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Creep life prediction of service-exposed turbine blades

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Abstract

The aim of this research work was to study the possibility of predicting the operational creep life of service-exposed blades used in industrial gas turbines. This prediction is based on the determination of blades creep life using stress–rupture test under accelerated test conditions where the applied stresses were 400,500 and 600 MPa and the test temperature was 850 °C. The study concentrated on creep behavior of service-exposed blades having different actual service lifes. The test specimens were prepared from first stage turbine blades made of Ni-based superalloy (IN-738). Larson–Miller parameter was used to extrapolate the stress–rupture test results to the actual operating conditions of blades. The operational creep life and the residual life of service-exposed blades were determined employing the life fraction rule.

Keywords: Stress–rupture test; Ni-based superalloy (IN 738); Larson–Miller parameter; Life fraction rule

1. Introduction

Materials used for elevated temperature service very often exhibit time-dependant deformation and temperature-induced changes in microstructure. This leads to a finite lifetime of the components because of the limited capability of the materials to deform plastically. The ultimate limit is given by fracture, proceeds by an increasing accumulation of creep damage [1].

Ni-based superalloys are one of these materials used for application at high temperatures such as in the manufacturing of hot gas path rotating turbine component. Turbine blades for example are subjected to elevated temperature under low to medium stresses for prolonged time; therefore creep will be the major form (mode) of damage under service condition microstructure heterogeneity, alignment and interconnection of carbides as well as oxygen diffusion into the stress fields ahead of the crack tip and formation of NiO sufficient to cause brittle decohesion of the grain boundaries supported by creep cavitation and dynamic embrittlement [2–4]. Further complications may be imposed by high temperature corrosion. Moreover, question always arises regarding the remaining useful life under assumed further operating conditions [5].

A more precise predication of the residual life becomes important if, for example by accident the operating conditions change, or a failure occurs at some points, or if by inspection defects are detected. Another important reason in estimation of the residual life is the high cost of replacement [1].

The search for an accurate method for predicting creep life during long time, high temperature service has lead to the development of a number of equations used to extrapolate the test results obtained from accelerated tests on the actual test conditions. Life fraction rule for example is widely used for this purpose. Also time–temperature parameters can be used to predict long term creep behavior by extrapolating short-time creep data [5].

Based on operation parameters, blade creep life in excess of 10^5 h was calculated for IN-378 blade. The blade life was extrapolated from accelerated high stress, high temperature data using widely accepted technique proposed by Larson and Miller [6], since testing under blade operating conditions was obviously impractical. The Larson–Miller parameter has been shown to give reliable predictions so long as no microstructural change occur in the blade alloy under prolonged exposure in a high temperature environment. Should microstructural changes occur then actual test result will be lower than the extrapolated values [7].

2. Experimental procedure and materials

Five sets of precision-cast IN-738 turbine blades were used in this study. They include:

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Table 1
Chemical composition of the blades

Actual service life of blade (h)	Chemical composition (%)												
	C	Mo	Cr	Ni	W	Fe	Co	Al	Ti	Nb	Ta	Zr	B
30000	0.17	1.58	15.51	61.0	2.67	0.12	8.36	3.14	3.69	0.90	1.88	0.07	0.1
45000	0.17	2.09	15.68	61.0	2.415	0.16	8.27	3.61	3.21	0.74	1.73	0.02	0.1
60000	0.17	1.60	16.37	61.0	2.725	0.15	8.69	3.54	3.32	0.74	1.63	0.07	0.1
80000	0.17	1.99	15.53	61.0	2.684	0.13	8,93	3.15	3.37	0.99	1.73	0.06	0.1
Unexposed	0.17	1.30	15.97	61.0	2.601	0.51	8.83	3.58	3.34	0.87	1.82	0.04	0.1

1. Materials in the as-cast and heat treated condition (unexposed).
2. Materials of service-exposed turbine blades. Their service exposure times were 30,000, 45,000, 60,000 and 80,000 h.

The chemical composition of each set is given in Table 1. They were analysed using EDX system attached to Stereoscan 250 MK 3 SEM.

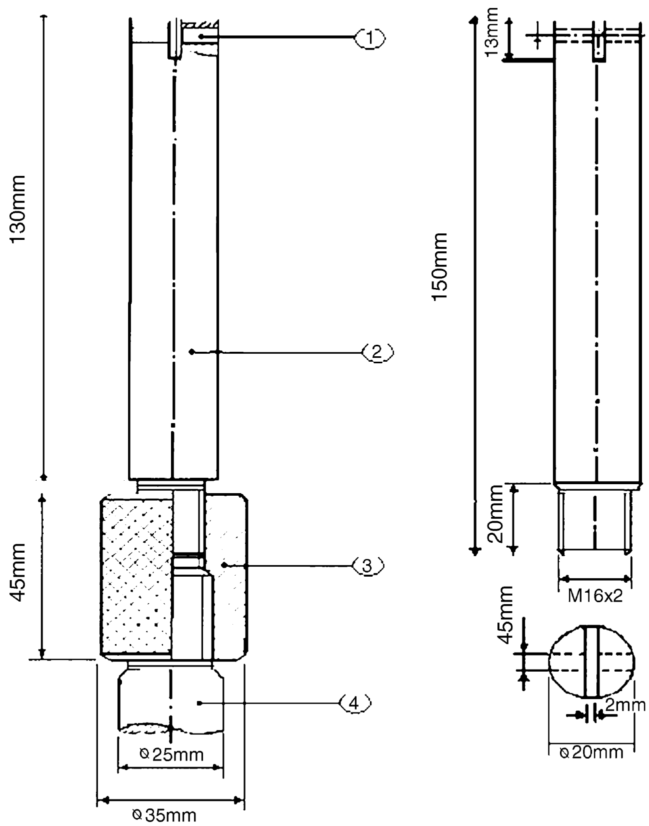
2.1. The stress–rupture test

Stress–rupture test was used to study the stress–rupture properties (time to rupture, total elongation and reduction in area) of each blade using accelerated test conditions. The stresses were 400, 500 and 600 MPa and the test temperature was 850 °C. Temperature variation along the specimen gauge length was within 5 °C. The stress–rupture tests were carried out in a creep machine type Mayes MK 2 TC/20 with lever ratio 10:1. A special jig was made for execution of the tests as shown in Fig. 1.

The test specimens were machined according to British Standard No. 3500 part 1 [8], as shown in Fig. 2, by wire cutting machine type Agieout wire. They 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 [9], as shown in Fig. 3. Two holes for loading the specimen were cut by electric discharge machine type Agietron EDM, and then they were ground using a surface grinding machine type SG-2.

2.2. Microstructure examination

Optical microscope and SEM type 250 MK 3 Cambridge instruments were utilized to study the microstructural changes associated with the blade operation. SEM was very useful in



Item	Name	Material
1	PIN	IN-738
2	PULLROD	ST. ST. 316L
3	COUPLING NUT	NIMONIC 80A
4	LOADING BAR	NIMONIC 80A

Fig. 1. Jig for SRT.

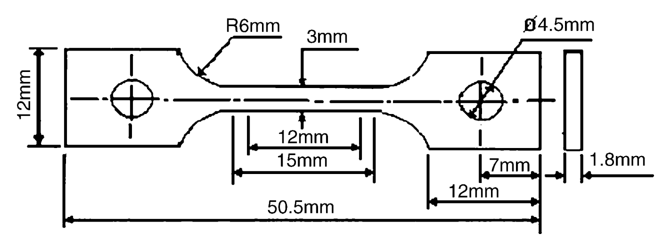


Fig. 2. SRT specimen.

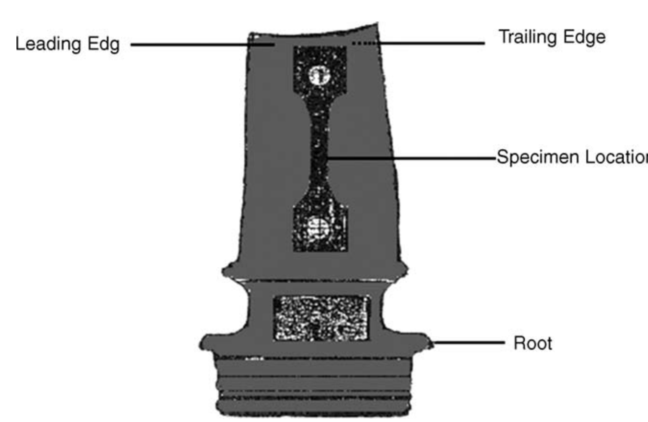


Fig. 3. Location of SRT specimen.

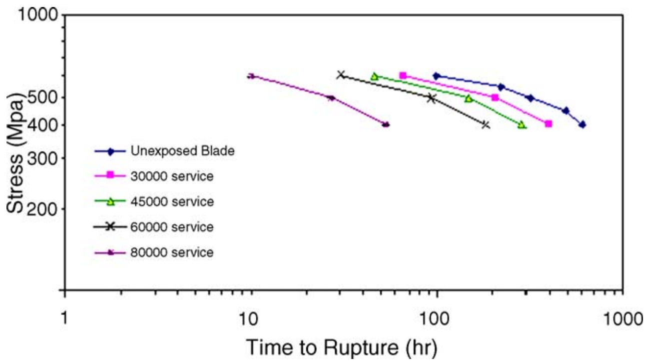


Fig. 4. Stress–rupture curve for unexposed and service-exposed blades.

examining the fracture surface of the stress–rupture test specimens.

3. Results

3.1. Stress–rupture properties

Stress–rupture test (SRT) is widely used in the estimation of creep life of high temperature materials instead of usual creep test because it does not need long periods of time and it gives good indication about the creep behavior of these materials [10].

For each blade the stress–rupture properties in accelerated test condition were determined. They include; time to rupture, total elongation and reduction in area. These data were used to construct the stress–rupture curves for the blades used as shown in Fig. 4. The effect of service life is shown clearly in the blades which were exposed to service for 80,000 h, they exhibit weak stress–rupture properties.

The creep strain data obtained from SRT are included in Table 2 and plotted in Fig. 5. It shows that the creep strain decreases with decreasing test stress and service life.

Based on the SRT the Larson–Miller parameter (P) was calculated and plotted versus the applied stress as shown in Fig. 6. It is obvious from the curves that the unexposed blades show the higher (P) for all applied stresses. The data for blades for

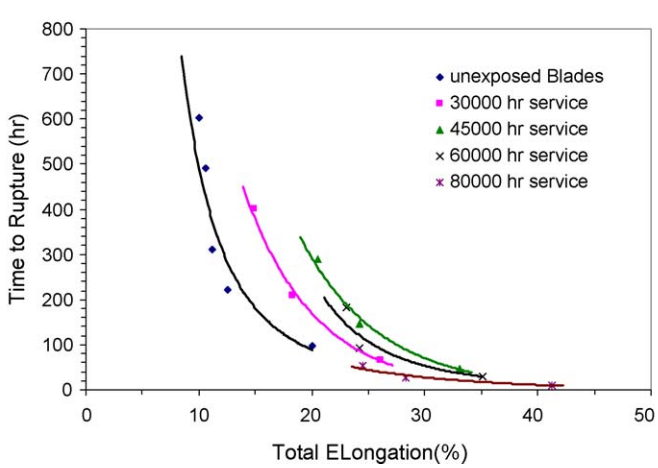


Fig. 5. Relationship between total elongation and time to rupture for unexposed and service-exposed blades.

Table 2
SRT Result for unexposed and service-exposed blade

Actual service life of blade (h)	Test condition (MPa)		Time to rupture (h)	Total elongation (%)	Reduction in area (%)
	Stress (MPa)	Temperature (°C)			
Unexposed	400	850	602	10.0	19.5
	450	850	491	10.6	18.9
	500	850	311	11.2	16.6
	550	850	221	11.3	21.3
	600	850	98	20.0	29.3
30000	400	850	401	14.9	21.8
	500	850	208	18.3	23.1
	600	850	65	26.1	35.6
45000	400	850	289	20.5	22.4
	500	850	147	24.2	25.5
	600	850	46	33.1	40.0
60000	400	850	183	23.1	27.1
	500	850	92	24.2	30.3
	600	850	30	35.1	40.4
80000	400	850	53	24.5	29.8
	500	850	27	28.3	32.7
	600	850	10	41.2	41.8

various periods are superimposed on the plot. The creep damage effects on rupture life are evident where the data fall below the limit for unexposed blades.

The life fraction rule proposed by Robinson [11] was used to determine the operation at creep life and residual life of the service-exposed blade.

$$\frac{T_s}{T_{rs}} + \frac{t_r}{t_r^*} = 1, \qquad \text{R.L.} = T_{rs} - T_s$$

where T_s is the actual service life of blade (h); T_{rs} is the operational creep life of service-exposed blade (h); t_r is the rupture time of service-exposed blade under accelerated test condition (h); t_r^* is the rupture time of the new materials (unexposed blade) under the same accelerated test conditions (h); R.L. is the residual life of service-exposed blades (h).

The results obtained are shown in Table 3. Based on these results the relationship between the residual life and the actual service life of blades were drawn as shown in Fig. 7.

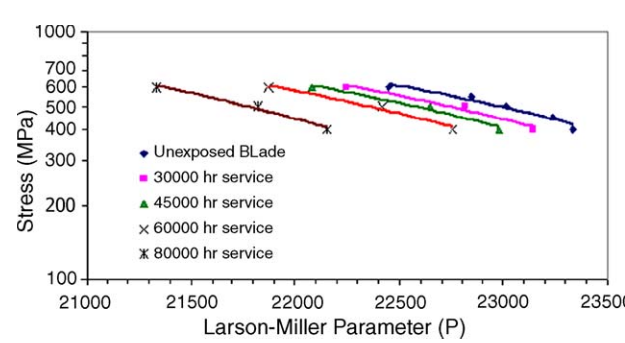


Fig. 6. Larson–Miller parameter for unexposed and exposed blades.

Table 3
Operation creep life and residual life of service-exposed blades based on life fraction rule

Actual service life of blades (h)	Test condition		Operational creep life (h)	Residual life (h)
	Stress (MPa)	Temperature (°C)		
30000	400	850	89850	59850
	500	850	90582	60582
	600	850	89090	59090
45000	400	850	86549	41549
	500	850	85335	40335
	600	850	84807	39807
60000	400	850	86205	26205
	500	850	85206	25206
	600	850	86470	26470
80000	400	850	87723	7723
	500	850	87605	7605
	600	850	89090	9090

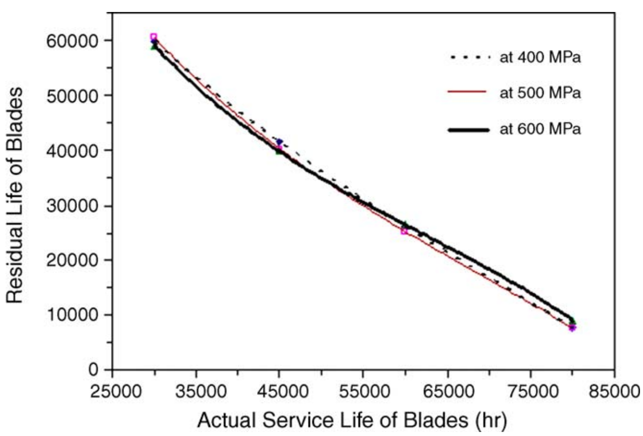
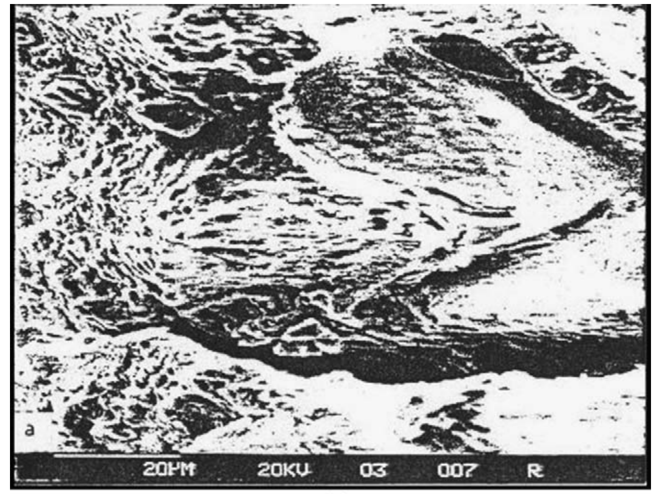


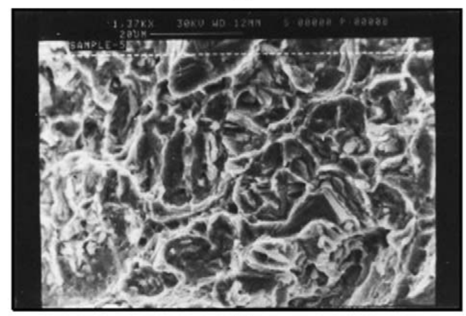
Fig. 7. Relationship between actual service life and residual life of service-exposed blades.

3.2. Microstructure examinations

These examinations show that the service-exposed turbine blades suffer from microstructural change. They include:



(a)

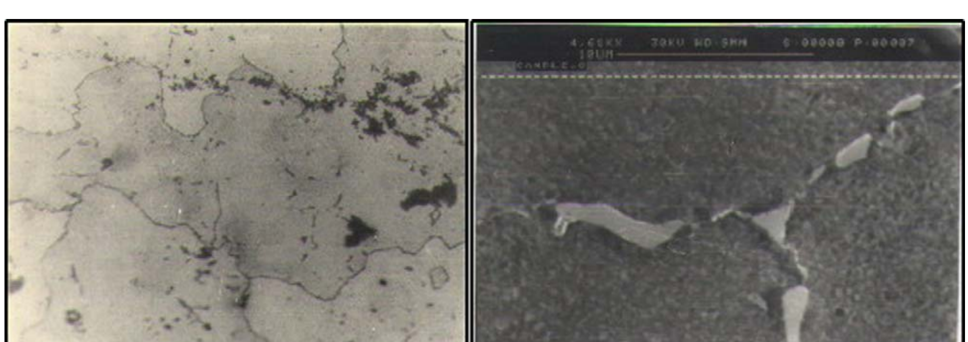


(b)

Fig. 9. Fracture surface of SRT specimens. (a) Unexposed blade, ×1100. (b) Service-exposed blade, 80,000 h, ×1370.

1. Disappearance of serrated grain boundaries as shown in Fig. 8a.
2. MC carbide degeneration and formation of continuous network of $M_{23}C_6$ carbide along the grain boundaries as shown in Fig. 8b.

SEM examination of the fracture surface of SRT specimens show that the fracture surface of unexposed blades was mainly transgranular fracture as shown in Fig. 9a.



(a) (b)

Fig. 8. Microstyctural examination of service-exposed blades: (a) disappearance of serrated grain boundaries, 60,000 h ×222; (b) formation of continuous network of $M_{23}C_6$ carbide along the grain boundaries, 60,000 h ×1833.

4. Discussion

From the stress–rupture test results shown in Fig. 4 it is obvious that all the curves are of the similar shape and nearly parallel at the beginning of the test but later the curves deviate and a change in the slope occurs. It is clear from this figure that the deterioration of the stress–rupture properties is faster in the blades exposed for longer periods. These observations are due to the microstructural change that occurs in the service-exposed blades during creep. These changes include disappearance of serrated grain boundaries formation of continuous network of $M_{23}C_6$ carbide along the grain boundaries and coarsening of γ' phase. Such microstructural changes will decrease the strength of the grain boundaries and the matrix, thus leading to deterioration of the mechanical properties and a decrease of the rupture time [9].

The total elongation (creep strain) of the specimens depends on the service life. It increases with increasing service life of the blades as shown in Fig. 5. This means that the blades exposed for longer periods are softened due to the coarsening of γ'-phase [5,9].

From Larson–Miller parameter shown in Fig. 6, it is evident that the rupture time of service-exposed blades is lower than the rupture time of unexposed blades. Accelerated SRT results showed that there is an enhancement in reduction of the creep rupture life with operating time relative to the creep rupture life of the new materials (unexposed blade) as shown in Fig. 6.

The relationship between the actual service life of the blades and the residual life is given in Fig. 7. It is clear from this figure that the residual life of the blades decreases with increasing service life due to the microstructural changes mentioned above.

Fracture surface examination of SRT specimens showed that the fracture mode is mainly transgranular in unexposed blades and in blades exposed to shorter service life (Fig. 9a) while it becomes trans-intergranlur fracture in service-exposed blades after longer periods (Fig. 9b). Intergranular fracture occurs due to various causes mentioned above [5,9], but at the same time a softening of the matrix takes place during the high temperature test and in service which results in more elongation but shorter rupture time as given in Table 2 and shown in Fig. 5.

5. Conclusions

(1) The rupture time of the specimens decreases with increasing the blade service life.
(2) The creep strain increases with increasing the service life of the blades at all the test conditions.
(3) Larson–Miller parameter can be used to extrapolate the results obtained from SRT to the actual service condition.
(4) The residual life of blades decreases with increasing service life.
(5) The operation at creep life of the blades should not exceed certain periods of time based on operation conditions.
(6) Turbine blades suffer from several microstructural changes, which affect their function. They are: disappearance of serrated grain boundaries, formation of continuous network of $M_{23}C_6$ carbide along the grain boundaries.

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