Thermo-Mechanical Fatigue (TMF) Life Prediction in Gas Turbine Blades

Arash Rahmani[1] , Ghiam Eslami [1], Ramin Soleimani[2]

[1] Department of Mechanical Engineering, Ahar Branch, Islamin Azad University, Ahar, Iran
[2] Departments of Engineering, Ajabshir Branch, Islamin Azad University, Ajabshir, Iran
* E-Mail of Coresponig Author: ara_rahmani@yahoo.com

Abstract: A Turbine blade, which is a main high temperature component of a gas-turbine for power generation does not tolerate the existence of cracks as it rotates at a high speed. Consequently, the development of an analytical method to evaluate the remaining life for crack initiation is required. The accuracy of remaining life evaluation by an analytical method largely depends on inelastic constitutive equations expressing on a creep-fatigue life evaluation method using such equations to estimate the remaining life for crack initiation. Therefore, in this paper, we studied creep-fatigue damage mechanism of gas turbine blades which is capable to describe inelastic behavior of the material and the damage mechanism. For this purpose we use Thermo-Mechanical Fatigue (TMF) life prediction models take into account the interaction between fatigue and creep at varying temperatures.

[Rahmani A, Eslami G, Soleimani R. **Thermo-Mechanical Fatigue (TMF) Life Prediction in Gas Turbine Blades** . *Life Sci J* 2013;10(3s):546-551] (ISSN:1097-8135). http://www.lifesciencesite.com. 86

Key Words: Fatigue-Creep, Life Time, TMF, Turbine Blades.

1. Introduction

Turbine hot-section components, such as blades, are designed to operate in high- temperature environments, with high thermal gradients and mechanical loads. Repeated engine start- up and shut-down operations subject components to cyclic strains which are generated both thermally and mechanically. These thermo-mechanical fatigue (TMF) cycles cause micro structural material damage to the components, and lead ultimately to fatigue crack initiation and failure. Advanced high temperature fatigue life prediction methodologies are needed to decide when to replace components, in order to increase reliability and service life, and reduce maintenance costs.

Predicting the lives of blades subject to thermo-mechanical fatigue continues to be a great challenge. In the last four decades much work has been performed in modeling fatigue crack initiation for a range of materials.

Many researches have examined creep-fatigue crack initiation and propagation modes in general [1, 2]. Some of them emphasizes on studying the effect of specific parameters such as hold time, Geometry, material parameters and metallurgical problems [3-5]. Also, a large number of models for isothermal crack initiation and life prediction approaches and variations exist, [6, 7].

In this paper, we define the inelastic deformation behavior and creep-fatigue damage mechanism for Ti-6Al-4V, a material for gas turbine blades. For this purpose we use Thermo-Mechanical Fatigue (TMF) life prediction models take into account the interaction. Because of the fatigue-creep process, it is necessary to utilize a viscoelastic material model in the finite element analysis.

3. Damage Analysis

Numerous approaches have been developed to predict the total life in material which operated in high temperature, the simplest and most common approach to predict fatigue life involves the linear damage summation model. The Linear Damage Summation (DS) model is the simplest expression for creep-fatigue life prediction. It ignores the micro-structural details of the damage process. It was introduced first by Taira [8] as follows:

$$D_{total} = D_{fatigue} + D_{creep} \quad (1)$$

D_{total} is the total damage, $D_{fatigue}$ and D_{creep} are the fatigue damage and creep damage respectively. The damage summation rule assumes that failure occurs when the sum of the fatigue damage and the creep damage is equal to a critical value.

If $D_{total} \geq 1$, the failure is occurred.

2. Fatigue Damage

There are commonly three recognized forms of fatigue, High Cycle Fatigue (HCF), Low Cycle Fatigue (LCF) and Thermo-Mechanical Fatigue (TMF). HCF is usually associated with low stress levels and low amplitude high frequency elastic strains. LCF is isothermal fatigue where the strain range during fatigue cycling exceeds elastic strain range and causes inelastic deformations so that the material exhibits a short number of cycles to failure. In the other words, Low- Cycle Fatigue (LCF) will take place when the temperature is below the creep regime or when a component is affected by isothermal cycling.

Isothermal LCF test has been used to determine the performance of materials applied in components as turbine blades and disks. Results of a LCF test may be used in the formulation of empirical relationships between cyclic variables of stress, total strain, plastic strain and fatigue life. They are normally presented as curves of cyclic stress or strain versus life or cyclic stress versus plastic strain and examination of such curves and comparison with monotonic stress, stress- strain curves gives useful information regarding cyclic stability of a material. LCF Life lies usually in the range between 10^2 to 10^5 cycles. The response of a material subjected to cyclic loading is presented in the form of hysterics loops. The total width of the loop is the total strain range $\Delta\varepsilon_t$ while the total height of the loop is the total stress range $\Delta\sigma_t$. The Total strain is the sum of the elastic strain and the plastic strain.

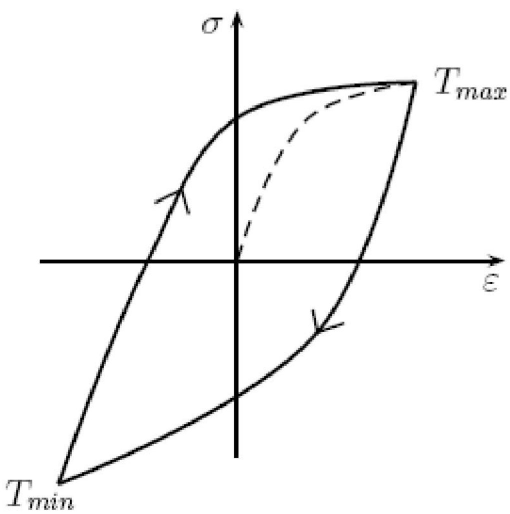


Figure 1: The In-Phase Thermo-mechanical Fatigue cycle

Thermo mechanical Fatigue (TMF) is a unique type of fatigue in which material is simultaneously, subjected to fluctuating loads and temperatures, and the theory of TMF Addresses the creep-fatigue interactions that occur. When hot-section components are subject to high temperature thermal cycles concurrently with mechanical strain cycles, TMF Conditions resulting in micro-structural damage occur. The lifetime of the components under such TMF Loading is quite different from isothermal life prediction obtained at the maximum temperature of operation, because in TMF the creep damage of the material should take into account and it is greatest.

There are two essential types of TMF cycles: In-Phase cycle and Out-of Phase cycle which are described as below:

In- Phase Cycle

This is when the strain and the temperature are cycled in phase, see Figure 1 typical example is a cold spot in a hot environment, which at high temperature will be loaded in tension and at low temperature loaded in compression.

Out- Of Phase Cycle

This is when the strain and the temperature are cycled in counter phase, see Figure 2 Typical example is a hot spot in a cold environment, which at low temperature will be loaded in tension and at high temperature loaded in compression.

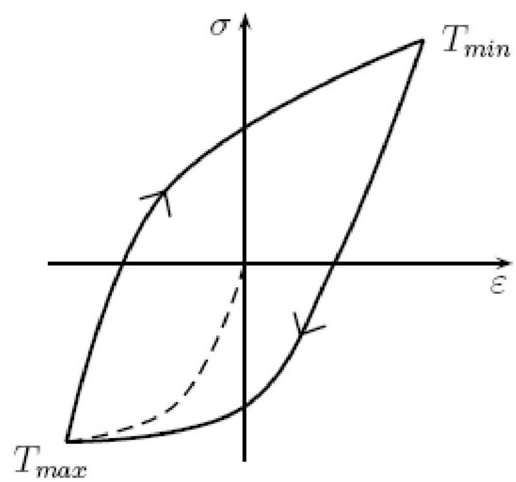


Figure 2: The Out-Phase Thermo-mechanical Fatigue cycle

As shown in Figure 3, under In-phase cyclic loading conditions, the maximum tensile strain occurs at the same time as the peak temperature, and the maximum compressive strain occurs at the minimum temperature. In contrast, under out- of-phase cycles, the maximum tensile strain occurs at the minimum temperature, and maximum compressive strain at the peak temperature.

Figure 3: In-Phase and Out- of- phase TMF loading patterns

For fatigue damage calculation we use the method of universal slopes. This method has the advantage of using material data obtainable from simple tensile tests. Based on The Basquin and Coffin- Manson relationship, the total strain range can be expressed as:

$$\Delta\varepsilon_t = \Delta\varepsilon_e + \Delta\varepsilon_p = B(N_f)^b + C(N_f)^c \qquad (2)$$

$$\frac{\Delta\varepsilon_t}{2} = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c \qquad (3)$$

Where σ'_f is the cyclic strength coefficient, b is the cyclic strength exponent and varying from -0.06 to -0.14, E is Young's modulus, N_f is the number cycles to failure at a given strain-range, ε'_f is fatigue ductility coefficient and c is fatigue ductility exponent and ranges from -05 to -0.7. The Strains in Eq. (3) are expressed as strain amplitudes hat are a half of the strain ranges. The Relation between strain and numbers of reversals to failure can be presented in a log-log plot as shown in Figure 4. Eq. (3) is written as:

$$\Delta\varepsilon_t = \frac{3.5\sigma_u}{E}(N_f)^{-0.12} + \varepsilon_f(N_f)^{-0.6} \qquad (4)$$

Where σ_u is ultimate fracture stress and,

$$\Delta\varepsilon_t = \frac{\sqrt{2}}{3}\left[(\Delta\varepsilon_x - \Delta\varepsilon_y)^2 + (\Delta\varepsilon_y - \Delta\varepsilon_z)^2 + (\Delta\varepsilon_z - \Delta\varepsilon_x)^2 + \frac{3}{2}(\Delta\gamma_{xy}^2 + \Delta\gamma_{yz}^2 + \Delta\gamma_{zx}^2)\right]^{1/2} \qquad (5)$$

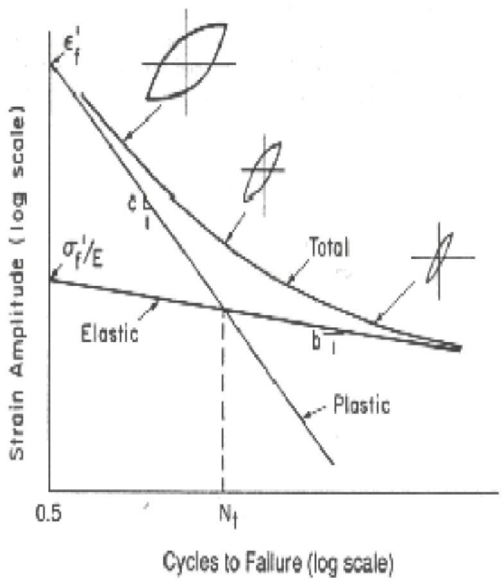


Figure 4: Strain-Life relations

Using Eqs. (4) And (5), we can estimate the value of N_f and then, the fatigue damage, D_f, is calculated as:

$$D_f = \frac{N}{N_f} \qquad (5)$$

Where N is number of completed cycles in particular stress, therefore:

$$D_{fatigue} = \sum_{i=1}^{n} \frac{N_i}{N_{f_i}} \qquad (6)$$

Where i implies the different case of loadings.

4. Creep Damage

When turbine blades operate at temperature which is greater than 40% T_{melt} creep occurs and should be considered as damage. Creep tests take a long time to perform making the generation of design data expensive and the lead time between developing a new alloy and its exploitation excessive. The fact that there is an Arrhenius relation between creep rate and temperature has led to a number of time-temperature parameters to be developed which enable extrapolation and prediction of creep rates or creep rupture times to longer times than have been measured. They also enable rating comparisons to be made between different materials. It is important that no structural changes occur in the region of extrapolation, but since these would occur at shorter times for higher temperatures it is safer to predict below the temperature for which data is known than above. One parameter used is the Larson-Miller Parameter, which is derived by taking natural logs of Arrhenius equation:

$$\dot{\varepsilon} = A\exp(\frac{Q}{RT}) \qquad (6)$$

$$Ln\,\dot{\varepsilon} = Ln\,A - \frac{Q}{RT} \quad \Rightarrow \quad Ln\,A - Ln\,\dot{\varepsilon} = \frac{Q}{RT} \qquad (7)$$

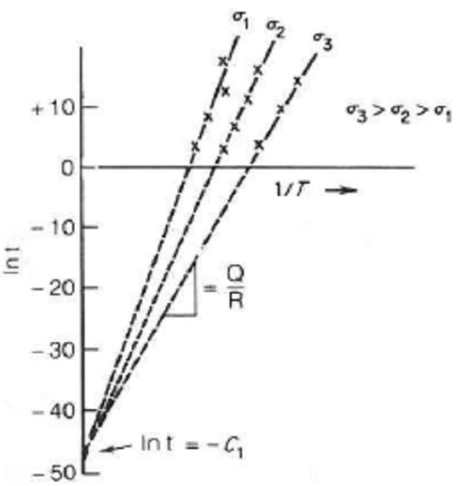
Where $A, \frac{Q}{R}$ are empirically determined creep constants corresponding to the time, T, at which the accrual of a pre-defined amount of creep strain is reached. If we assume that the creep strain to rupture, ε_r, is a constant over the temperature range of interest, and the major part of the creep strain is steady state creep, then the average creep rate over the life to rupture, t_r, of the specimen is:

$$\dot{\varepsilon} = \frac{\varepsilon_r}{t_r} \Rightarrow \quad Ln\,A - Ln(\frac{\varepsilon_r}{t_r}) = Ln\,A - Ln\,\varepsilon_r + Ln\,t_r = \frac{Q}{RT} \qquad (8)$$

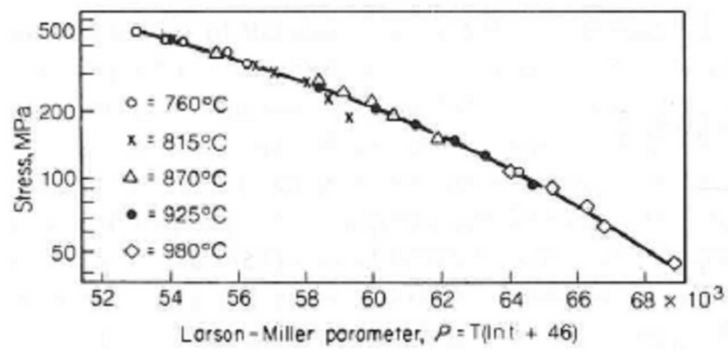
$$\Rightarrow \quad T(C_1 + Ln\,t_r) = \frac{Q}{R} = P \qquad (9)$$

Where $C_1 = Ln\,A - Ln\,t_r$, is the Larson-miller Constant and P is the Larson-Miller Parameter for a particular stress, $Q=(Q_0-\nu\sigma)$. Plotting experimental data of $Ln\,t_r$ versus $\frac{1}{T}$ gives a straight line with slope P and intercept at $\frac{1}{T}=0$ of $-C_1$. (7)

The values of C_1 range from 35 to 60, but is typically 46. Figure 5 shows that C_1 is independent of stress but P is function of stress and temperature.



(a)



(b)

Figure 5: (a) Stress rupture data as rupture time. (b) L-M Parameter

According to the Larson-Miller equation, we calculate the rupture time and consequently, creep damage as:

$$D_{creep}=\sum_{i=1}^{n}\frac{t_i}{t_{R_i}} \qquad (10)$$

Where t_i , t_{R_i} are the time spent and rupture time at a particular stress/ temperature.

5. Finite Element Model

The Finite Element (FE) model consists of two interrelated models. The thermal model calculates the temperature distribution in the component, based on the heat input from the hot gas. The mechanical model calculates the stresses and strains in the blades, caused by the varying temperature distribution and the externally applied loads.

The thermal model calculates the temperature distribution in the component. For each finite element on the surface of the component, the heat transfer coefficient follows from the CFD model. With the thermal conductivity α of the material, the temperature distribution in the blade can be calculated. The material which is used to FE model is Ti-6Al-4V with below chemical, physical and mechanical properties:

Table1: Chemical properties of Ti-6Al-4V (Grade 5)

N	C	H	Fe	O	Al	V	Ti
0.05	0.08	0.15	0.4	0.2	5.5-6.75	3.5-4.5	Balance

Table2: Physical properties of Ti-6Al-4V (Grade 5)

$\rho\ (g/cc)$	$\alpha\ (w/mK)$	Reduction of Area (%)	Elongation (%) in 4D
4.43	6.6-6.8	25	10-12

Table3: Mechanical properties of Ti-6Al-4V (Grade 5)

Young's modulus [Gap]	Yield strength [Mpa]	Ultimate strength [Mpa]	Poisson Ratio	HRC
100-114	825-869	895-930	0.34	36

6. Results

A mesh was produced using 50420-nodded isoparametric brick elements, each with 27 integration points, while convection boundary conditions were obtained from CFD analyses. A transient thermal analysis was then performed, and used in the stress analysis. The final distribution of the blade metal temperatures is shown in Figure 6. These results were used in a static stress analysis to determine the thermal stresses and, in particular, the maximum stress value at each point in the blade.

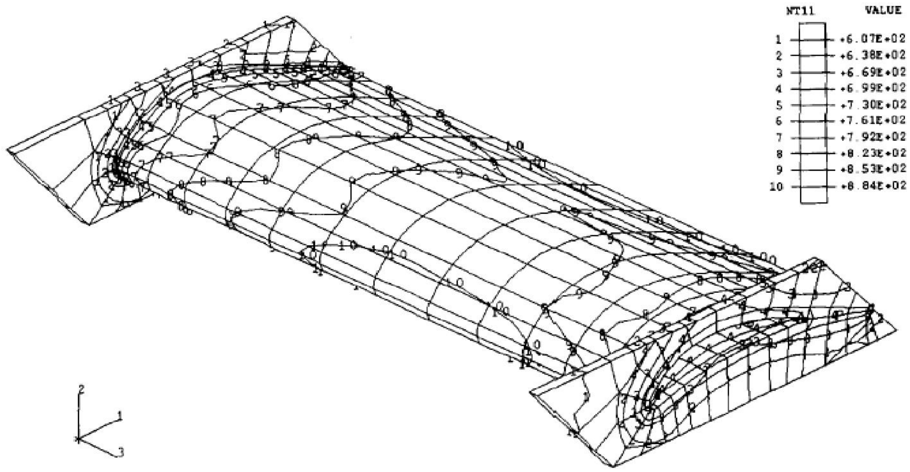


Figure 6: Temperature distribution by thermal analysis

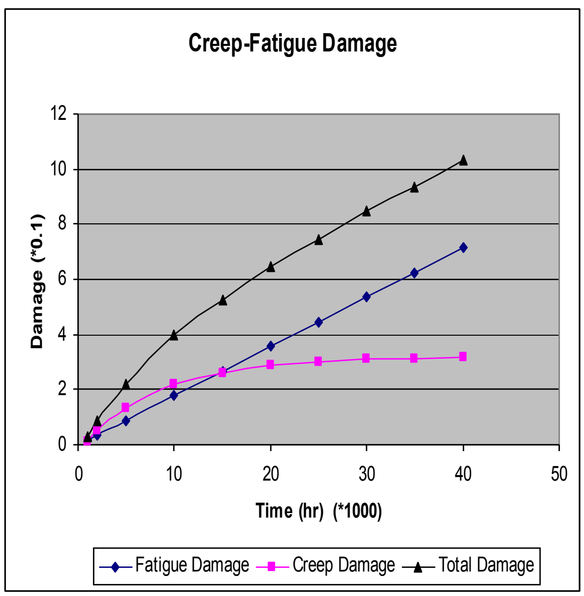


Figure 7: Damage Plots

Once the stresses were found, a creep step was performed, which reach to the total damage parameter $D_{total} = 1$. At this point a crack was assumed to have formed at the relevant element.

Figure 7 shows maximum values of fatigue, creep and total damage with conditions that are used ti solved this problem. It Is clear that fatigue damage is more than creep damage and blades are involved a failure when they operate more than 39200 hour where total damage exceeded a value of unity, $D_{total} = 1$. Also, The Creep damage rate was initially higher than the fatigue rate, but as stress relaxation occurred, this dropped off considerably.

7. Conclusion

In this paper, we use an integrated analysis for life prediction of gas turbine blades by TMF model and creep-fatigue interaction. For this, the accuracy of the temperatures calculated with the thermal FE Model is mainly determined by the accuracy of the heat transfer coefficient value which is calculated by CFD. Then, the results provide a codeing in MATLAB involved the following calculations:

1- Full creep analysis consists of creep strain calculations (Eq. 6), predicted creep rupture (Eq. 8), creep damage (Eq. 10).

2- Cycles number to failure, N_f , (Eq. 3), fatigue and total damages (Eqs. 6,1).

References

1. Ryuichi. O, Takayuki. K, Mitsuyoshi. T, Hideki. M, " Initiation And Growth Of Small Cracks In Creep Fatigue Of Oxide Dispersion-Strengthened Superalloys At Elevated Temperature," Japan Society Of Mechanical Engineers, Transactions A, Vol. 59, No. 560, pp. 933- 938, April 1993.
2. Maile. K, Klenk. A, Granacher J, Schellenberg. G, Tramer M, "Creep and Creep Fatigue Crack Behavior of ICr- and 9Cr- Steels," Key Engineering Materials (1013- 9826), Vols. 171-174, pp. 85- 97, 2000.
3. Gemma A. E, "Hold- Time Effect of a Single Overload on Crack Retardation At Elevated Temperature," Engineering Fracture Mechanics, Vol. 11, No. 4, pp. 763- 769, 1979.
4. Duggan T. V and Sabin. P," The Effect of Geometry on Crack Formation, Advances In Research on the Strength and Fracture of Materials," Proceedings of the Fourth International Conference on Fracture, Vol. 3A (A78- 33601 13- 23), New York, Pergamon Press, pp. 285- 292, 1978.
5. Berman I, Gangadharan A. C, Jaisingh G. H, Gupta G. D, " Effects Of Material Parameter Variability On Buckling And Creep Fatigue Interaction At Elevated Temperature" Transactions, Serie JJournal Of Pressure Vessel Technology, Vol. 98, pp. 75- 80, February 1976.
6. Salam I, Tauqir A, Khan A. Q, "Creep- Fatigue Failure of an Aero Engine Turbine Blades," Engineering Failure Analysis, Vol. 9, pp. 335-347, 2002.

M. H. Sabour, R. B. Bhat, "Lifetime Prediction in Creep-Fatigue Environment".

7. Taira, S., “Relationship Between Thermal Fatigue And Low- Cycle Fatigue At Elevated Temperature,” ASTM STP 520, pp. 80- 101, 1973.

1/8/2013