development of Nickel-based Superalloy

Table 2.1: Type of Materials and Chemical Compositions of IGT Blades [8]

Grade	Chemical composition	Remarks
CrMoV steel	Fe1Cr0.5Ni1.25Mo0.25V0.30C	Medium carbon low alloy steel
M152	Fe12Cr2.5Ni1.7Mo0.3V0.12C	12% Cr steel
A286	Fe15Cr25Ni1.2Mo2Ti0.3Al0.25V0.08C 0.006B	Iron-base superalloy
706	Ni16Cr37Fe1.8Ti2.9Cb0.03C	Nickel-iron-base superalloy
718	Ni19Cr18.5Fe3Mo0.9Ti0.5Al5.1Cb 0.03C	Nickel-iron-base superalloy
Udimet 720	55Ni18Cr14.8Co3Mo1.25W5Ti2.5Al0.035C0.033B0.03Zr	Nickel-base superalloy
Udimet 720LI	57Ni16Cr15Co3Mo1.25W5Ti2.5Al0.025C0.018B0.03Zr	Nickel-base superalloy

2.3 CREEP

Creep, also known as cold flow is the tendency of a solid material to change slowly or deform permanently under the exposure of mechanical stresses. It is a time dependent deformation under certain applied load. Creep generally occurs at high temperature for a long period. In engineering materials, creep become a concern at homologous temperatures equals to or greater than 0.5 [10]. The homologous temperature is defined as $\frac{T\ (absolute)}{T_{mp}\ (absolute)}$; where T is the absolute temperature of the application and T_{mp} is the absolute temperature of the melting point of the materials .

The rate of deformation is known as the creep rate. It is related the properties of material, exposure time, exposure temperature and the applied structural load. The deformation may cause the component fails to execute its function. For example, the creep of a turbine blade may cause the blade touching the casing and resulting in the failure of the turbine system. Creep is called time-dependant deformation because it does not occur immediately after the applied stress. Instead, the strain will accumulate as a result of long-term stress. However, creep deformation caused by temperature range depends on the type of materials.

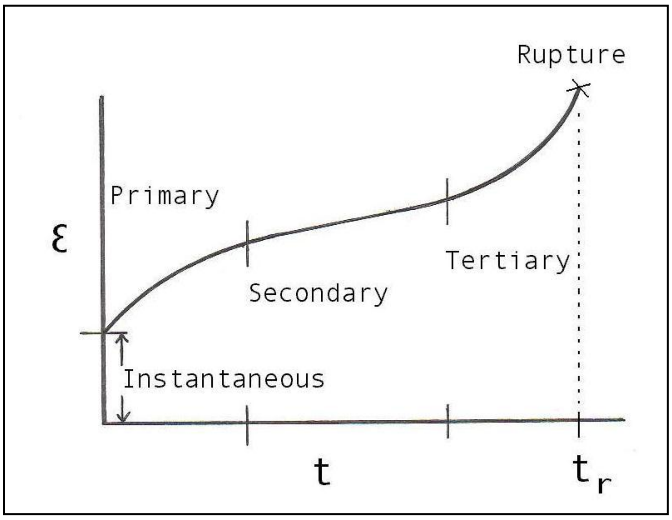


FIGURE 2.3: Creep Strain vs. Time Curve [10] [11]

Figure 2.3 shows the three stages involved in creep deformation, which are Primary Creep, Secondary Creep and Tertiary Creep. During the Primary Creep, the creep strain starts at a rapid rate and slows with time, due to material deformation. At Secondary Creep, the strain has a relatively uniform rate. This is due to the balance between work hardening and annealing. In Tertiary Creep, the strain has an accelerated creep rate and terminates when the material breaks or rupture. It is associated with both necking and formation of grain boundary voids [10] [11].

2.3.1 Effect of Creep on Gas Turbine Blade

Creep can be one of the critical factors in determining the integrity of materials at elevated temperature for a period of time. During the operation of gas turbine, especially in hot sections, some components such as turbine blades are subjected to sustained loads at high temperature. Creep on the turbine blade can also cause dimensional changes of its structure that can affect either its efficiency or lead to elongation that touch the engine casing, which will induce additional vibration and noise [9]. Moreover, creep damage will cost to significant reduction in service life of the gas turbine.

2.3.2 Remaining Creep Life Prediction Method

Stress rupture test (SRT) is one of the proper methods to investigate and predict the remaining creep life of gas turbine blade. The procedure to perform stress rupture test is similar to the creep test. The only difference is during stress rupture test, a higher stress level is used until the specimen fails and the time at failure is measured. Dieter said that the stress rupture test is carried out under a constant load (high load) to the specimen and maintained at a constant temperature for a given period time [11]. Rupture strength and failure time will be plotted and an analysis should be done to estimate the remaining creep life. This test will be connected with the equations that will be used to predict the remaining creep life of gas turbine blade. These equations are the **Larson-Miller Parameter and Life fraction Rule**.

Creep-stress rupture data for high temperature alloys usually plotted as log stress to rupture versus a combination of log time to rupture and temperature. These parameters represent the **Larsen-Miller (L.M.) Parameter** that will be used to predict the lifetime of materials. The Larson-Miller parameter will provide a reliable prediction as long as there is no microstructure change in the turbine blade [12]. The equation of Larson-Miller Parameter is:

$$P\ (L.M.) = T[\log t_r + C] \qquad [11]$$

Note: T is the operating temperature (in Kelvin, K); t_r is the stress-rupture time (in hours, h); and C is the material specific constant (approximate as 20). The experimental data obtain will be extrapolate using this relation.

Second equation that useful for this project is the **Life Fraction Rule**. The Life Fraction Rule will help to determine the operation of creep life and remaining life of the turbine blade [12]. The equations for Life fraction Rule is:

$$\frac{T_s}{T_{rs}} + \frac{t_r}{t_{r*}} = 1 \qquad [12]$$

$$R.L. = T_{rs} - T_s \qquad [12]$$

Note: T_s is the actual service life of blades (in hours, h); T_{rs} is the operational creep life of service-exposed blades (in hours, h); t_r is the rupture time of service-exposed blades under accelerated test condition (in hours, h); t_{r*} is the rupture time of the new materials or unexposed blades under the same accelerated test conditions (in hours, h); and R.L. is the residual life of service exposed blades (in hours, h).

2.4 STRESS RUPTURE PROPERTIES

The stress rupture properties in accelerated test conditions are the important parameters in conducting the SRT. The stress-rupture properties are included the time to rupture, total elongation and also reduction in area of the blades. Previous research had been done by Marahleh in 2006 to study in the possibility of predicting the operational creep life of service-exposed blades used in the industrial gas turbine [12]. Five sets of precision-cast IN-738 turbine blades were used in his study.

Figure 2.4 shows the rupture time for six different service blades at the applied stress. The effect of service life is shown clearly in the blades with the highest service life that exhibit weak stress-rupture properties. Figure 2.5 shows the plot of Larson-Miller Parameter versus the applied stress. The data for the blades at various periods are superimposed on the plot. The creep damage effects on the rupture are the evident where the data fall below the limit for unexposed blades [12].

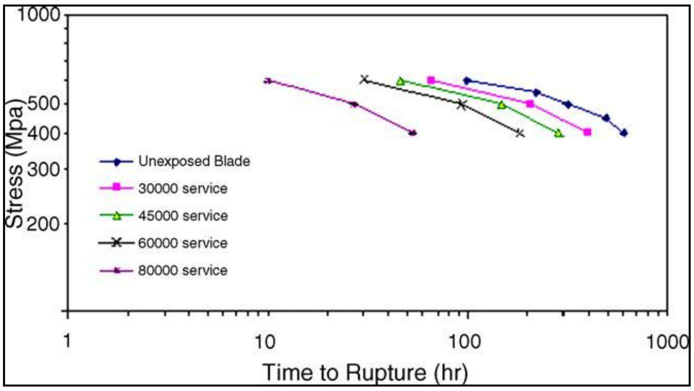


FIGURE 2.4: Example of Stress-Rupture Curve for Unexposed and Service-Exposed Blade [12]

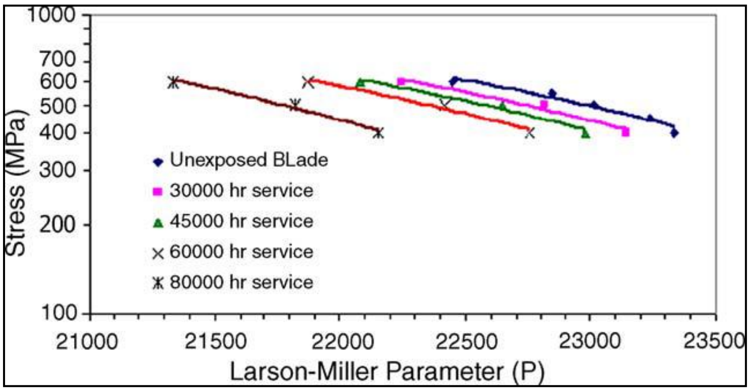


FIGURE 2.5: Example of Larson-Miller parameter for Unexposed and Service-Exposed Blades [12]

Figure 2.6 shows the plot of total elongation of each blade versus time to rupture. It shows that the creep strain decreases with decreasing test stress and service life. The relationship between actual service life and residual life of the blades is shown in Figure 2.7. The residual life of the blades decreases with increasing service life due to the microstructure changes. These changes include the disappearance of serrated grain boundaries, formation of continuous of $M_{23}C_6$ carbide along the grain boundaries and coarsening of γ' phase [12]. As a result, the strength of the grain boundaries and the matrix will decrease thus leading to deterioration of the mechanical properties and a decrease of the rupture time.

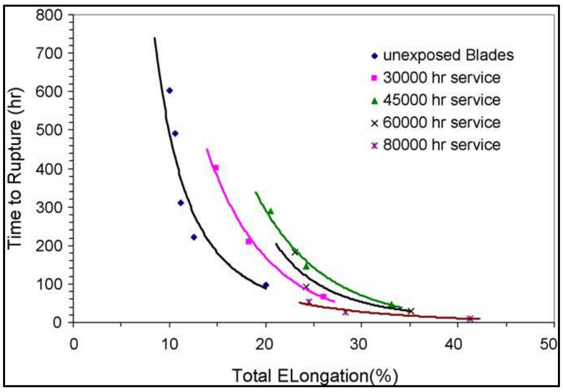


FIGURE 2.6: Example of Relationship between Total Elongation and Time to Rupture for Unexposed and Service-Exposed Blades [12]

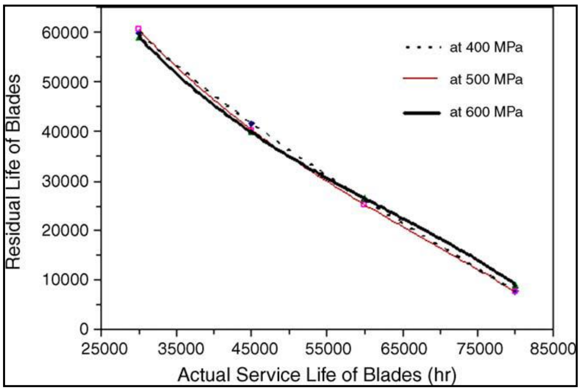


FIGURE 2.7: Example of Relationship between Actual Service Life and Residual Life of Service-Exposed Blades [12]

2.5 PREPARATION OF THE SPECIMEN

The dimension for the test specimen is very important before conducting the stress rupture test (SRT). There are a few standards that can be followed, such as International Organization of Standardization (ISO), American Society for Testing and Material (ASTM) or British Standard. As the blades are small in size, the most suitable standard for test sample preparation is ISO Standard.

The standard test method for uniaxial creep testing in tension for metallic materials is ISO 204. These test methods include the determination of the creep elongation and the time to rupture for metallic materials at a specified temperature. The test consists of heating the specimen at specified temperature and straining the test piece at a constant tensile applied to its longitudinal axis for a period of time.

The size and shape of test specimens are the important requirements to conduct stress rupture test. The specimens are in rectangular shape and some modification of the standard specimens needs to be done by referring **ISO 204 [13]**. The test piece must be machined according to the standards given in order to minimize any residual deformation or surface defects. Figure 2.8 shows the feasible location on the blades for conducting SRT. The guideline for preparation of the test specimens are shown in Figure 2.9.

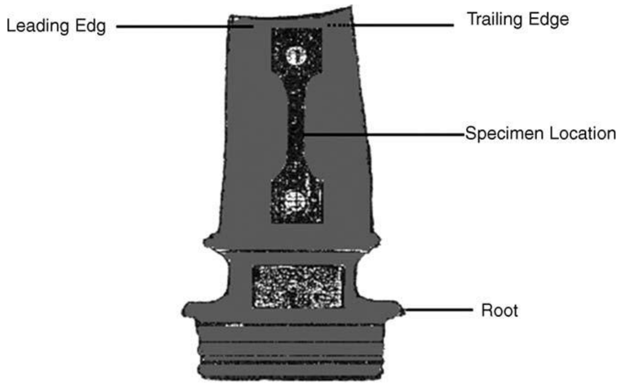
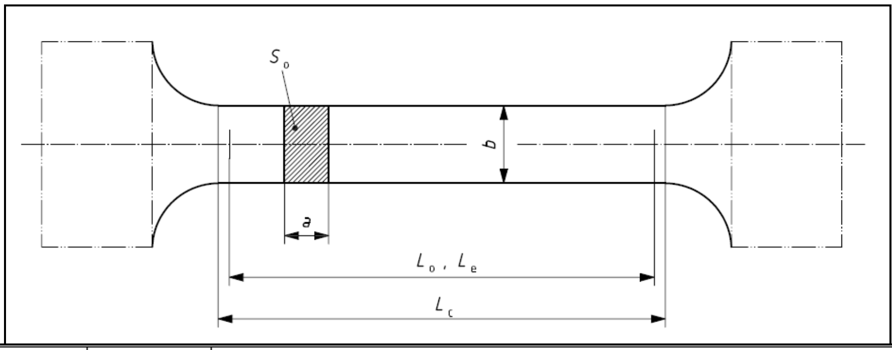


FIGURE 2.8: Feasible Location for Preparation of Test Specimen [12]



Symbol	Unit	Remarks
b	mm	Width of the cross-section of the parallel length of a test piece of square or rectangular cross-section
S_o	mm^2	Original cross-sectional area of the parallel length
a	mm	Thickness of a test piece of square or rectangular cross-section
L_o	mm	Original gauge length
L_e	mm	Extensometer gauge length
L_c	mm	Parallel length

FIGURE 2.9: Test Specimen Guideline for Square or Rectangular Shape (ISO 204) [13]

There are several rules for the sample preparation according to ISO 204. Generally, L_{ro} (original reference length) should not exceed L_c by more than 15% for square and rectangular shape. The transition radius (R) must be in between 0.25b and 1b for rectangular and square test pieces. If the sample size does not permit the shape, the original cross sectional area (S_o) must be greater than or equal to 7 mm^2 [13]. Table 2.2 shows the shape tolerances for the width of the test specimen.

TABLE 2.2: Shape Tolerance for Specimen with Square or Rectangular Cross Sections [13]

Nominal dimension b	Shape tolerances [a]
$3 < b \leqslant 6$	0,02
$6 < b \leqslant 10$	0,03
$10 < b \leqslant 18$	0,04
$18 < b \leqslant 30$	0,05

CHAPTER 3

METHODOLOGY / PROJECT WORK

3.1 PROJECT ACTIVITIES

3.1.1 Sample Preparation for Stress Rupture Test

Due to unavailability of Wire Cut Machine at Universiti Teknologi PETRONAS (UTP) for sample preparation, the author decided to find other alternatives to proceed with the process. After considering the time constraint, the only possible ways for the preparation of test specimen is by dealing with vendors. ALTA Precision Engineering Sdn Bhd is one of the vendors that provide the service of jigs, fixtures and precision machining. So, the author needs to provide the dimension of the specimen according to ISO 204 to the vendor for the machining process (refer to Figure 3.1). Besides that, the dimension of the specimens need to be compatible with the jig (refer Figure 3.2), as a reference because it will be used as the holder during the experiment.

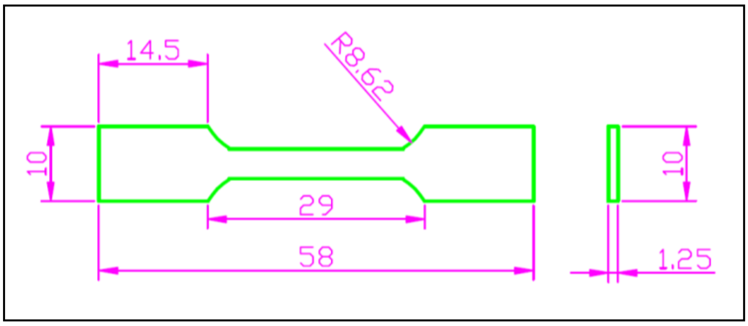


FIGURE 3.1: Sample Dimension Guideline (Unit in mm)

FIGURE 3.2: Picture of the Jig as Reference for Sample Dimension

The machine used to cut the specimen for sample preparation is Wire Cut Machine, as shown in Figure 3.3. There are total three samples needed from the turbine blade for the experimental purpose.

FIGURE 3.3: Wire Cut Machine for Sample Preparation

The procedure of specimen preparation using Wire Cut Machine as follows:

1) The desired dimension of specimen was provided and the data will be used as instruction to the Wire Cut Machine.

2) A flat metal base was glued to the roof of the blade to ensure that the angle of the blade is 90° to the wire during cutting process.

3) The wire cutting was done based on the dimension desire. The specimens were cut from blade airfoil in spanwise direction in order to ensure that the test was in the same direction as the major service stress caused by centrifugal loading.

4) Steps 1 to 3 were repeated to produce the other samples.

3.1.2 Stress Rupture Test (SRT)

Stress-rupture test was used to study the stress-rupture properties of each blade using accelerated test conditions [12]. On 31st October 2014, the author had a visit to Tenaga Nasional Berhad (TNB) Research at Bangi to survey the availability of the SRT Machine. This machine is not available in UTP. So, the author takes the initiative to consult with the staff at TNB Research to ensure that this project can be done successfully. From the visit, the author had booked the machine to conduct the experiment and learn the capabilities and constraints of the machine before preparing the test sample.

There are several **important outcomes** of the visit:

- The SRT machine (refer Figure 3.4) is available to conduct the experiment.
- The jig also available at TNB Research and will be used as a reference for preparation of test specimen and as the holder during the experiment.

The stresses used for the stress-rupture test were between 400 - 600MPa and the test temperature was 850°C. The stress-rupture tests were carried out in a creep machine type PHOENIX 50 kN.

FIGURE 3.4: Stress-Rupture Test Machine at TNB Research

The procedures of conducting Stress-Rupture test by using PHOENIX 50 kN Creep Machine as follows:

1. Test specimen was prepared according to ISO 204.

2. Ensure that the test specimens fit with the jig that will be used during conducting the experiment.

3. Provide the operating conditions to conduct the SRT – Stress and Temperature at accelerated conditions.

(A) Heating of the test piece

1) The test piece was heated to the specified temperature (T).

2) This condition was maintained for at least one hour before application of the force to the test piece.

3) In the uninterrupted test, the maximum time that the test piece was held at the test temperature before applying the force shall not exceed 24 hours.

4) During the heating period, the temperature of the test piece should not, at any time, exceed the specified temperature (T).

(B) Application of the test force

1) The test force was applied along the test axis in such a manner to minimize bending and torsion of the test piece.

2) The applied force was known to an accuracy of at least ± 1%.

3) The application of the test force was made without shock and as rapid as possible.

4) The beginning of the creep test and measurement of creep elongation is the time (t = 0) when the full load of the initial stress was applied to the test piece.

4. The data was plotted and recorded until the specimen rupture.

5. The results were analysed to estimate the residual life of the blades.

3.1.3 Simulation for Creep Properties of Materials

The samples of gas turbine blades were supplied by PETRONAS Carigali Kertih. The turbine blades received are service-exposed turbine blades, means that they already operated at specified operating life – 52000 hours and made up of Nickel-base superalloys.

The information on operating parameter of the turbine blades as follows:

- Operating Hours : 52 000 hours
- Operating Temperature : 720 °C
- Operating Pressure : 1 200 kPaG
- Output Power of Gas Turbine : 20 000 hp

Simulation analysis for the creep properties of the blades material, which is Nickel-Based Superalloy can be done directly by using JMatPro Software. JMatPro is a simulation software which evaluates the materials properties of alloys used in industrial practices [14]. The simulation is needed to estimate the rupture time of the new materials (unexposed blade) that will be used for analyzing the data from the experiment by using Life Fraction Rule equation. The simulation for 52000 h service-exposed blades also can be done through simulation.

The compositions of materials are needed to run the simulation. The compositions of materials for 52000 h service-exposed blades are referred to the study by Haziq on the effects of operating temperature on microstructure of gas turbine blades [15], which used the same operating conditions of the blades. The results from the study are tabulated in Table 3.1.

TABLE 3.1: Chemical Compositions of the Blades [15]

Actual Service Life of Blade (h)	**Chemical Compositions**											
	Ni	**Al**	**Co**	**Cr**	**Fe**	**Nb**	**Ta**	**Ti**	**W**	**Zr**	**B**	**C**
52000	57.01	3.01	6.5	10.5	9.63	0.87	1.18	2.76	8.01	0.09	0.1	0.17
Unexposed	57.01	3.58	7.4	6.55	10.48	0.87	1.82	3.34	8.64	0.04	0.1	0.17

The procedure of simulation analysis of unexposed blade by using JMatPro Software as follows:

1. The compositions of the unexposed blades were listed based on the previous research on the microstructure properties of gas turbine blade (refer Table 3.1).

2. Select creep properties at specified temperature and stress (accelerated test conditions).

3. Stress versus Rupture Life graph will be plotted.

4. The rupture life value at the operated conditions was determined and recorded.

3.2 LIST OF MACHINES AND HARDWARE/SOFTWARE USED

There are total 4 numbers of machines and hardware/software used to investigate the remaining useful life of gas turbine blades. The functions for each equipment are listed in Table 3.2.

TABLE 3.2: List of Machines and Hardware/Software Used

No	Machines / Hardware / Software	Function
1	EDM Wire Cut Machine	Used for machining the turbine blades into desired dimension
2	PHOENIX 50 kN Creep Machine	Used for conducting the Stress Rupture Test (SRT)
3	JMatPro Software	Used for simulating the creep properties of the blades material
4	Microsoft Excel	Used for analyzing the results of SRT

3.3 RESEARCH METHODOLOGY (FLOW CHART)

The detail flow of this research is important to provide the general idea on how the research is going to be done from the START until the END. The research methodology (flow chart) of the project is shown in Figure 3.5.

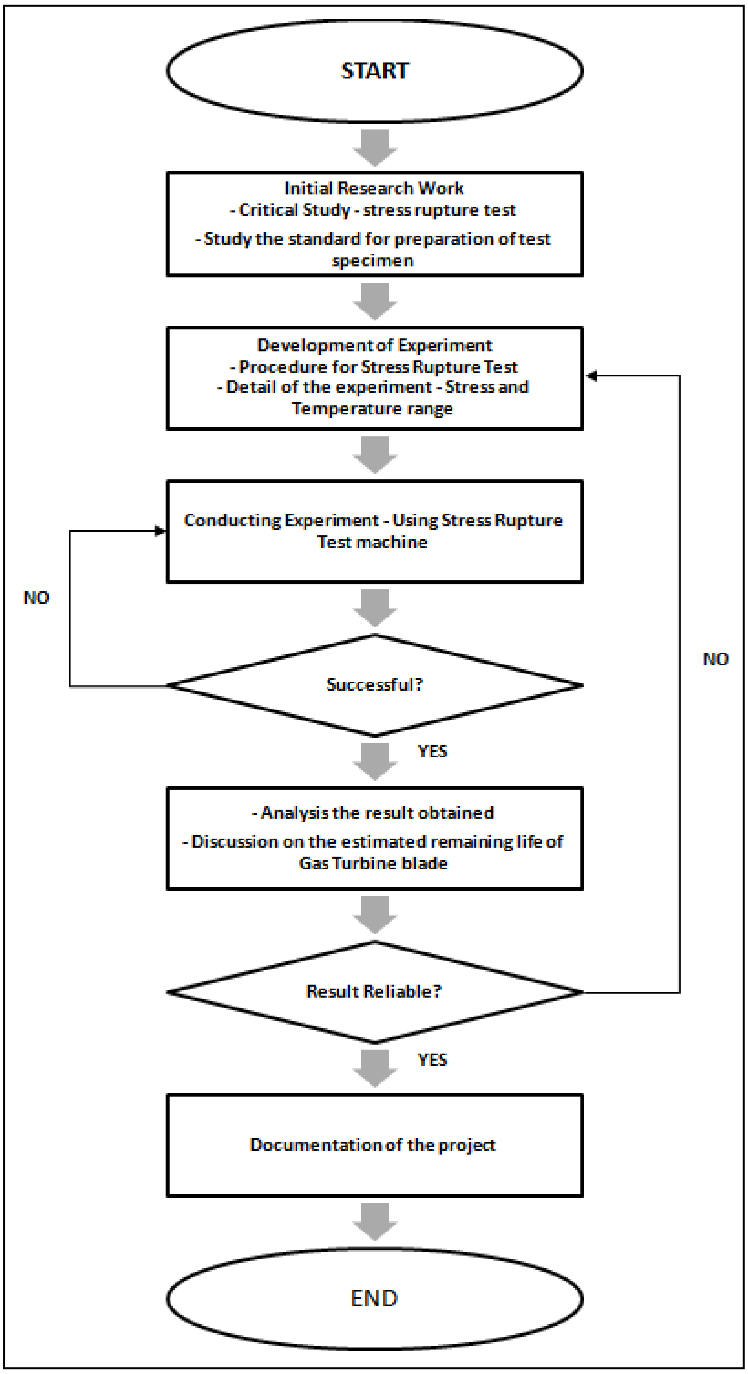


FIGURE 3.5: Flow Chart of the Project

3.4 EXPERIMENTAL PROCEDURES

There are 3 major steps to summarize the experimental procedures that had been done to estimate the residual life of the blade. The summary of the experimental procedures are shown in Figure 3.6.

STEP 1: Preparation of Test Specimen
- Dimensions Refer ISO 204
- Using Wire Cut Machine

Wire Cut Machine

Sample of Test Specimen

STEP 2: Conducting Experiment
- Using PHOENIX 50 kN Creep Machine
- Jig is used as a holder during the experiment

SRT Machine

Jig Used for SRT

STEP 3: Interpretation of the SRT Result
- Analyzing the rupture time for the specimen
- Using Larson Miller Parameter equation
- Using Life Fraction Rule equation

$$P\ (L.M.) = T[\log t_r + C]$$

Larson Miller Parameter

$$\frac{T_s}{T_{rs}} + \frac{t_r}{t_{r*}} = 1$$

$$R.L. = T_{rs} - T_s$$

Life Fraction Rule

FIGURE 3.6: Experimental Procedures

3.5 GANTT CHART AND KEY MILESTONES

TABLE 3.3: Gantt Chart & Key Milestones (FYP 1)

No	Task	Duration (Week)	1	2	3	4	5	6	7		8	9	10	11	12	13	14
			Week														
1	**Investigation of Remaining Useful Life of Gas Turbine Blade**	**14**	■	■	■	■	■	■	■		■	■	■	■	■	■	■
2	Selection of Project Topic & Supervisor	**2**	■	■													
3	Preliminary Research Work on the Project	**4**		■	■	■	■										
	- Background of Study	**1**		■													
	- Problem Statement	**2**			■	■											
	- Objective & Scope of Study	**2**			■	■											
	- Critical Analysis of Literature	**3**			■	■	■										
4	Submission of Extended Proposal	-						●		**Mid-Semester Break**							
5	Site visit to TNB Research – booking for jig & SRT machine	**2**						■	■								
6	Check availability of cutting machine in UTP – for specimen	**2**									■	■					
7	Presentation of Proposal Defence	-										●					
8	Project Work Continues	**5**											■	■	■	■	■
	- Study the Procedure	**2**											■	■			
	- Preparation of Test Specimen (ISO Standard)	**3**													■	■	■
	- Preparation of Tools and Equipment	**3**													■	■	■
10	Submission of Interim Draft Report	-														●	
11	Submission of Interim report	-															●

● **Suggested Milestone**
■ **Process**

TABLE 3.4: Gantt Chart & Key Milestones (FYP 2)

No	Task	Duration (Week)	Week 1	2	3	4	5	6	7	Mid-Semester Break	8	9	10	11	12	13	14
1	**Investigation of Remaining Useful Life of Gas Turbine Blade**	**14**	■	■	■	■	■	■	■		■	■	■	■	■	■	■
2	Project Development	**7**	■	■	■	■	■	■	■								
	- Finishing for test specimens (fit with the jig)	**2**	■	■													
	- Start the SRT experiment – 3 specimens (different stresses applied)	**4**			■	■	■	■									
	- Obtain creep strain data from SRT machine	**1**							■								
3	Submission of Progress Report	-							●								
4	Project Work Continues - Analyze the results obtained	**5**									■	■	■	■	■		
	- Plot Stress- Rupture curve	**2**									■						
	- Plot Larson – Miller Parameter Curve (P)	**1**										■	■				
	- Estimate the remaining life - Use the equation of Larson – Miller Parameter & Life Fraction Rule	**2**												■	■		
5	Pre - SEDEX	-											●				
6	Submission of Draft Final Report	-												●			
7	Submission of Dissertation (Soft Bound)	-													●		
8	Submission of Technical Paper	-													●		
9	Viva	-														●	
10	Submission of Project Dissertation (Hard Bound)	-															●

● **Suggested Milestone**
■ **Process**

CHAPTER 4

RESULT AND DISCUSSION

4.1 SAMPLE PREPARATION

The sample preparation for the test specimen was successfully done before conducting the stress rupture. There are total three specimens (dog-bone shape) that can be obtained from one turbine blade by using Wire Cut machine. Figure 4.1 shows the three different locations of the specimens on the turbine blade that is possible to perform stress rupture test.

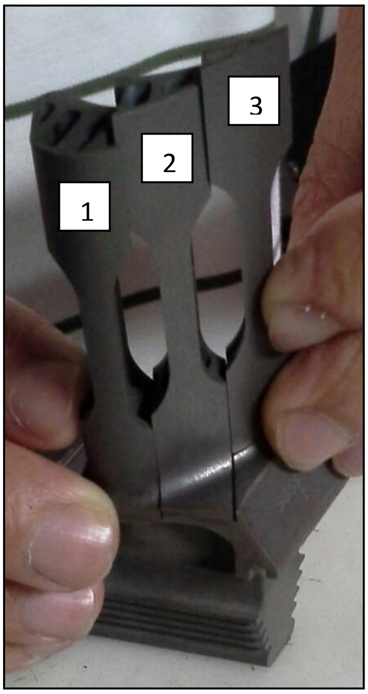


FIGURE 4.1: Locations of the Sample Specimens of Turbine Blade

The detail views of the specimens are shown in Figure 4.2. There are **three characteristics** to take into consideration in choosing the best sample specimen to conduct stress rupture test.

1) Thickness of the specimen (minimum thickness is 0.7 mm).
2) Minimum angle slope of the specimen.
3) Can be fitted inside the jig that will be used during SRT.

Sample 1	**Sample 2**	**Sample 3**
		

FIGURE 4.2: Detail View of the Sample Specimens

After analyzing and comparing the three specimens, the best specimen is **SAMPLE 2,** which is located in the middle of the blade (refer Figure 4.3) and will be used to proceed with the stress rupture test (SRT). Then, the sample was grinding (refer Figure 4.4) to meets the criteria needed, which are:

1) Thickness is around 1.4 mm (more than minimum requirement, 0.7 mm)
2) Angle slope of the specimen is minimum compared to other samples.
3) Fit nicely inside the jig.

FIGURE 4.3: Location of Sample 2 Specimen

FIGURE 4.4: Sample Specimen 2 (after grinding)

4.2 SIMULATION OF CREEP PROPERTIES OF NEW MATERIALS (UNEXPOSED BLADE)

The estimation of rupture life for new blade, which is unexposed blade, is done by using JMatPro Software. The rupture life values are needed for analyzing the data from the experiment by using Life Fraction Rule equation. The graph obtained for the creep simulation using the software is shown in Figure 4.5.

Test condition:

- Temperature = 850°C
- Stress = 400, 500 & 600 MPa

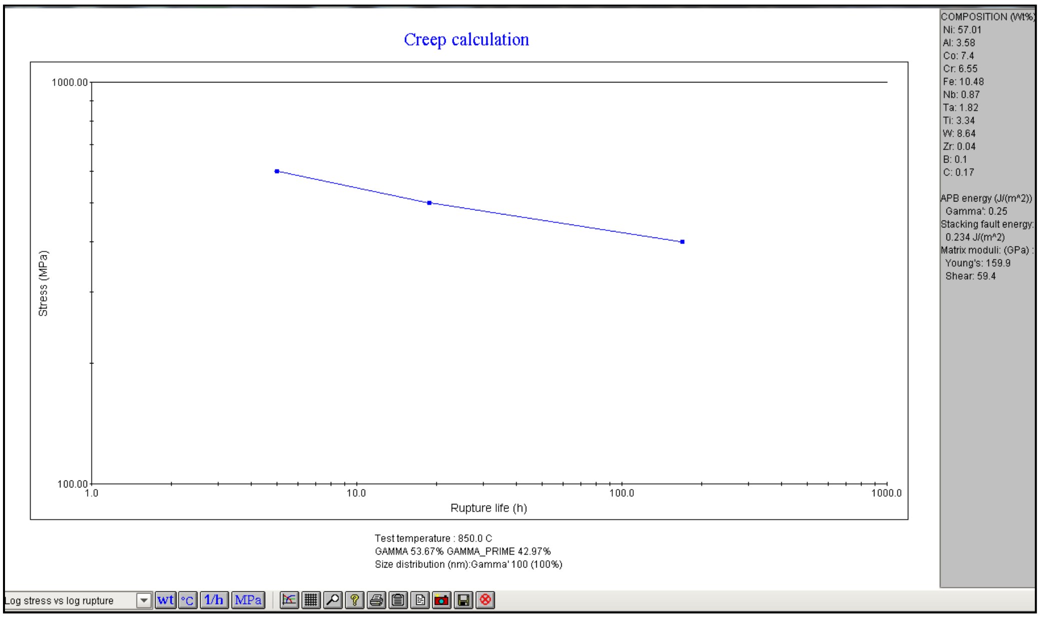


FIGURE 4.5: Creep Simulation of New Material

TABLE 4.1: Resuls of Rupture Life (New Material)

Stress (MPa)	**Rupture life (h)**
400	169.42
500	18.78
600	5.0

4.3 STRESS-RUPTURE PROPERTIES

Based on the SRT and simulations, the time to rupture for the blades in accelerated test condition was determined. The stress-rupture data obtained from SRT and simulations are recorded in Table 4.2 and plotted in Figure 4.6. It is clearly shown that the 52000 hour service-exposed blades exhibit weak stress-rupture properties than unexposed blades. Time to rupture for the blades also increased when the applied stress decreased.

TABLE 4.2: SRT Results for Unexposed and Service-Exposed Blades

Actual Service Life of Blade (h)	**Test Condition**		**Time to Rupture (h)**
	Stress (MPa)	**Temperature (ºC)**	
Unexposed	400	850	169.42
	500	850	18.78
	600	850	5.0
52000 (Simulation)	400	850	18.48
	500	850	4.56
	600	850	1.7
52000 (SRT)	400	850	*N/A
	500	850	3.5
	600	850	*N/A

Note: *N/A – The experiment was postponed due to the unavailability of the SRT machines (under maintenance).

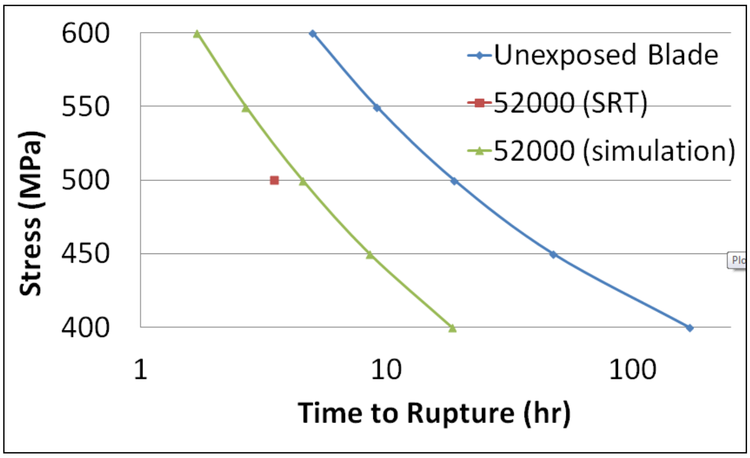


FIGURE 4.6: Stress-Rupture Curve for Unexposed and Service-Exposed Blades

Based on the results, the Larson-Miller Parameter (P) was calculated and plotted versus the applied stress as shown in Figure 4.7. The data was tabulated in Table 4.3. It is obvious from the curves that the unexposed blades show higher P than 52000 hours service-exposed blades for all applied stresses. The creep damage effects on rupture life are the evident where the data fall below the limit for unexposed blades.

TABLE 4.3: Calculation Results of Larson-Miller Parameter

Actual Service Life of Blade (h)	**Test Condition**		**Time to Rupture, t_r (h)**	**Material Specific Constant, C**	**Larson Miller Parameter, P**
	Stress, S (MPa)	**Temperature, T (°C)**			
Unexposed	400	850	169.42	20	24963
	500	850	18.78	20	23890
	600	850	5.0	20	23245
52000 (Simulation)	400	850	18.48	20	23883
	500	850	4.56	20	23200
	600	850	1.7	20	22719
52000 (SRT)	400	850	*N/A	20	*N/A
	500	850	3.5	20	23071
	600	850	*N/A	20	*N/A

Note: *N/A – The experiment was postponed due to the unavailability of the SRT machines (under maintenance).

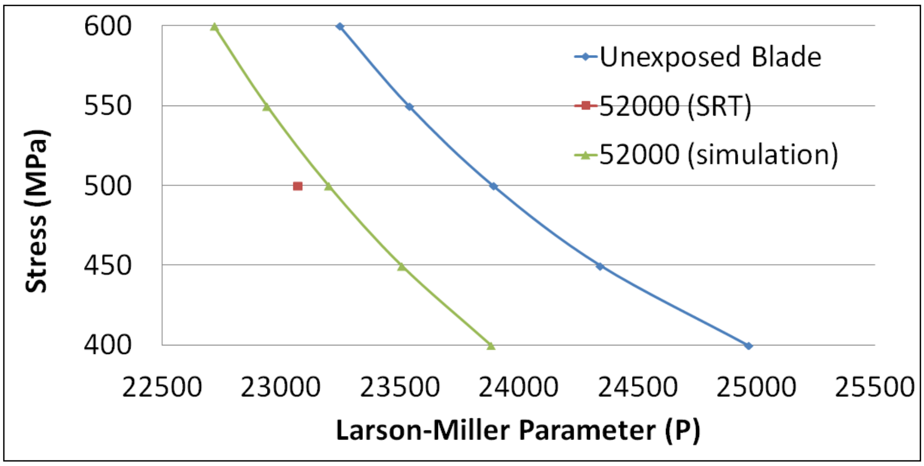


FIGURE 4.7: Larson-Miller Parameter for Unexposed and Service-Exposed Blades

The Life Fraction Rule Equations were used to determine the operation at creep life and residual life of the 52000 hours service-exposed blade. Based on the SRT, the results were analyzed to obtain the operational creep life and the residual life of the blades by using the equations. The results are tabulated in Table 4.4.

TABLE 4.4: Operational Creep Life and Residual Life of Service-Exposed Blades Based on Life Fraction Rule

Actual Service Life of Blade (h)	**Test Condition**		**Time to Rupture (h)**	**Operational Creep Life (h)**	**Residual Life (h)**
	Stress (MPa)	**Temperature (°C)**			
52000 (Simulation)	400	850	18.48	58367	6367
	500	850	4.56	68675	16675
	600	850	1.7	78787	26787
52000 (SRT)	400	850	*N/A	*N/A	*N/A
	500	850	3.5	63911	11911
	600	850	*N/A	*N/A	*N/A

Note: *N/A – The experiment was postponed due to the unavailability of the SRT machines (under maintenance).

Based on the stress-rupture test and simulation results in Figure 4.6, it shows that all the curves are quite similar shape and nearly parallel slope at the beginning but later the curves deviate and a change in the slope occurs. It is clear from the plot that the rupture time for the 52000 h service-exposed blades are faster than unexposed blades. This is due to the microstructure changes that occur in the service-exposed blades during the creep, due to the formation of $M_{23}C_6$ carbide along the grain boundaries [15]. Larson-Miller parameter plot in Figure 4.7 shows the evidence that the rupture time of service-exposed blades is lower than unexposed blades.

Table 4.4 shows the results of the operational creep life and residual life of 52000 h service-exposed blades for both simulation and SRT. From the SRT results, the residual life of the 52000 h service-exposed blades is 11911 h and the residual life of the blades will decrease with increasing of service life due to the microstructure changes to the blades. Simulation result shows that the residual life of 52000 h service-exposed blades is 16675 hours. The percentage difference between residual life results for SRT and Simulation is around 30%. This is due to probably some error during determining the chemical compositions of the blades and some of the elements cannot be captured by XRF and FESEM machines.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

In conclusion, the main objective of the study was achieved, which is to investigate the remaining useful life of gas turbine blades. Gas turbine blade is one of the important parts of gas turbine. It is costly to purchase as it is made up of high quality materials that can withstand the environment inside the gas turbine, which are high in temperature and stress. Replacement of turbine blade is the common practice in PETRONAS Company once it meets the manufacturer's expected useful life. So, this experiment will help to investigate the remaining useful life of gas turbine blade based on its creep life. Its remaining life can be predicted by conducting stress-rupture test (SRT) and some equations are needed to study in detail about its creep life. The equations are Larson-Miller Parameter and Life Fraction Rule. This study has proven that the turbine blade is able to operate until its optimum lifespan and also help to avoid wasting in term of money, time and manpower. Based on the results of the remaining useful life analysis, the 52000 h service-exposed blade has the condition to operate until up to another 11911 hours (≈ 1 year 4 months). The findings also show that the residual life of the blades will decrease with increasing of service life.

5.2 RECOMMENDATION

There are three recommendations that can be highlighted. The Stress Rupture Test (SRT) machine that will be used to conduct the experiment is not available in Universiti Teknologi PETRONAS (UTP). So, the author needs to find other alternatives to ensure that this research can be done within two semesters (September 2014 – May 2015). Tenaga Nasional Berhad (TNB) Research in Bangi is one of the alternatives and the author had consult with the staff of TNB Research to conduct the experiments there. In the future, hopefully UTP will have its own SRT machine to ease the students in conducting the experiments related to the topics.

Secondly, the Stress Rupture Test (SRT) in this study was conducted for one specimen only at one operating conditions (temperature and stress). This is due to the unavailability of the SRT machine in TNB Research which was scheduled for maintenance for 2 months. So, the remains two specimens were unable to continue for analyzing the creep-rupture properties based on SRT. In the future, hopefully the experiment can be conducted earlier and plan accordingly to avoid any unexpected situations.

Lastly, this study was focused on the creep properties of 52000 h service-exposed blades. Due to the difficulties to obtain several samples of turbine blades at different actual service life, the analysis of the results only focus on the samples at the same operating conditions. In the future, hopefully the scopes of analysis on the creep properties of the blades can vary for several samples of turbine blades at different operating conditions. This will lead to a more precise result.

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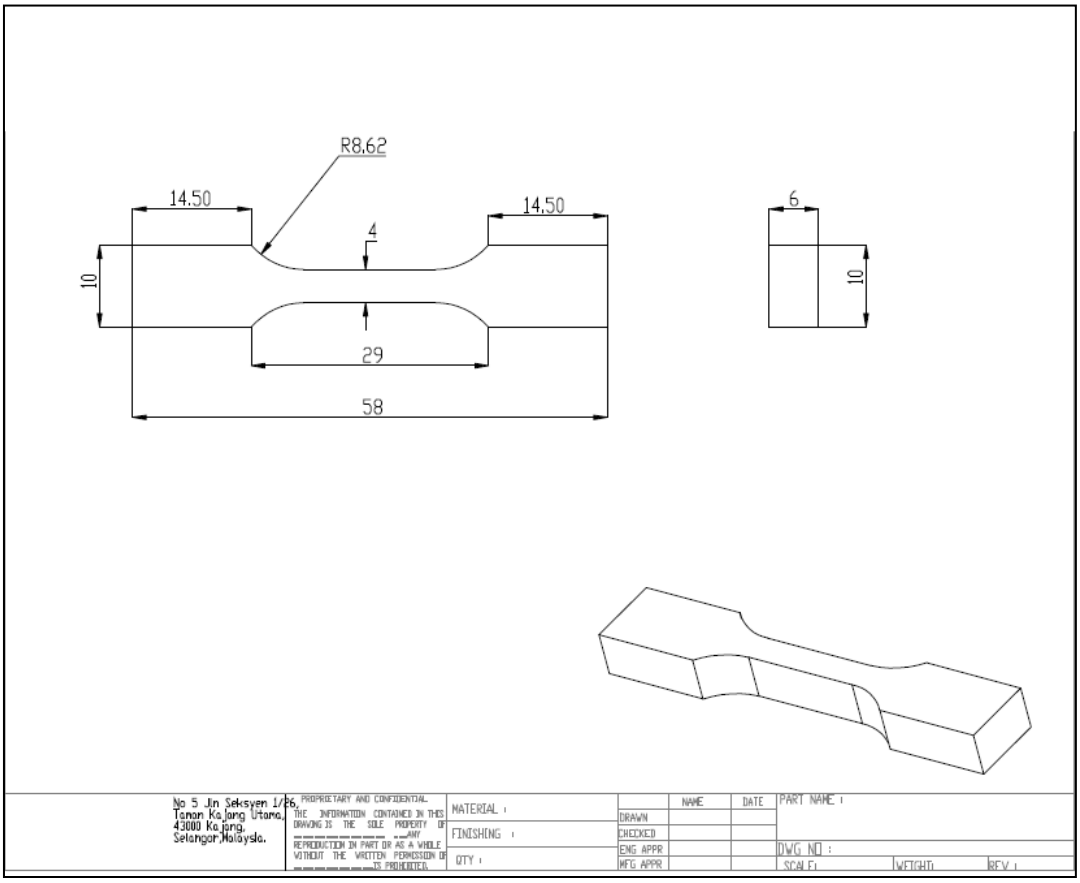
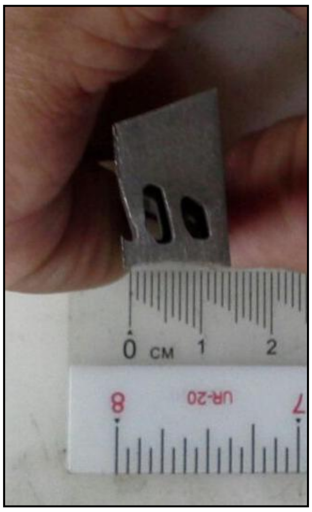
APPENDICES



APPENDIX A: Technical Drawing of the Specimen from the Vendor (Unit in mm)



APPENDIX B: Existing Profile of Sample 2 Specimen

APPENDIX C: Sample Calculation of Larson-Miller Parameter

$$P\ (L.M.) = T[\log t_r + C]$$ .... (1)

From SRT result of 52000 hours service blade at T= 850°C and S = 500 MPa;

- $\boldsymbol{T = 850℃ + 273 = 1123\ K}$
- $\boldsymbol{t_r = 3.5\ h}$
- $\boldsymbol{C = 20}$

Therefore, from Equation 1;

$$\boldsymbol{P(L.M.) = 1125\ (\log 3.5 + 20) = 23071}$$

APPENDIX D: Sample Calculation of Life Fraction Rule

$$\frac{T_s}{T_{rs}} + \frac{t_r}{t_{r*}} = 1$$ .... (2)

$$R.L. = T_{rs} - T_s$$ .... (3)

From SRT result of 52000 hours service blade and simulation of creep properties of unexposed blades at T= 850°C and S = 500 MPa;

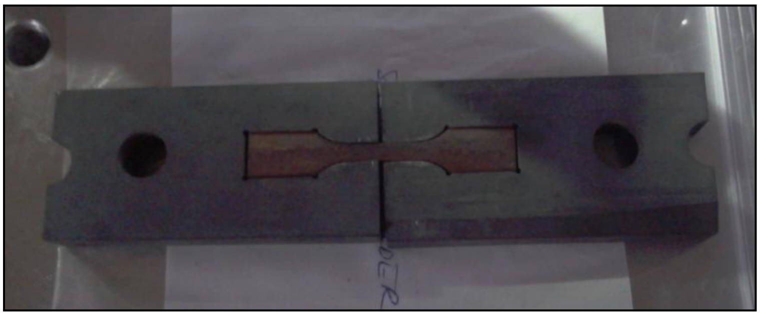
- $\boldsymbol{T_s = 52000\ h}$
- $\boldsymbol{t_r = 3.5\ h}$
- $\boldsymbol{t_{r*} = 18.78\ h}$

From Equation 2; $\frac{52000}{T_{rs}} + \frac{3.5}{18.78} = 1$; $\boldsymbol{T_{rs} = 63911\ h}$

Therefore, from Equation 3;

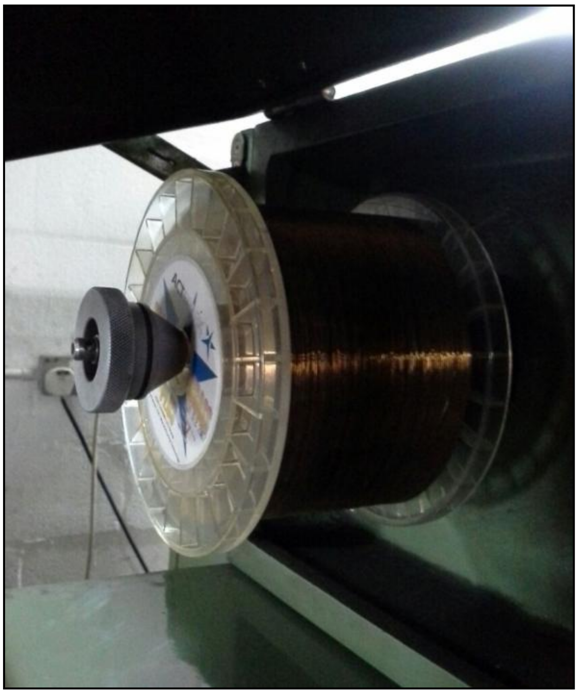
$$\boldsymbol{Residual\ Life\ (R.L) = 63911 - 52000 = 11911\ h}$$

APPENDIX E: First Visit to TNB Research for Booking the SRT Machines



APPENDIX F: Position of the Specimens inside the Jig

APPENDIX G: Vernier Calliper Used for measuring the Thickness of the Specimens



APPENDIX H: Wire Cut Used for Machining the Specimens