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STRESS ANALYSIS AND LIFE ASSESSMENT OF A GAS TURBINE BLADE

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ABSTRACT

This paper describes the stress analysis and life assessment of a first-stage air-cooled blade made of the superalloy IN738LC. Three-dimensional finite element thermal and stress analyses of the blade were carried out for the steady-state full-load operation. The results of these analyses were used for determination of the regions where the combination of high temperature and high tensile stress was sufficient for significant creep-fatigue crack growth. Accordingly, a critical point at the leading edge of the airfoil, near the root, was selected for crack modeling. With the assumption of occurrence of small-scale creep and thermal-fatigue during each start-stop cycle, the pertinent crack tip parameters were calculated using the energy domain integral method. An incremental crack growth scheme was considered and the total life for the growth of a 0.5mm surface crack to a 5mm through-thickness crack was calculated.

KEYWORDS: Life Assessment, Fatigue, Creep, Crack Growth, Turbine blade, Finite Element.

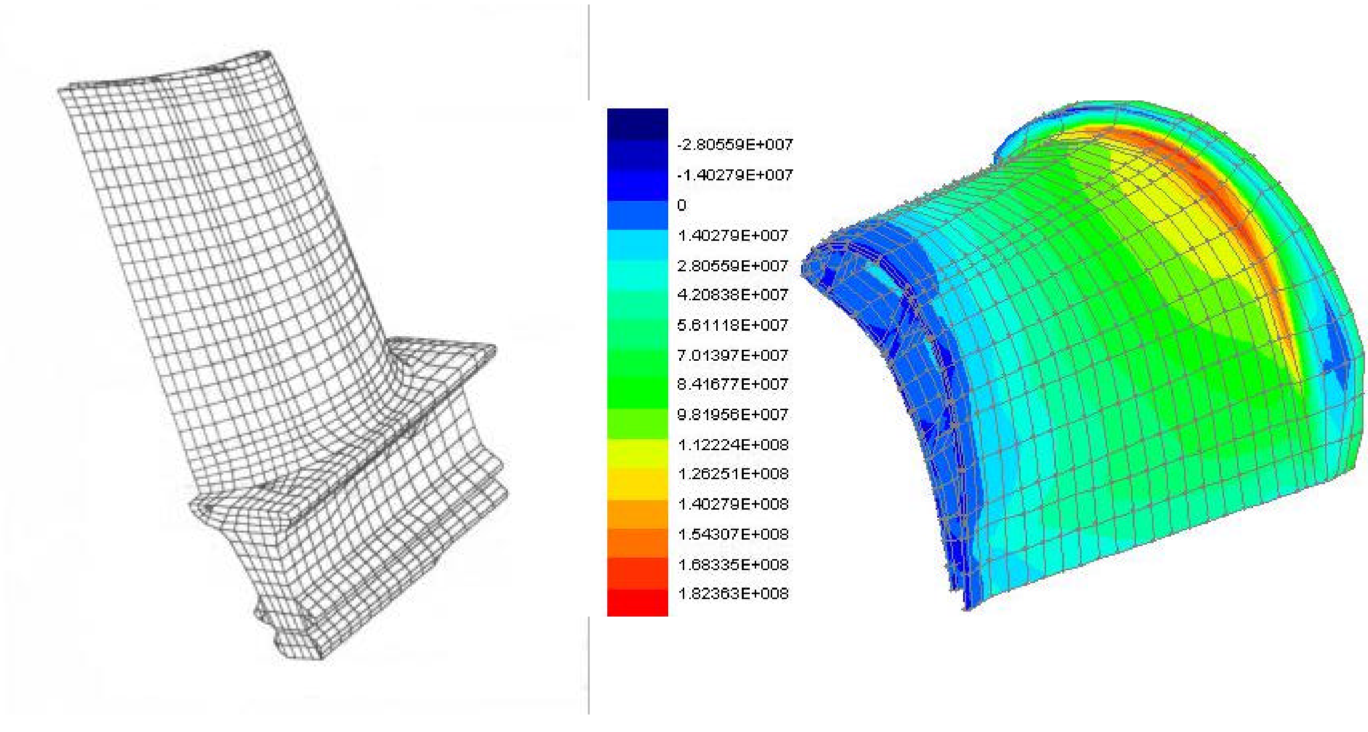
INTRODUCTION

The most sever cyclic duty for an industrial turbine blade is the peak-load generation commonly experienced in the utility combined-cycle plants, where the blades are subjected to frequent startups and shutdowns and also large numbers of working hours. Since these blades are made of superalloys and require costly manufacturing processes, they are very expensive to replace. Hence, it is essential to have accurate estimates of their useful life. Turbine blades are highly stressed components and because of their limited tolerance to cracks their life assessment is carried out in terms of crack initiation events [1]. However, the usage of Fracture Mechanics principles for modeling fatigue and creep crack growth can be considered as an important part of a comprehensive life assessment program. The accurate determination of fracture mechanics parameters is essential for modeling fatigue and creep crack growth. The investigation, partly reported in this paper, aims at fatigue and creep life assessment of a first-stage air-cooled blade made of the superalloy IN738LC.

Detailed failure analysis of cracked first-stage blades, for General Electric MS1001E industrial gas turbine, made of IN738LC has been reported by Bernstein and Allen [2]. They observed extensive leading edge cracking for a blade that had experienced 1800 start-stop cycles and 24000 hours of operation, with cracks penetrated through to the leading edge cooling hole. For an 11000-hour blade with 874 start-stop cycles, they observed a 0.5mm crack at the same location. In our investigation, we have tried to model a similar type of crack growth, for Siemens KWU V94 industrial gas turbine, using the results obtained from our finite element analyses and the material properties of the IN738LC obtained from the literature. The details of the thermal and mechanical stress analyses of the blade without crack were reported in [3,4]. The results of these analyses indicated that the maximum tensile stresses occur at the suction side of the airfoil at the corner of an internal rib. The computation of crack tip parameters for cracks modeled at the suction side of the blade using the point-matching methods was reported in [5]. The calculations of crack growth parameters at this location showed that the crack driving forces are not sufficient for creep crack growth, mainly because of relatively low temperatures. In the current paper, semi-elliptical surface cracks were modeled at a critical region at the leading edge of the airfoil, near the root, which is the hottest region in the blade. The computation of crack tip parameters was performed using the energy domain integral method. With the assumption of occurrence of small-scale creep and thermal-mechanical fatigue during each start-stop cycle, the pertinent crack tip parameters were calculated. An incremental crack growth scheme was considered and the total life was calculated.

STRESS ANALYSIS

The thermal and mechanical stress analyses were carried out using the general-purpose finite element package LUSAS. The finite element models of the blade were constructed using 8-noded and 20-noded brick elements. Figure 1a depicts the finite element mesh of the entire blade. The centrifugal forces were applied as body forces for the rotor running speed of 3000 rev/min. The pressure distribution, obtained from an aerothermal analysis of the turbine, varied between 0.2 to 1 MPa on different locations on the pressure side of the blade. The gas temperature distribution around the blade, also obtained from an aerothermal analysis, varied between 350° to 850°C. Figure 1b shows the distribution of the maximum principal stress component, due to the centrifugal and pressure loadings, in the airfoil. It is clear that the maximum tensile stress occurs at the suction side of the airfoil near the root. However, if the mechanical and thermal stresses are combined, the location of the maximum tensile stress will shift to the corner of an internal rib, which is in fact the coolest point according to the thermal analysis results depicted in Figure 2a. The results also indicate that the leading edge is the hottest region of the blade. Hence, the crack modeling was performed in a critical region of the leading edge near the root, in spite of relatively lower tensile stresses in this region.



(a) (b)

Figure 1: a) Finite Element mesh of the entire blade. b) Contours of maximum principal stress due to the mechanical loadings (stresses are in Pascal).

CRACK GROWTH ANALYSIS

The two major parameters used for correlating creep crack growth data are the stress intensity factor K and the integral C^*. The applicability of K is limited to situations where the size of the crack-tip creep zone is small relative to the crack length and other geometric parameters of the component. This is the so-called Small Scale condition (SSC), as opposed to the Steady State condition (SS) in which the crack propagation is accompanied by extensive creep deformation ahead of the crack tip. In the latter condition, the path-independent integral C^* is usually used. The transition time for SSC condition to turn to SS condition can be estimated by [6]:

$$t_1 = \frac{1+2\boldsymbol{b}_n}{n+1}\frac{K^2(t_1)(1-\boldsymbol{n}^2)}{C^*(t_1)E} \tag{1}$$

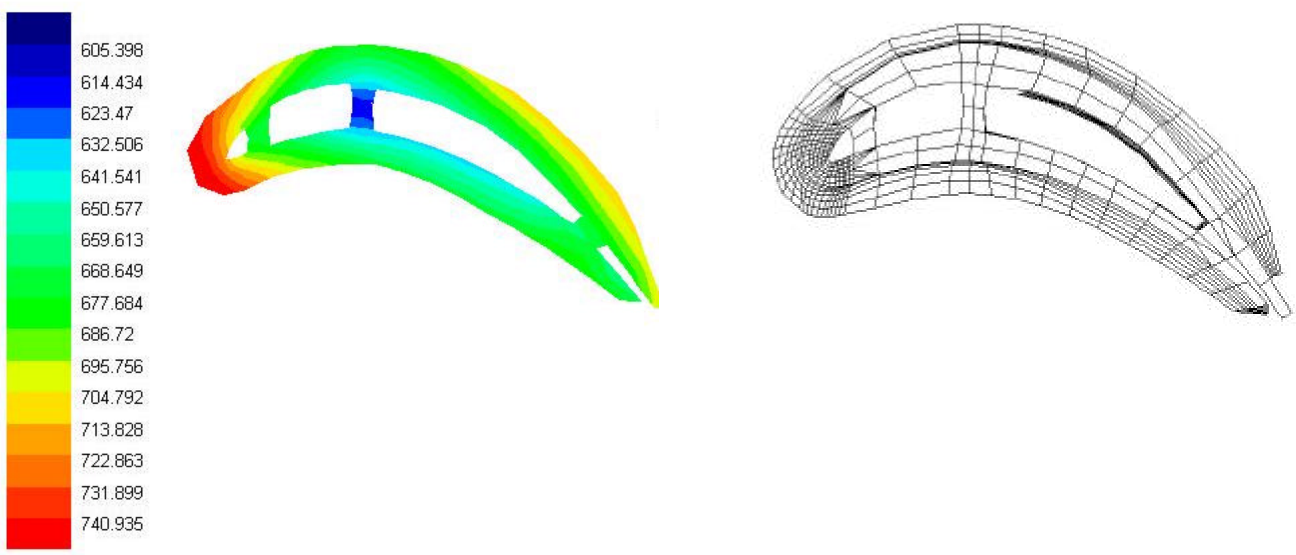
in which â is dependent on the waveform of loading and is defined by:

$$K(t) = K_1 t^b$$

where K(t) is the applied stress intensity parameter as a function of time and K_1 is a constant, í is the Poisson’s ratio, E is the elastic modulus, n is the Norton Law exponent, and C^* is the creep integral. If the cycle time t_C is less than t_1 then K is the correct crack tip parameter for correlating creep crack growth. Since the IN738LC is a high-strength creep-resistant material and the start-stop cycle-time of the peak load turbines are usually less than 10 hours, the assumptions of SSC condition and validity of applying K as the correlation parameter were considered in this study. Several procedures are available for numerical evaluation of stress intensity factors. In this study we used the energy domain integral method for calculation of the J integral and the SIF.

Crack Modeling

Figure 2b depicts the section of the airfoil at the crack location, where the mesh was refined for crack modeling. In order to model the crack, new nodes were added on the crack plane. Accordingly, the elements above the crack plane were redefined using the new nodes. In this way semi-elliptical cracks with different lengths from 0.5mm to 5mm were modeled in the area of refined mesh.



(a) (b)

Figure 2: a) Temperature distribution in a section of the airfoil near the root (C°). b) Modified finite element mesh at the same section for crack modeling.

Computation of the J Integral

The general formulation of the energy domain integral method, as proposed by Shih et. al. [7,8], in the absence of plastic strains and crack surface tractions can be written as:

$$J = \int_{A^*} \left\{ \left[\boldsymbol{s}_{ij} \frac{\partial u_j}{\partial x_1} - W \boldsymbol{d}_{1i} \right] \frac{\partial q}{\partial x_i} + \left[\boldsymbol{a s}_{ii} \frac{\partial \boldsymbol{q}}{\partial x_1} - F_i \frac{\partial u_j}{\partial x_1} \right] q \right\} dA \qquad (2)$$

in which W is the stress work given by: $W = \int_0^{e_{kl}} \boldsymbol{s}_{ij} d\boldsymbol{e}_{ij}$

In the above equations A^* is the integration area, ó$_{ij}$ and å$_{ij}$ are the Cauchy stress and strain tensors, u_j is the displacement vector, ä is the Kronecker delta, q is an arbitrary function that is equal to unity on Ã$_0$ and zero on Ã$_1$ (the inner and the outer integration paths respectively), á is the coefficient of thermal expansion, è is the temperature, and F_i are body forces. The detailed instructions for the finite element implementation of the domain integral method are described in [9]. In the absence of thermal strains and body forces within the integration area, the discretized form of the domain integral can be written as:

$$J = \sum_{A^*} \sum_{P=1}^{m} \left\{ \left[\left(\boldsymbol{s}_{ij} \frac{\partial u_j}{\partial x_1} - W \boldsymbol{d}_{1i} \right) \frac{\partial q}{\partial x_i} \right] \det \left(\frac{\partial x_j}{\partial \boldsymbol{x}_k} \right) \right\}_P \boldsymbol{f}_P \qquad (3)$$

in which m is the number of Gaussian points per element, î$_k$ are the parametric coordinates for the element, and ö$_P$ is a weighting factor. The above expression was evaluated for different crack lengths by a computer program [10], using the pertinent values obtained from the output files of LUSAS. Accordingly, the K values were calculated using the following expression:

$$J = \frac{\left(1 - \boldsymbol{n}^2\right)}{E} K_I^2 \qquad (4)$$

Finally, using a regression analysis, the following expression was obtained for the variation of K with the crack length at the desired region:

$$K_I = 58.4 \times a^{0.206} \qquad (5)$$

Crack Growth Calculations

The following expressions were obtained for fatigue and creep crack growth rates of IN738LC, based on the data presented in [11,12]:

$$\left. \frac{da}{dN} \right|_{Fatigue} = 6.7 \times 10^{-12} \Delta K^{3.5} \qquad \dot{a}(K) = \left. \frac{da}{dt} \right|_{Creep} = 2.07 \times 10^{-19} K^{7.18} \qquad (6)$$

The total crack growth per working cycle, da/dN, was then expressed as:

$$\frac{da}{dN} = \left. \frac{da}{dN} \right|_{Fatigue} + \int_0^{t_C} \dot{a}(K) dt \qquad (7)$$

in which, t_C is the holding time during each start-stop cycle. The numerical integration of the above equation between the two crack lengths of 0.5mm and 5mm, for a holding time of 8 hours, resulted in a total life of 11368 hours and 1421 start-stop cycles.

CONCLUSIONS

Three dimensional finite element thermal and mechanical analyses of an air-cooled gas turbine blade were carried out under steady-state full-load operation. It was found that the maximum tensile stress due to the mechanical loadings occurs at the suction side of the airfoil near the root. However, if the mechanical and thermal stresses are combined, the location of the maximum tensile stress will shift to the corner of an internal rib, which is in fact the coolest point of the section. The results also indicate that the leading edge is the hottest region of the blade. Hence, the crack modeling was performed in a critical region of the leading edge near the root, in spite of relatively lower tensile stresses in this region. Since the IN738LC is a high-strength creep-resistant material and the start-stop cycle time of the peak load turbines are usually less than 10 hours, the assumptions of small scale creep condition and validity of applying K as the correlation parameter were considered in this study. The computation of crack tip parameters was performed using the energy domain integral method. An expression for total crack growth per working cycle was obtained using the results obtained from our finite element analyses and the material properties of the IN738LC obtained from the literature. The numerical integration of the fatigue-creep crack growth expression between the two crack lengths of 0.5mm and 5mm, for a holding time of 8 hours, resulted in a total life of 11368 hours and 1421 start-stop cycles. It can be concluded that the blade under study has a very good tolerance to the existence of relatively large and detectable cracks. However, the more reliable predictions of crack growth rates and lifetime assessments require more sophisticated analyses that should consider the effects of thermal transients during each start-stop cycle.

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