Determination of Remaining Useful Life of Gas Turbine Blade

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Abstract. The aim of this research is to determine the remaining useful life of gas turbine blade, using service-exposed turbine blades. This task is performed 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°C. The study will focus on the creep behaviour of the 52000 hours service-exposed blades, complemented with creep-rupture modelling using JMatPro software and microstructure examination using optical microscope. The test specimens, made up of Ni-based superalloy of the first stage turbine blades, are machined based on International Standard (ISO) 24. The results from the SRT will be analyzed using these two main equations – Larson-Miller Parameter and Life Fraction Rule. Based on the results of the remaining useful life analysis, the 52000h service-exposed blade has the condition to operate in the range of another 4751 hr to 18362 hr. The microstructure examinations shows traces of carbide precipitation that deteriorate the grain boundaries that occurs during creep process. Creep-rupture life modelling using JMatPro software has shown good agreement with the accelerated creep rupture test with minimal error.

1 Introduction

Gas turbine blade is made up of exotic materials like superalloys to withstand in the difficult environment inside the gas turbine [1]. As a consequence of operating the gas turbine at high temperature and high stresses, the turbine blades are subjected to certain deformation (creep) [2]. Presently in any energy-related industries, 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. Therefore, this research will investigate and predict the remaining useful life of gas turbine blade based on its creep service life.

Stress rupture test (SRT) is one of the proper methods to investigate and predict the remaining creep life of gas turbine blade. 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 [3]. 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.

2 Test Specimen and Procedure

Three sets of turbine blades were used in this study and the composition of materials are given in Table 1. 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 with given operating time of 52000 hours. A newly unexposed turbine blade is also been investigated to be used as the reference data.

2.1 Preparation of the Test Specimen

The dimension for the test specimen is very important before conducting the accelerated stress rupture test (SRT). The test specimens were machined according to ISO 24 [5], as shown in Figure 1, by using wire cutting machine. Some portion of the blade were cut 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], as shown in Figure 2.

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Figure 1. SRT Specimen Dimension Guideline (in mm).

Figure 2. Portion of the blade used to make the stress-rupture specimen

2.2 The Accelerated Stress-Rupture test

Accelerated stress rupture was used to study rupture properties of each blade under accelerated conditions. The stresses used for the test were between 400 – 600 MPa and the test temperature was 850°C. The stress – rupture tests were carried out in a creep machine type PHOENIX 50 kN. A jig was prepared for execution of the tests as shown in Figure 3.

Figure 3. Jig used for stress-rupture test

2.3 Simulation of Creep Properties

Simulation analysis for the creep properties of the blades material, which is nickel-based superalloy is performed using JMatPro Software. JMatPro is simulation software which evaluates the materials properties of alloys used in industrial practices [6].

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 to compare the simulation results with SRT results. The compositions of the blades were referred to the data in Table 1.

Table 1. Chemical composition of 52000 h-service exposed gas turbine blade

Actual Service Life of Blade	Chemical Composition (%)					
	Ni	Al	Co	Cr	Fe	Nb
52000 hr	57.0	3.0	6.5	10.4	9.62	0.87
	07	36	82	5		
Unexposed	57.0	3.5	7.4	6.55	10.4	0.87
	8	8				
Actual Service Life of Blade	Chemical Composition (%)					
	Ni	Al	Co	Cr	Fe	Nb
52000 hr	57.0	3.0	6.5	10.4	9.62	0.87
	1	07	36	82	5	
Unexposed	57.0	3.5	7.4	6.55	10.4	0.87
	1	8			8	

3 Results and Discussion

3.1 Accelerated Stress-Rupture test

Figure 4. Stress-rupture curve from the SRT

The stress-rupture data obtained from accelerated SRT and simulation are recorded in Table 2 and plotted in Figure 4. 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 2. Time to rupture data.

Actual Service Life of Blade (h)	Test Condition		Time to Rupture (h)
	Stress (MPa)	Temperature (°C)	
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	14.2
	500	850	3.5
	600	850	1.3

3.2 Larson-Miller Parameter

Based on the results, the Larson – Miller Parameter was calculated and plotted versus the applied stress, as shown in Figure 5. It is obvious from the curves that the unexposed blades show higher P than 52000 h service-exposed blades for all applied stresses.

$$P = T[\log t_r + C]$$

where P (L.M.) is the Larson-Miller parameter; 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).

Figure 5. Larson-Miller parameter for unexposed and service-exposed blades

3.3 Operational Creep Life and Residual Life

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 and simulations, 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 3.

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

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

where 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).

Table 3. Operational creep life and residual life

Actual Service Life of Blade (h)	Test Condition		Operational Creep Life (h)	Residual Life (h)
	Stress (MPa)	Temp (°C)		
52000 (Simulation)	400	850	58367	6367
	500	850	68675	16675
	600	850	78787	26787
52000 (SRT)	400	850	56751	4751
	500	850	63911	11911
	600	850	70362	18362

3.4 Microstructural Study

A microstructure study was conducted to examine qualitatively the condition of the microstructure of the turbine blade. In Figure 6, two optical microscope images from different locations on the 52000 hr operation-exposed turbine blade of x500 magnification. The two locations are within the region of the accelerated stress rupture test specimen as shown in Figure 1. The two images shown vividly the presence of heterogeneous distribution of γ' phase and carbides precipitation in grain boundaries. Carbide precipitation signifies the formation of uninterrupted films and dispersed particles that affects the ductility and strength of the 52000 hr operation-exposed turbine blades [8]. This microstructure condition reflects the condition of a middle stage secondary creep.

Figure 6. Optical microscope image of two locations on the 52000 hr operation-exposed turbine blade

4 Discussion

The stress-rupture test and simulation results in Figure 4 exhibit that both curves have the same pattern where at the beginning, the slope is same but later become dissimilar, as the curves change. It is clear from the figure that the rupture time for the 52000 h service-exposed blades are faster than unexposed blades. The curves indicate the declining of the stress rupture properties for service-exposed blades. According to Marahleh et al. [4], this declination is due to the alteration in microstructure during the creep process that weakens the strength of grain boundaries and the matrix. Among the changes are the diminishing of serrated grain boundaries and coarsening of γ' phase. These changes leads to deterioration of mechanical properties and reduces the rupture time.

Table 3 shows the result 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 between the range of 4751 hr to 18362 hr. In comparing with the unexposed blade, it is evident that the the residual life of the blades will decrease with increasing of service life due to the microstructural change to the blades.

From the microstructural study, it is evident that for the 52000 hr service-exposed turbine blade, microstructural changes occur, where the carbides are realigned on the grain boundaries which affects the ductility and toughness of the blades, during the creep process. The changes in the microstructure condition complement the notion that through out the service operation, the turbine blades are deteriorating in its matrix.

The simulation using JMatPro to predict the rupture life of the 52000 hr service-exposed complements the accelerated stress rupture test results, as the simulated rupture life data exhibit the same pattern with the range of difference to the accelerated stress rupture test from 1 hr to 4.2 hr. The feature of the program that requires only input on the composition, precipitate size, stress and

temperature. This reduces the need to use empirical data in calculations within the program like other existing material properties simulation software [9].

5 Conclusion

The remaining useful life of gas turbine blade was investigated by conducting stress-rupture test and using the equations of Larson-Miller Parameter and Life Fraction Rule. Based on the results, the 52000 hour service-exposed blade can be allowed to operate in the range of 4751 hr to 18362 hr. The residual life of the blades will decrease with increasing of service life due to the effect of high temperature and stress condition on the blade microstructure. The microstructure examinations shows traces of carbide precipitation that deteriorate the grain boundaries that occurs during creep process. Creep-rupture life modelling using JMatPro software has shown good agreement with the accelerated creep rupture test with minimal error.

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