LIFE EVALUATION METHOD FOR GAS TURBINE BLADES MADE OF INCONEL718 ALLOY

SK Bhatti S Chandra Prasad D Radha Krishna IN Niranjan Kumar BVA Rao
Dept of Marine Engineering,
Andhra University,
Visakhapatnam – 530003,
INDIA

ABSTRACT
In turbo jet engines, rotating discs are simultaneously subjected to mechanical and thermal loads. A disc may be under internal pressure due to shrink fit on a shaft, in addition blade effects may be modelled by an external tensile load at the outer radius of the disc when the disc rotates with significant angular velocity while the gases crossing through fins exert a temperature gradient on the disc. Since material behaviour is temperature dependent changes in material properties throughout the blade should be considered. In order to attain a certain and reliable analysis for blade and to derive corresponding stress distribution, solution should consider changes in material specifications caused by temperature. To achieve this goal, an inhomogeneous blade model is considered. Using the variable material properties method stresses are analysed to evaluate the crack initiation and life for the first row blades to reduce the maintenance costs of gas turbines. The temperature and stress analyses are conducted on blades made of INCONEL718 at a temperature of 1300°C. Crack initiation and life evaluation is made based on multi-axial thermo mechanical fatigue (TMF) loading conditions.

KEY WORDS
Axial Flow Gas Turbine, Life Evaluation Stresses, Modelling

1. Introduction

In many turbine engine components, particularly the combustor and turbine structures of the engine, the stress and temperature conditions may be sufficiently severe as to require evaluation of the effect of inelastic material behaviour [l-3]. The development of crack growth prediction methods, the generation of experimental data, and the reliable application of the data to engine components are difficult because of the severe engine operating conditions. The requirement to accurately identify and experimentally duplicate the salient feature of the high-temperature, high stress crack propagation process presents a difficult experimental challenge, and the accompanying requirement for developing effective correlation and generalization parameters presents similar, strenuous analytical requirements. Current prediction model for hot section components of gas turbine provide crack initiation data which are calibrated with available experimental data [4]. While the ultimate removal life is related to the predicted crack initiation life, experience has shown that the time (or cycles) involved in propagating cracks is often a factor of two to ten times the predicted crack initiation life [3-5]. Since components are rarely removed because of short cracks and since the relationship between crack propagation rate and strain, temperature, hold time, etc. are different than for initiation, it is apparent that an improved prediction capability is warranted. High temperature low cycle fatigue is a strain-controlled process and for this reason strain-based approaches have been (and are being) preferred.

2. Experimental Procedure

The material selected for this purpose is INCONEL 718. It is a high strength, heat resistant superalloy (HRSA) that is used extensively by the aerospace industry for the hot sections of gas turbine engines for components such as, turbine disks, blades, combustors, casings, etc. The properties that make INCONEL 718 an important engineering material are also responsible for its generally poor machinability. Low thermal conductivity (11.4 W/m/K) leads to high cutting temperatures being developed in the cutting zone. These have been shown to rise from around 900^{o}C at a relatively low cutting speed of 30 m/min up to 1300^{o}C at 300 m/min [13]. The cutting forces generated are also very high, around double that found when cutting medium carbon alloy steels. Literature detailing the effects of operating parameters on tool life when machining nickel based superalloys is comprehensive, however, relatively little of this data refers to the effects of machining on work piece surface integrity. The main problems reported are surface tearing, cavities, cracking, metallurgical recrystalisation, plastic deformation, microhardness increases and the formation of residual stresses [14–20].
Figure 1 shows a meshed model of a turbine blade and the temperature distribution through the component at a particular time in its cyclic use. The model is developed

from the CAD description of the component at temperature of 1300°C.

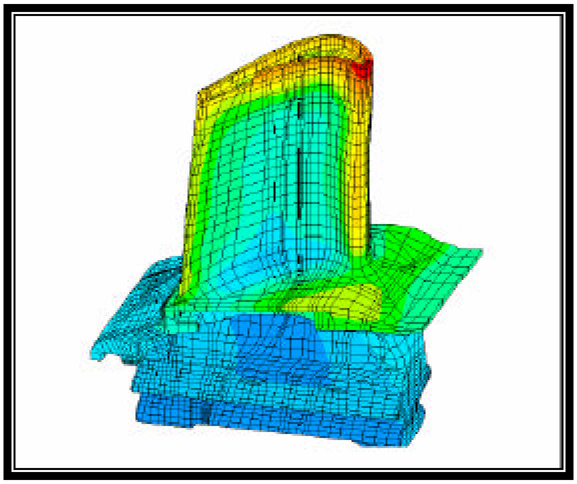

Figure 1 Temperature distributions with in turbine blade

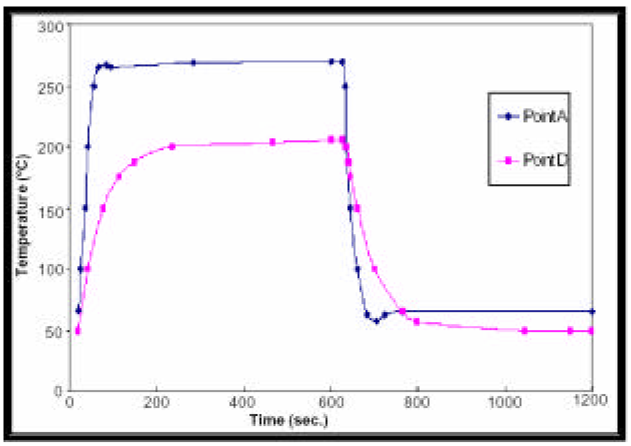

Figure 2 Variation of temperature with time in a turbine blade at two nodes during a load cycle.

Figure 2 shows the variation of temperature as a function of time. The calculated temperatures provide a measure of the structural distortion arise during the service to be expected and are used to compute thermal strains. The temperature distribution varies as a function of time and this is illustrated in this Figure where the temperatures of two blade positions are plotted with respect to key stages in the operating cycle. These data is used to identify whether any element has exceeded the design criteria defined by the material property data [20, 21].

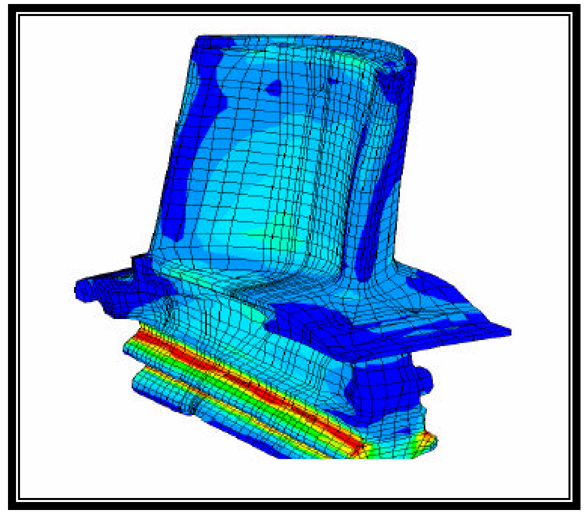

Figure 3 Stress distributions within a turbine blade

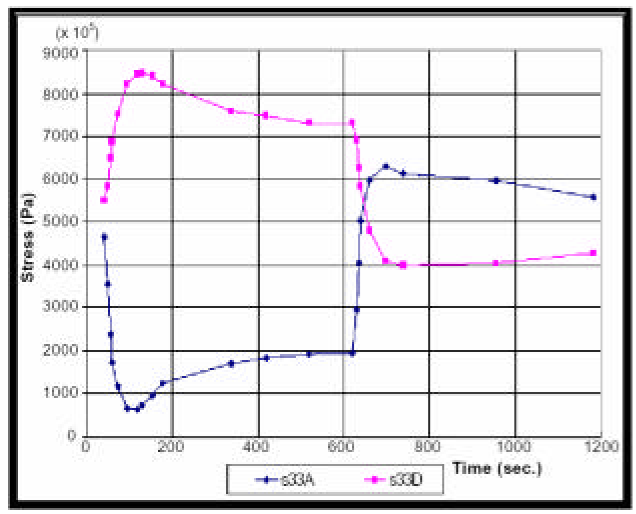

Figure 4 Variation of stress with time in a turbine blade at two nodes during a load cycle.

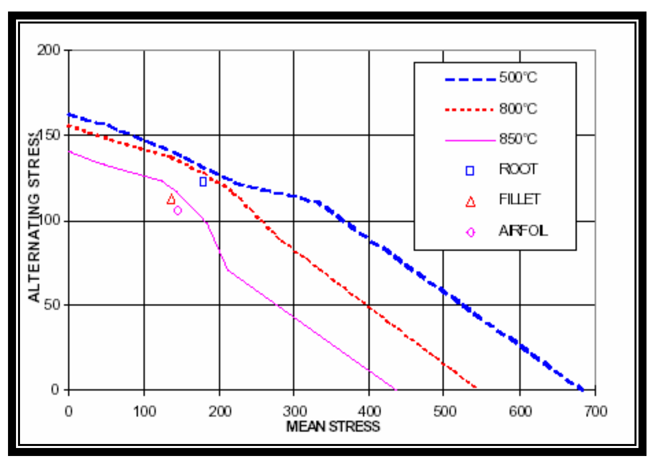

Figure 5 Comparison of stress in component with properties of INCONEL 718 at locations of interest

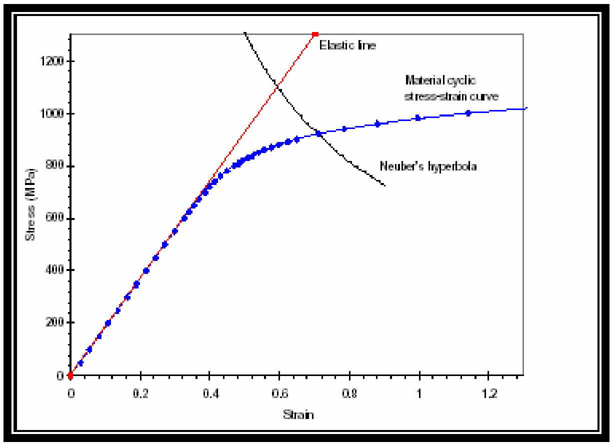

Figure 6 Stress strain curve and Neuber correction

The usual way of representing high cycle fatigue data which combines fatigue strength (stress to produce failure in 10^8 cycles at various stress ratios) with tensile and stress rupture values are represented in Figure 5. The criteria for maximum mean stress varies between application to application but 90% of the typical 0.2% proof stress or the stress to produce rupture in 1000 hours, which ever is the lower, is common. A strain-based low cycle fatigue calculation is used to assess the elastic results which demonstrate the stress at some locations where exceeds the 'yield stress' or a particular proof stress. This local stress will be accommodated by plastic deformation, the extent of which is calculated by means of a Neuber correction as shown in Figure 6

Neuber's rule is most commonly expressed in the form

$$K_t^{\,2} = K_t K_s \; = \frac{s}{S}\frac{e}{e}$$

For nominally elastic behaviour, $e = \dfrac{S}{E}$. When the Ramberg–Osgood equation for the stress–strain relation is combined with Neuber's rule for nominally elastic behaviour it leads to $\dfrac{S^2 K_t^2}{E} = \dfrac{s^2}{E} + s\left(\dfrac{s}{K}\right)^{\frac{1}{n}}$ If the nominal stress is larger than about $0.8S_y$, nominal behaviour usually becomes inelastic and non-linear stress– strain relations for calculating both the nominal and the local stresses and strains are used, resulting in

$$K_t^{\,2}\left[\frac{S^2}{E} + S\left(\frac{S}{K}\right)^{1/n}\right] = \frac{s^2}{E} + s\left(\frac{s}{K}\right)^{\frac{1}{n}}$$

Based on the results of displacement, strain and stress distribution from structural analysis, the deformation of turbine blade, its creep life, fatigue life (HCF or LCF), etc, are estimated for INCONAL 718 which are found to be with in the tolerable limits.

3 Life Estimation Of The Blades

The turbine blade is a rotating component and is free to extend as a function of time. There are two factors which limit its life; the first is excessive extension due to creep which may cause excessive wear or damage to the tip or shroud and the second, cracking leading to fracture, possibly accelerated by vibration. The first estimation assumes that the preliminary design criteria have been met with regard to stress limit and vibration and can conclude that its performance apparently meet the design requirements. However, use of the thermal, fatigue and structural analyses in conjunction with the cyclic stress strain variation throughout the cycle enables time and cycle dependent strains to be computed and assessed against the tensile, HCF, creep rupture or % creep strain and strain controlled fatigue data for each element in the model.

It is important to evaluate the crack initiation and life for the first row blades to reduce the maintenance costs of gas turbines. The temperature and stress analyses are conducted at a temperature of 1100°C. Crack initiation and life evaluation is made based on multi-axial thermo mechanical fatigue (TMF) loading conditions.

It is observed that biaxial TMF life of the INCONEL 718 alloy is not correlated with Mises equivalent strain range, which correlated with the biaxial TMF life of the alloy, due to the biaxial TMF life depending on not only the maximum shear strain but also normal strain on the maximum shear strain as shown in Figure 7.

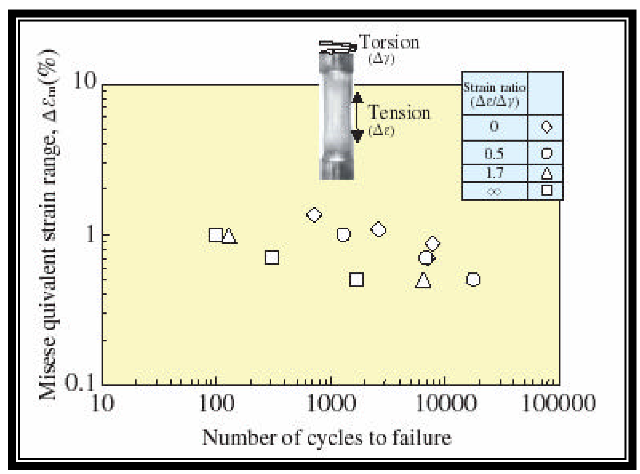

Figure 7 Mises equivalent strain range

An equivalent shear strain range, which is function of the maximum shear strain and normal strain on the maximum shear strain, is derived based on the G-plane theory (Theory that both the maximum shear strain and normal strain on the maximum shear strain plane control crack initiation under multi-axial stress condition)

A biaxial TMF life evaluation procedure for the 1300°C gas turbine blades is developed by incorporating the "equivalent shear strain range" to earlier researchers proposed procedure for the 1100°C class gas turbine blades is shown in Figure 8. The biaxial TMF life obtained from simulated actual blade temperature and strain conditions is predicted by the life evaluation model within factor of 1.5.

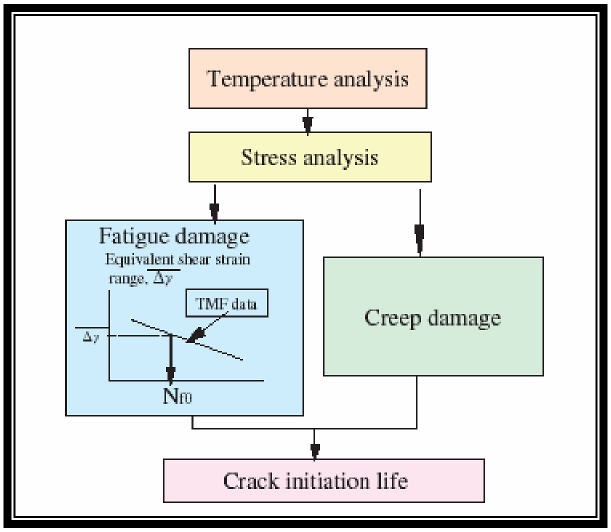

Figure 8 TMF Life evaluation flow

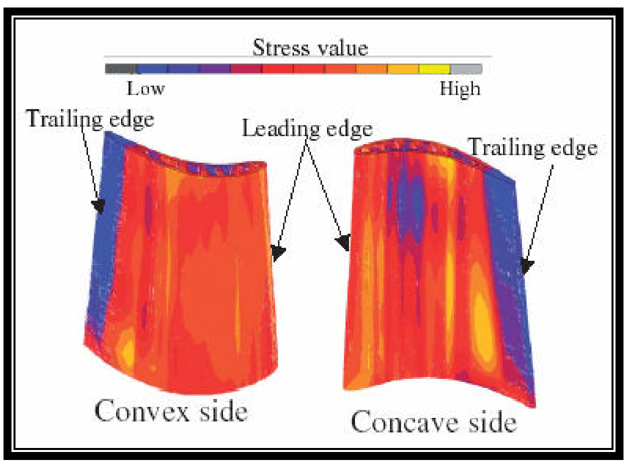

Figure 9 Stress analysis result of the blade

A crack initiation life assessment system based on a finite element analysis for INCONEL718 alloy gas turbine blades at 1300°C is developed by composing an inelastic constitutive equation. Which describes stress-strain behaviour of the alloy precisely, and the above mentioned TMF life evaluation method. Temperature and stress distributions within first row blades are analysed by using the system as shown in Figure 9.

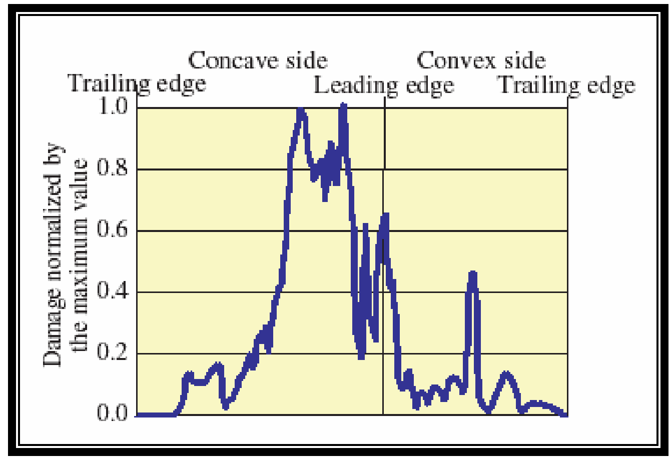

Figure 10 Damage distributions at mid height of the blade

From the temperature and stress analysis results, TMF life at mid height portion of the blade is predicted. It is found that convex side near leading edge had the maximum value of a damage ratio, which is defined as reversed number of the TMF life, and those values at the leading edge and at mid height in concave side were approximately 0.6 to 0.4 times of the maximum value as shown in figure 10.

3. Conclusion

There are different factors which influence blade life. High mechanical stresses and high thermal stresses are the main factors which cause damage and lead to the failure of the blades. High temperature gradient which is established between the rim and bore is the predominant factor in producing thermal stresses. These stresses when coexist with centrifugal forces generate high Thermal fatigue. For predicting the stress distributions on the blades, Calculations for temperature distribution are made. A finite element model is employed and the thermal problem is solved for the temperature distribution after attaining steady state conditions. Crack initiation and life expectation for the first row blades of gas turbine is analysed. The temperature and stress analyses are conducted on blades made of INCONEL718 at a temperature of 1100°C, as well as at 1300°C. TMF life at mid height portion of the blade is predicted and is found that convex side near leading edge had the maximum value of a damage ratio which is approximately 0.6 to 0.4 times of the maximum value.

References

1. **V. Moreno, G. J. Meyers, A. Kaufmann and G. R. Halford**, Non-linear structural and life analysis of a combustor liner. NASA TM-82846 (1982).

2. **R. L. McKnight, J. H. Laflen, and G. T. Spamer**, Turbine blade tip durability analysis. NASA CR-16268 (1981).

3. **V. Moreno, D. M. Nissley and L. S. Lin**, Creep-fatigue life prediction for engine hot section materials. NASA CR-1744844, Springfield, VA (1984).

4. **G. J. Meyers,** Fracture mechanics criteria for turbine engine hot section components. NASA CR-167896. Springfield, VA (1982).

5. **J. M. Larsen and T. Nicholas**, Cumulative damage modelling of fatigue crack growth in turbine engine materials. *Ennnn Fracture Me&.* 22. 713-730 (1984).

6. **R. P. Skelton,** Crack initiation and growth'in simple metals components during thermal cycling, in *Fatigue at High* Temperature, (Edited by R. P. Shelton) pp. 1-62. Appl. Sci. (1983).

7. **C. A. Rau,** A. E. Gemma and G. R. Leverant, Thermal-mechanical fatigue crack propagation in nickel- and cobalt-base superalloys under strain-temperature cycles. ASTM STP 520, 166-178 (1973).

8. **A. E. Gemma, B. S. Langer and G. R** Leverant, Thermomechanical fatigue crack propagation in an anisotropic (directionally solidified) nickel-base superalloys. ASTM STP 612, 199-213 (1976).

9. **A. E. Gemma, F. X. Ashland and R. M. Masci**, The effects of stress dwells and varying mean strain on crack growth during thermal-mechanical fatigue. J. *Test. Ed.* 9, 209-215 (1981).

10. **E. H. Jordan and G. J. Meyers**, Fracture mechanics applied to non-isothermal fatigue crack growth. Engng Fracture *Med.* 23, 345-358 (1986).

11. **E.A. Loria**, The status and prospects of alloy 718, J. Met. (July) (1988) 36–41.

12. **E. Bradley,** Superalloys: A Technical Guide, ASM International, Metals Park, 1989, ISBN 0-87170-327.

13. **T. Kitagawa, A. Kubo, K. Maekawa,** Temperature and wear of cutting tools in high speed machining of Inconel 718 and Ti–6Al–6V–2Sn, Wear 202 (1997) 142–148.

14. **R. Arunachalam, M.A. Mannan**, Machinability of nickel based high temperature alloys, Mach. Sci. Technol. 4 (1) (2000) 127–168.

15. **E.O. Ezugwu, Z.M. Wang, C.I. Okeke,** Tool life and surface integrity when machining Inconel 718 with PVD and CVD coated tools, Tribol. Transact. 42 (2) (1999) 353–360.

16. **A.B. Sadat,** Surface region damage of machined Inconel 718 nickel base superalloy using natural and controlled contact length tools, Wear 119 (1987) 225–235.

17. **F.W. Gorsler**, High speed machining of aircraft engine alloys, in: Proceedings of the International Conference on High Productivity Machining,Materials and Processing, New Orleans, LA, May 7–9, 1985, pp. 57–67.

18. **A.B. Sadat, M.Y. Reddy,** Surface integrity of Inconel 718 nickel base superalloy using controlled and natural contact length tools. Part 1: lubricated, Exp. Mech. (September) (1992) 282–288.

19. **A.R.C. Sharman, J.I. Hughes, K. Ridgway,** Workpiece surface integrity when turning Inconel 718TM nickel based superalloy, J. Mach. Sci. Technol. 8 (3) (2004) 1–16.

20. **Bullough and Piearcey**, "An on-line materials database for the design of gas turbine components", ASME Paper No. 97-GT-167, June 1997.

21. **C K Bullough,** Transactions of the ASME, Vol. 120, No. 3, p. 588. July 1998.