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Creep Life Prediction of Inconel 738 Gas Turbine Blade

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Abstract: The aim of this study is life prediction of IN738 LC gas turbine blade via Larson- Miller parameter method and fulfillment of some systematic metallographic, creep and hardness tests. Various calculative methods of remaining life prediction have been considered and Larson-Miller parameter method is used in order to predict remaining life of ABB-130 gas turbine blade. By investigation of the metallographic images it was observed that the hardening phase (γ') becomes bigger after passing of a long time and under high temperature (780°C) and has been converted from cubic to almost spherical status. It results in a decrease in the strength of the matrix and degradation of alloy's metallurgical properties and eventually generation of continuous carbides in the grain boundaries, bigness and joining of γ' particles, grain boundary refining and generation of creep voids, all of which resulted in satisfactorily calculation of remaining life time.

Key words: Remaining life prediction, gas turbine blade, nickel-based superalloy, Larson-Miller parameter

INTRODUCTION

Designing those parts which are working at low temperature and below creep temperature is usually performed with respect to yield strength, tensile strength and rupture strength via applying proper safety factor. In these conditions, deformation and fracture is not dependent on the time. So, working time for these parts has no meaning and the parts will continue working until the stresses applied thereof are not exceeding the designing stresses. However, about the parts which are working at high temperatures and the creep phenomenon occurs therein, deformation and fracture of the parts depends on the time. Hence, the maximum working time is defined for them. However, there are various definitions about failure of any part. The components most commonly rejected are the blades, from both the compressor and the turbine and the turbine vanes. The two principal causes are damage caused by ingested materials and the high temperature operation (Carter, 2005). Turbine blades operate at very high temperatures, very near of the edge of metallurgical alloy development. This working condition implies, additionally to be required to resist high mechanical loadings, that the material is degraded along the in service life. Three possible damage mechanisms threaten the integrity of the turbine blades; creep, multi-axial fatigue (associated with the interaction of low cycle fatigue in their longitudinal direction and vibrations induced by the gas flow in the perpendicular one) and high temperature corrosion (Silveira *et al*., 2009). Nowadays, development of manufacturing technology of the gas turbines and demand for more effectiveness require materials with the capability of supporting higher stresses and temperatures in longer periods of time. 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 (Marahleh *et al*., 2006). Erosion resistance, hot corrosion resistance and creep resistance in high temperatures (620-1200°C) are of the characteristics of superalloys. Among the super alloys, nickel-based superalloys which have been strengthen by the secondary precipitation hardening phase (γ') have complex physical metallurgy. The turbine blades are mainly made of cast nickel based super alloys. The IN738 superalloy is one of the important nickel based super alloys that has been developed in 1968 through following a series of extensive researches on the optimization of chemical composition in order to simultaneous improve the creep, hot corrosion and oxidation resistances of the alloys used in land based gas turbines. This alloy has been designed in two different types of high carbon IN738 C (for casting of thin parts) and low carbon IN738 LC (for casting of heavy parts). This alloy has high rupture-creep strength and excellent corrosion resistance in high temperatures. The nickel based superalloys strength is function of volume fraction, grains sizes, form and composition of γ' sediment, which it is possible to control these factors with respect to different degrees using heat treatment. Change in the mechanical properties can be resulted from the structural changes dependent on the time accompanied with lumping or change in the γ'

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phase performance. After passing of a long time the γ' grows under high temperature and converts from cubic to almost spherical shape. Also under these conditions some undesired phases such as TCP phases and some of continuous carbides such as $M_{23}C_6$ in the grain boundary are composed. Generation of these specifications in the structure results in degradation of metallurgical and mechanical properties of the blade and eventually its destruction. Up to now, many researches performed about investigation of creep and fatigue effects on the mechanical properties of superalloys and life prediction (Silveira *et al*., 2009; Marahleh *et al*., 2006; Leinster, 2008; Wilshire *et al*., 2008; Yue *et al*., 2008; Dobes and Milicka, 2008; MacLachlanand and Knowles, 2001; Baumshtein *et al*., 1985; Ohta *et al*., 1989; Yue *et al*., 1996). Identification and prediction of the blade remaining life prior to occurrence of the irreparable damages is significant issue due to the high production costs.

MATERIALS AND METHODS

This study was conducted from October, 2006 to September, 2008. It was an internship project and sponsored by Babol University of Technology and Bandar Imam Petrochemical Co., (BIPC). It was related to the gas turbine of BIPC's power plant.

The testing turbine blade is the 3rd stage IN738 LC blade (small blade). The chemical analysis of this blade has been shown in Table 1.

The metallographic pictures have been taken using an optical microscope, composed of two parts of airfoil and root of the blade. The creep tests of the three specimens taken from the three parts of upper airfoil, middle airfoil (shank) and root was performed. Also hardness test on the three specimens taken from the aforementioned three parts was performed. Figure 1 shows location of the specimens schematically.

Table 1: Chemical analysis of testing blade

C (%)	Co (%)	Al (%)	Nb (%)	Ti (%)	Mg (%)	Zr (%)	Si (%)	Cr (%)	Mo (%)	W (%)
0.09	8.0	5.0	0.88	0.42	0.03	0.03	0.03	14.9	2.22	3.0

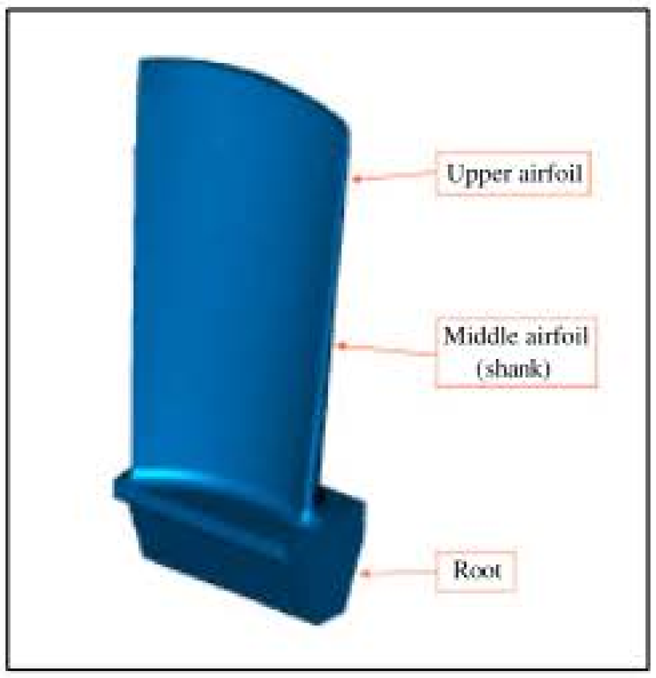

Fig. 1: Location of the specimens: upper airfoil, shank and root

RESULTS AND DISCUSSION

Metallographic investigations: By investigation of the metallographic pictures (OM) from two parts of airfoil and root, at the Fig. 2 and 3, it can be seen that the hardening phase or γ' becomes bigger after passing of a long time (61,000 h) under high temperature (780°C) and results in degradation of alloy metallurgical properties.

γ' growth depends on diffusion under high temperature that it results in joining γ' particles together and increasing the percentage of Mismatch γ'/γ. Increase of Mismatch level results in an increase in the strain energy resulted from the interface and also results that the γ' sediments become unstable even in absence of stress. There are two important carbides, namely MC and $M_{23}C_6$, in the blade. After passing of time and under high

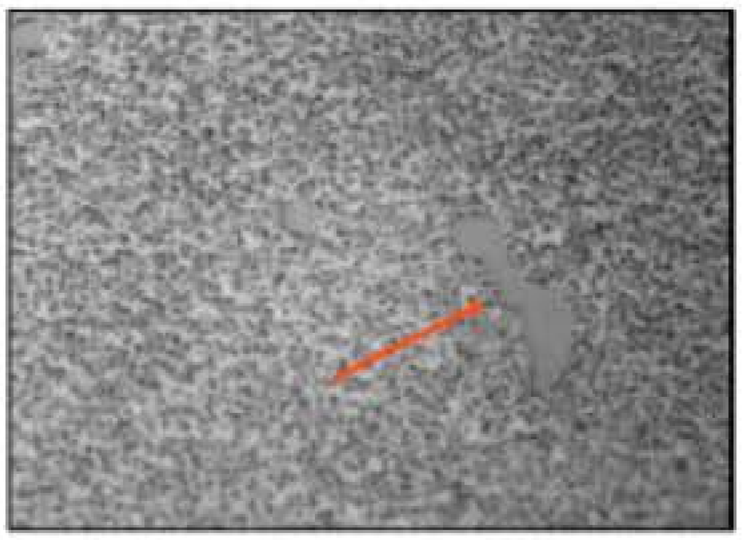

Fig. 2: Optical microscope image of the blade airfoil part, x1000

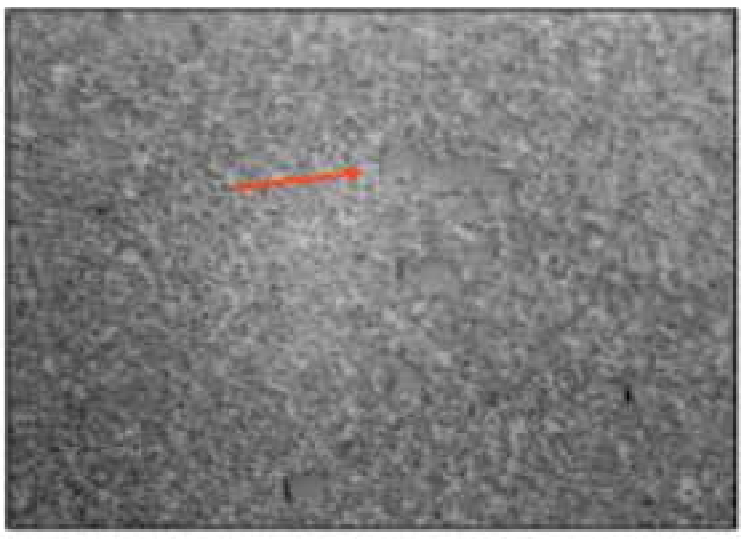

Fig. 3: Optical microscope image of the blade root part, x1000

Fig. 4: Composition of continues $M_{23}C_6$ carbides on grain boundary, x500

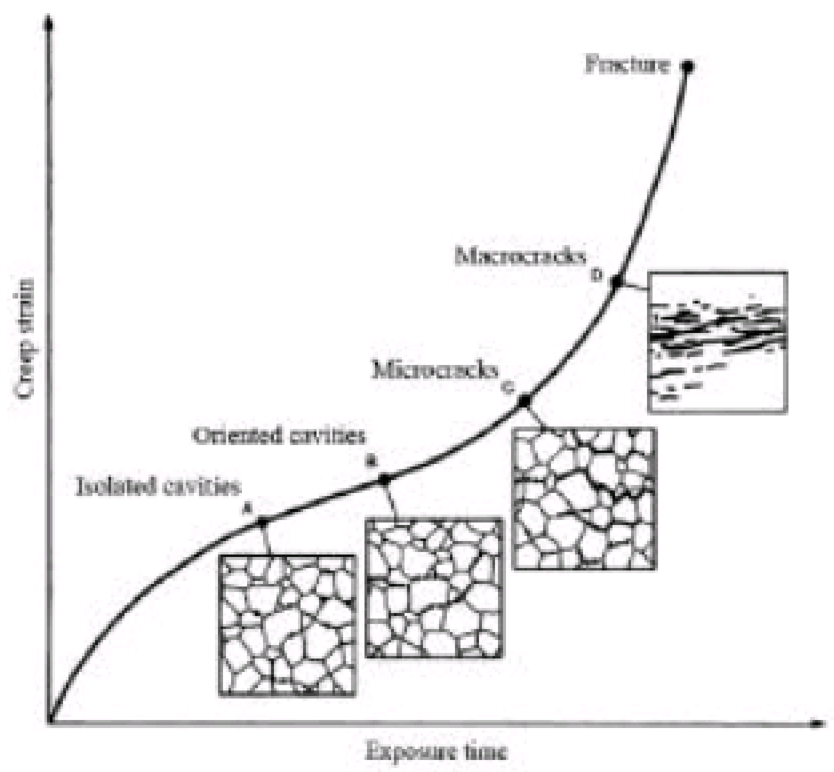

Fig. 5: Creep life assessment based on cavity classification (Neubauer and Wedel, 1983)

temperatures the $M_{23}C_6$ carbide is made on the grain boundaries and in long time a continuous layer of carbide covers the grain boundaries. Figure 4 shows this matter in the airfoil of testing blade. Composition of continuous carbide network at the grain boundaries significantly affects in reducing the mechanical and thermo-mechanical properties of the blade, which will be clarified significantly by creep and hot tension tests.

The first published attempt to relate creep-life consumption of plant components to cavitation was that of Neubauer and Wedel (1983). They characterized cavity evolution at four stage as shown in Fig. 5.

Group A: Isolated cavities
Group B: Oriented cavities
Group C: Linked cavities (microcracks)
Group D: Macrocracks

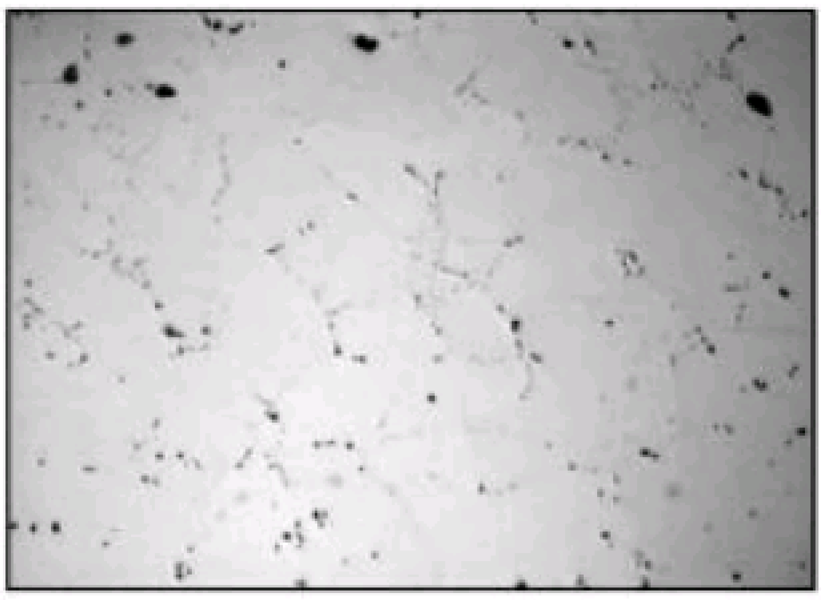

Fig. 6: Composition of isolated cavities in the blade airfoil area, x100

For the A region, there is no need for any safety proceeding, but for group B the inspection periods are defined between 1 to 3 years and for group C the replacement of the parts shall be performed within 6 months and in group D the parts shall be promptly replaced. Figure 6 shows generation of creep cavities during service in the testing blade. The cavities generated at the Fig. 6, show composition of group A or isolated cavities, which according to the aforementioned researchers' idea, there is no safety and emergency proceeding required and the part still has effective remaining life.

At most of the engineering parts, a series of reactions occur between the alloys and the environment which result in generation of some phases on the surface of alloy, in a way that the alloy loses its satisfactory applicability. The level of corrosion of the hot parts in gas turbines, with respect to the type of fuel consumed thereof, is different. The effect of fuel type on the parts lifetime, results from the distribution of the energy obtained from fuel at the combustion step. For instance the liquid fuels which make more radiating energy, depending on their atomizing capabilities, have the highest destruction at part compare with the gas fuel.

Also the suspended particles and the fuel compositions are other effective factors on the lifetime of the part. From the affecting the parts lifetime points of view, gas fuel is better than all other fuels, as it gives the best energy in combustion and has low sediment effects. After gas, gasoline has been reported as a proper fuel, after which are the heavy fuel and crude oil. The effect of corrosion on the airfoil surface of testing blade has been shown in Fig. 7.

Investigation of creep and hardness tests: The creep test results on three specimens specified thereof, have been shown in Table 2.

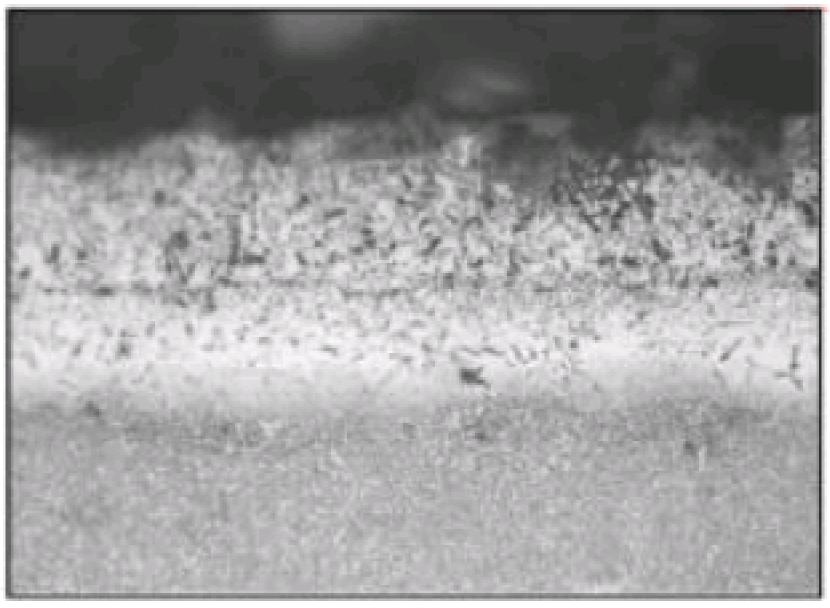

Fig. 7: The image of corrosion products in the airfoil area, x500

Table 2: The creeping test associated with the three regions specified on the blade

Creeping test	Upper airfoil	Middle airfoil	Root
Stress (MPA)	152.00	152.00	152.00
Gauge length (mm)	19.00	19.00	19.00
Primary dia. (mm)	3.54	3.49	3.48
Secondary dia. (mm)	3.35	3.37	3.32
Primary length (mm)	43.98	44.72	43.67
Secondary length (mm)	45.55	46.28	44.80
Temperature (°C)	982.00	982.00	982.00
Rupture time (h)	10.63	10.03	15.18

Table 3: The results of hardness test

	Upper airfoil	Middle airfoil	Root
Hardness	372 HV30	355 HV30	362 HV30

It is evident that by comparing the aforementioned results with the results of the unused blade we understand that creep properties of the used blade is definitely decreased and has a variety of reasons such as decreased volume fraction of primary and secondary γ', increased sizes of γ' particles, grain boundaries refining and generation of continuous chains of carbides. The wavy grain boundaries by preventing grain boundary slipping, can improve blade creep properties.

The results of hardness test on the three specimens which obtained from airfoil, shank and root of the blade have been shown in Table 3.

The IN738 LC alloy hardness (unused blade) is about 400 HV, while comparing this with the same specified in Table 3 it shows that the used blade level of hardness has been decreased for 10 to 15%, the reason of which depends on the γ' particles sizes increase and also their decreased volume fraction during the service.

Remaining life prediction: Various calculative methods of life prediction include the following:

Larson-Miller parameter: L-M parameter is useful in understanding and quantifying the time versus temperature trade-off for various materials. Its use results in a very effective method for rationalizing the time-temperature (and even rate-temperature) effects observed in stress-rupture and creep testing. L-M parameter is specified with respect to the Eq. 1 (Larson and Miller, 1952):

$$\text{LMP} = \text{T}\times10^{-3}\,(\text{C}+\log t_r) \tag{1}$$

where, C is a coefficient, whose value is dependent on the material chosen. In the Larson-Miller study, data for some 40 materials were evaluated: it was found that the constant C was very close to 20 for all materials (Naeem *et al*., 1998).

Manson-Haferd (M-H) parameter: This relation due to its higher flexibility shows the best conformity in extrapolation of rupture data. However, it is not used broadly to show the creep damages. The Manson-Haferd relation is defined by Eq. 2 (Manson and Haferd, 1953):

$$\text{MHP} = (\log(t_r)-\log(t_a))/(\text{T}-\text{T}_a) \tag{2}$$

where, T_a and log t_a are constant values resulted from the test data which for most of the nickel based superalloys strengthen by γ' have approx. values of 100 and 17, respectively.

Monkman-Grant relation: Monkman and Grant (1956) offered the following relation (Eq. 3) between the minimum creep rate with creep lifetime:

$$t_r\times\dot{\varepsilon}_m^n = C_M \tag{3}$$

Exponent n is found to range from about 0.8 to about 0.95 and the constant C_M ranges from about 2 to about 15, depending on the material (Baldan, 1992).

Dobes-Milicka relation: Dobes and Milicka (1976) gave a better relation between the rupture life and strain rate with respect to the M-G equation for the complex alloys. The Dobes-Milicka relation is defined by Eq. 4:

$$\frac{t_r}{\varepsilon_r}\times(\dot{\varepsilon}_S)^{m^*} = C^* \tag{4}$$

Koul equations: Koul *et al*. (1984) presented some new models for life prediction of blades by evaluation of the existing models. They announced that creep behavior of superalloys containing the γ' strengthener phase has a major difference with the behaviors of other engineering alloys, as a main part of the alloy lifetime is existed at the tertiary creep step. Thus, in the models presented by them, the different parts of the creep curve include strain of primary, secondary and tertiary stages creep and also the times of different creep steps have significant roles. Their first model has been specified by Eq. 5 (Koul *et al*., 1984):

$$\frac{t_p + t_s}{\varepsilon_p + \varepsilon_s}(\dot{\varepsilon}^M) = K \tag{5}$$

Equation 5 is accurate over a wide range of stresses (350-700 MPa) and temperatures (760-890°C) in IN-738LC. The method systematically reveals the creep degeneration effects with increasing service life. The relationship appears to be independent of any changes in the predominant deformation mechanism.

Regarding to the metallographic pictures (OM) and dispersed creep voids in Fig. 6 and also considering the voids have not reached the critical amount, we proceed with remaining life prediction of the used blade using the Larson-Miller parameter calculation method. First of all it should be mentioned that according to the aforementioned blade operating documentations, the blade superficial temperature during service was approx. 780°C, the stress applied thereto was 156 MPa and the blade service time was about 61,000 h. The L-M parameter can be obtained from the Larson-Miller curve associated with IN738 LC alloy. For this alloy it is approx. equal to 22.7. Also it should be mentioned that the C parameter associated with the aforementioned curve is equal to 16.59.

Thus regarding to the Larson-Miller parameter relationship, $t_r = 93325$ h and $t_{rem} = 93325\text{-}61000 \approx 32000$ h (approx.)

CONCLUSIONS

In this study, two methods (calculative and experimental) have been implemented for remaining life prediction of IN738 LC gas turbine blade. The Larson-Miller method used as calculative method for prediction of remaining life. Also effects of creep on the IN738 LC superalloy microstructure have been considered via., implementation of metallographic, creep and hardness tests. Results show that:

- Regarding to the OM pictures there can be seen some changes such as continuous carbides in the grain boundaries, bigness and joining of γ' particles, grain boundary refining and generation of creep cavities, which results in degradation of mechanical properties of the blade within the expectations of Larson-Miller
- By using the Larson-Miller method, the used 3rd stage blade (ABB-13D type) remaining life was estimated to be equal to 32,000 h, which also confirms the aforementioned matter, with respect to the manufacturer technical documentations
- Regarding to the metallographic pictures and hardness test on the specimens, it may be claimed that the aforementioned blade passed through proper service conditions

NOMENCLATURES

t_r : Rupture time
T : Operating temperature (K)
LMP : Larson-Miller parameter
C : Material constant
MHP : Manson-Haferd parameter
T_a : Material constant
Log (t_a) : Material constant
n : Exponent
C_M : Material constant
M : Constant value
K : Constant value
t_p : Primary creep life
t_s : Secondary creep life
ε_p : Primary creep strain
ε_s : Secondary creep strain
$\dot{\varepsilon}$: Creep rate
$\dot{\varepsilon}_s$: Secondary creep strain rate
$\dot{\varepsilon}_m$: Minimum creep rate
C* : Constant value
m* : Constant value
ε_r : Creep ductility

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