ANALYSIS & MODELLING OF THERMAL MECHANICAL FATIGUE CRACK PROPAGATION OF TURBINE BLADE STRUCTURE

Prabhat Kumar Sinha, Mohd Kaleem, Ivan Sunit Rout, Raisul Islam

Mechanical Engineering Department
Shepherd School of Engineering and Technology
Sam Higginbottom Institute of Agriculture, Technology and Sciences
(Formerly Allahabad Agriculture Institute) Allahabad 211007

ABSTRACT

The main aim of this work is to assess damage tolerance of framework by using computational mechanics software. The work is presented through this methodology simulating cracks gradation in the surface of texture of the walls of turbine blade. A study model the 2D ANSYS auxiliary thermal/structural model was created to facilitate sensitivity study. Geometry derived a model was used for finite elements model and Crack simulation have been computed. The analysis was made under combined loads of thermal and mechanical loads. The present data were taken from typical turbine blade used to run a heat transfer analysis and study of thermal structural analysis. Final result got through the analysis of thermal structural fracture mechanics. The interact between thermal and mechanical loads acting on the framework at a specified place structural reaction to approach the crack extremely is accounted for by employing a structure sub modelling and interpolation tactics. Factor of stress intensity are calculated using expansion of the M-integral method by the embed in France 3D/NG. Crack trajectories are resolute by applying the maxima stress principle. Crack augmentation result in on specified place is mesh of special element and destructive region are treatment automatically applicable developed all quadrilateral meshing algorithm the forecasted custom fatigue crack propagation results of the proposed methodology compares well with published in field of observation of failed blades. The effectiveness of the methodology and its applicability to execution practical analysis of actual structure is demonstrated by simulating curvilinear crack augmentation in a airfoil wall from cooling hole, which represent a typical turbine blade micro feature, at last a effected tolerance design methodology is proposed, where the effects of thermal mechanical fatigue are based on the combined respond the both un cracked and cracked blade geometry, the advantage of
according to plans methodology are that if can accurately and parametrically of vary different input (complex model geometry, temperature gradient and material properties) to show the impact on the stress and strain as well as crack behaviour. The expected results can be estimate intensity of effects depends upon turbine engine condition and its specification.

**Keywords**: Thermomechanical fatigue, fracture mechanics, fatigue crack propagation

1. **INTRODUCTION**

1.1 **Turbine blades used in aircraft engines.**

Turbine blades and vanes used in aircraft engines are typically the most demanding structural applications for high temperature materials due to combination of high operating temperature, corrosive environment, high monotonic and cyclic stresses, long expected component lifetimes, and the enormous consequence of structural failure.

1.2 **Problem statement**

It is the intention of this paper to develop a novel sub-model methodology of advanced materials TMF crack propagation. This method enables prediction of a crack growth rate and trajectory. It is important to emphasize the sub-modeling approach to greatly reduce the amount of processed data. We will implement this new method into finite element software through development of user subroutines. The developed crack propagation framework and model predictions would lead to the formulation of damage tolerant failure criteria and possible design optimization.

2. **BACKGROUND AND LITERATURE REVIEW**

The primary goal of this article is to develop a methodology that accurately characterizes a crack growth resulting from TMF in turbine blades. To date, there has not been comprehensive research published in open literature which addresses this specific problem. To the best of our knowledge this is the first systematic study on this subject. However, when separating this problem into the general engineering issues that are connected to the application, some published researches are applicable. For example, any material undergoing cyclic loading involves fatigue research. When heat is also cyclically applied, the study of thermo-mechanical fatigue (TMF) research as is reasonable. Crack resulting from TMF involves a study of the effects of thermal gradients distribution, any study related to cracking concerns fracture mechanics and fatigue crack [23] growth. Additionally, modelling each of these types of the problems with FEA can be a research area by itself. So once these contributing subjects have been identified, a survey of the previous research in each of these areas should be done before investigating the more specific problem. Thus we will analyze: 1) thermal fatigue and TMF research, 2) fracture mechanics and fatigue crack [23] growth, 3) Thermal stress analysis and 4) sub – modelling approach.

3. **Thermal mechanical fatigue of the turbine blades**

There are 2 types of TMF – Cycle I and Cycle II. Cycle I, or the linear out of phase cycle, has a strain temperature profile characterized by the simultaneous occurrence of minimum strain and maximum temperature. Cycle I is generally the more damaging of the
two for high strength, low ductility materials because the compressive mechanical strains in conjunction with elevated temperatures may promote compressive creep, thereby causing the mean stress to shift upwards during each cycle and cause fatigue damage to increase. Rotor TMF crack initiation [20], if it does occur, is generally similar to a Cycle I type (Figure 1) since fatigue capability under this condition may be less than that determined isothermally.

Figure 1 In-phaseload and temperature waveform [10]

Cycle II, or in-phase TMF, occurs when the maximum strain is directly in phase with the maximum temperature. In these conditions, the mean stress can relax towards compression, which may delay crack formation and propagation depending on the damage mode (e.g., trans granular or inter granular). This type of cycle often occurs in conditions where thermal

Figure 2 Out-of phase load and temperature waveforms [10]
Expansion is not controlled by the adjacent material (Figure 2) or in cases where the rotational speed, as opposed to gas path temperature, dominates the total stress response. A wide variety of thermal and mechanical loading cycles are experienced by turbine airfoils. These are dependent on the location along the airfoil and the speed of the particular power transient. The phasing between thermal and mechanical loads defines the TMF response of the airfoil[10]. The extremes of load-temperature phasing are in-phase (Figure 1) and out-of-phase (Figure 2). In-phase cycles occur when an unconstrained local area of the blade is mechanically loaded at the same time the temperature increases. Out-of-phase cycling occurs when a locally constrained area of the blade tries to expand both mechanically and thermally as temperature increases. This usually causes the blade to go into compression. Out-of-phase cycling is generally the most harmful because stress relaxation at the maximum temperature develops high mean stresses. While actual turbine blade[24] TMF cycles are a combination of in-phase and out-of-phase cycles, TMF characterization of turbine blade materials is generally performed using out-of-phase cycles [10].

Figure 3 Typical Quadrilateral TMF Cycle[10]

Figure 3 An Typical strain and temperature cycle similar to those seen in turbine blade analysis. Temperature and strain are nearly out-of-phase. The points are individual time steps in the mission.
However, during in-phase TMF cycles the high temperature creep [19] is much more pronounced. The creep induced damage and creep induced residual stresses play the key role in IP TMF.

TMF life prediction in turbine blades commonly begins with 3D elastic finite element stress analysis. The elastic stresses and strains are combined in a TMF parameter to predict TMF life. Often the finite element analysis identifies the high strain locations within the blade and focuses detailed stress-strain constitutive analysis on those areas. The hysteresis loop predictions are used to define the shakedown stress state which can be applied to an appropriate TMF life prediction technique.
Thermal-mechanical fatigue damage mechanisms may occur in locations undergoing constrained thermal growth. Since environmental and creep damage can become active under these conditions with high temperatures, isothermal life predictions can be inadequate. The interaction of these effects needs to understand to develop a reliable and physically based predictive methodology for components that are subject to TMF conditions.

In summary [12], the following general rules apply for the TMF of nickel-base super alloys:

- The greatest TMF resistance has been obtained in the [001] direction. The elastic modulus and thus the stresses developed is lower than in other directions for single crystals.
- The mean stresses to be sustained and do not relax because of the TMF unsteadiness during the inelastic deformation. The mean stresses play a considerable role at finite lives, because the plastic strain range is smaller than the elastic strain range.
- Complex chemistries of oxides form with properties different from those of the substrate, resulting in internal stresses and oxide fracture that channels the crack into the material.
- TMF results display strain-rate sensitivity generally for the majority of nickel-base alloys at temperatures above 700° C. If the strain rate is reduced or hold periods are introduced, the cycles to failure are lowered.
- TMF IP damage is larger than TMF OP damage at high strain amplitudes, whereas the trend is reversed at long lives for most nickel super alloys. The diamond cycle often produces lives that fall between the TMF IP and TMF OP extremes.

4. THERMAL STRESS ANALYSIS

4.1 Analytical elasticity based solution for the crack nucleation.

One of cause because of which stresses may be set up in an elastic body is the unequal heating of different parts of the body. With a few exceptions, the elements of a body expand as the temperature is increased. If the element is allowed to expand freely, the body will be strained but there will not be any stress due to such an expansion. However, if the temperature rise in the body is not uniform and the body is continuous, the expansion of the elements cannot proceed freely and thermal stresses are produced.

Let us consider first an unstrained elastic body with a uniform temperature T0. Now imagine that the body is heated to some temperature T1 above T0. The body will be stressed if T varies from point to point in the body. The strain of an element may be considered as consisting of two parts. One part is due to the expansion of the element because of the change of its temperature. If \( \alpha \) is the coefficient of linear expansion of the material, which is defined as the change in length per unit length per degree rise in temperature, this part of longitudinal strain will be \( \alpha T \). There will be no shearing strains produced, because the expansion of a small element, due to change of temperature, will not produce angular distortion in an isotropic material. If the element is allowed to expand freely, this is the only component of strain and the element will not be stressed. Now, if the element is not allowed to expand freely, stresses will be produced and the total strain of the element must be the sum of that part due to the stresses and that due to the change of the temperature. Now let us consider a thin circular disk with uneven temperature distribution. Figure 4
Assume the temperature T is a function of the radial distance r only. We have a case of plane stress with rotational symmetry. In terms of cylindrical coordinates, we find:

\[ \sigma_r = \frac{1}{E} (\sigma_r - \nu \sigma_\theta) + \alpha T \]  (1)
\[ \sigma_\theta = \frac{1}{E} (\sigma_\theta - \nu \sigma_r) + \alpha T \]

The equilibrium equation
\[ r \frac{d}{dr} \left( \frac{d\sigma_r}{dr} \right) - \frac{\partial}{\partial r} (r \sigma_\theta) = 0 \]  (2)
is identically satisfied if we introduce the stress function \( \Phi \) such that
\[ \sigma_r = \frac{\Phi}{r}, \sigma_\theta = \frac{d\Phi}{dr}, \]  (3)
Substituting (1) and (2) into the compatibility equation
\[ \frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_\theta}{r} = 0 \]
and simplifying, we find
\[ \frac{d^2}{dr^2} \left( \frac{1}{r} \frac{d\Phi}{dr} \right) = -\alpha E \frac{dT}{dr} \]
Or
\[ \frac{d}{dr} \left[ \frac{1}{r} \frac{d\Phi}{dr} (r \Phi) \right] = -\alpha E \frac{dT}{dr} \]  (4)
This equation can be easily integrated, and the solution is
\[ \Phi = -\alpha E \int_a^r T r dr + \frac{c_1}{r} + \frac{c_2}{r^2} \]  (5)
Where the lower limit a in the integral can be chosen arbitrarily. For a disk with a hole, it may be the inner radius. For a solid disk we may take it as Zero.

The stress components can now be found by substituting (5) into formulas (3)

Hence
\[ \sigma_r = (\alpha E \int_a^r T r dr) + \frac{c_1}{r} - \frac{c_2}{r^2} \]  (6)

Consider a think disk which receives heat over its faces and rejects it at its circumference in such a way that the temperature at any point in the disk is essentially uniform through the thickness. If \( T_0 \) is the temperature at the edge of the disk and \( T_1 \) is the temperature at the centre, the temperature rise at a radius \( r \) is given by
\[ T = (T_1 - T) - (T_1 - T_0) \frac{r^2}{b^2} \]
Substituting the expression of $T$ given by the above formula into Eqs.(6) and integrating we obtain

$$\sigma_r = - \frac{1}{4} ae (T_1 - T_3) \left( 1 - \frac{r^2}{b^2} \right)$$

If there is a circular hole of the hole of radius $a$ at the centre of the disk and the edges are free of external force we have

$$\sigma_r = 0 \quad atr = \text{bandr} = a$$

Then

$$\frac{c_1}{2} + \frac{c_2}{b^2} = - \frac{aE}{b^2} \int_a^b Trdr \frac{c_1}{2} + \frac{c_2}{b^2} = 0$$

From which it follows that

$$\frac{c_1}{2} = \frac{aE}{b^2 - a^2} \int_a^b Trdr \quad c_2 = - \frac{a^2 aE}{b^2 - a^2} \int_a^b Trdr A$$

And

$$\sigma_r = aE \left[ - \frac{1}{r^2} \int_a^r Trdr + \frac{1}{b^2 - a^2} \int_a^r Tdr - \frac{a^2}{r^2 (b^2 - a^2)} \int_a^r Tdr \right]$$

$$\sigma_\theta = aE \left[ - T - \frac{1}{r^2} \int_a^r Trdr + \frac{1}{b^2 - a^2} \int_a^r Tdr - \frac{a^2}{r^2 (b^2 - a^2)} \int_a^r Tdr \right]$$

(7)

![Figure 5: Thermal stress components plot](image-url)
The plot of induced stresses shows that areas adjacent to the cooling holes always under tensile condition. Figure 5. The results reveal that the existence of cooling holes causes the stress and strain concentrations near the holes. Tensile stresses develop around the hole during cooling, as the area near the hole cools faster than the periphery. Therefore the hole is not allowed to shrink freely by the hotter material surrounding it. These conditions provoke crack initiation; because of tensile hoop stresses.

4.2 Finite element solution for the crack nucleation
4.2.1 CAD and FE geometry, thermal analysis
A few 2D models were created. The square plates with hole diameters 0.160” and side sizes 0.5”, 1”, 2”, 4” and 2” disk with 0.160” hole were meshed, the 300°F were applied to the hole edge and 1000 °F to the outer edge.

Thermal analysis completed based on the steady-state heat transfer problem. The different sizes of the finite element mesh and singularity issues have been reviewed. The heat conduction problem with convection boundary conditions analyzed using ANSYS.
4.1.2 The sensitivity study for boundary conditions

The reason to review the different temperature – stress scenarios is a simulation of flight conditions that brings crack propagation [21] at airfoil. This allows avoid full scale transient analysis. The discrete flight trajectory points were introduced by specifying temperature distribution and applying boundary conditions, and then analyzed to determine worst case loads for strain and deflection.

The sensitivity study of the boundary conditions was performed. The existence of a solution was evaluated by applying thermal loads and different boundary conditions. The finite element models were examined by performing thermal-structural analysis.

For the 2D model the different loading constrains were reviewed to identify possible Crack propagation [21] condition and eliminate improper displacement restrictions. The Approach to simplify mechanical loading conditions by remain the one node fixed in most applicable location an internal rib fixed in space for all two directions, and one other node at the same internal rib is fixed in the <010> axis or y-direction looks pretty much accurate for 3D study. Figure 7

The criterions for the crack location were predetermined by observed failure results [10],[11],[9]-crack initiation [22] possible from cooling hole; the location close to blade platform, pressure side of airfoils[10]. The LEFM crack propagation condition is expected on blade surface under tensile state of stress.

![Figure 7 Structural BC - the one node fixed in most applicable location an internal rib fixed in space for all two directions, and one other node at the same internal rib is fixed in the <010> axis or y-direction](image)
Figure 8 The combined deflected and undeformed shape and stress contour plots. Deformed shape is exaggerated. Structural BC: the leading and trailing edges are fixed.

Figure 9 The combined deflected and undeformed shape and stress contour plots. Deformed shape is exaggerated. Structural BC: the internal ribs and trailing edge are fixed.
The fixed internal ribs BC were analyzed. Figure 9, another approach to fix the leading and trailing edges, Figure 3-8. The displacements were applied to leading and trailing edges with an internal rib fixed in space for all two directions, and one other node at the same internal rib is fixed in the <010> axis or y-direction.

Figure 10 Structural BC: the vertical down displacements were applied to leading and trailing edges with an internal rib fixed in space for all two directions, and one other node at the same internal rib is fixed in the <010> axis or y. No temperature load.

Figure 11 Structural BC: the vertical up displacements were applied to leading and trailing edges with an internal rib fixed in space for all two directions, and one other node at the same internal rib is fixed in the <010> axis or y. No temperature load.
Figures 10 and 11 analysis completed to define the local tensile stresses location due to mechanical blade deformation. A few more random constrain location have been reviewed. In creating these studies no thermal distribution properties were altered from one case to another.

4.2 Thermal-stress analysis results

According to test results [2], [13] the mechanical boundary condition will be sensitive to the crystal anisotropy and structural and body loads applied. For the real blade model are such that the bottom and top planes (nodal components with displacements) must be interpolated from full blade model by using ANSYS submodeling technique. The approach to simplify mechanical loading conditions by remain the bottom plane fixed in the direction of the blade stacking axis, the <001> axis or the z-direction; and one node fixed in most applicable location an internal rib fixed in space for all three directions, <100>, <010>, and <001>, and one other node near edge is fixed in the <010> axis or y-direction with top plane nodes are constrained to remain coupled and planar can be used if these boundary conditions can be replicated from full model structural analysis and can give the non-accurate results.

The primary loading experienced by the blade section is the centrifugal force caused by the rotating mass of the blade; in order to simulate this, a uniformly distributed load is applied normal to the top phase of the blade section. The assumption is that there is sufficient constraint, because of the surrounding blade material, to counteract bending moments seen as a result of temperature gradients and non-uniform deformation rates [11]. The blade deformation will largely be controlled by the conditions at the ends of the blade. At the root, the blade will experience a relatively lower and more uniform temperature. Thus, if the root of the blade experiences a more uniform temperature, any other cross-section will be forced to deform at a uniform rate [11]. Therefore, to a first approximation, the constraint of planar sections has been applied in the blade model. The mechanical boundary conditions are prescribed to the model to determine the stress and strains fields from a subsequent ANSYS run. The thermal-mechanical results are then used as input for the following life analysis.

Figure 12 Possible Temperature distribution were chosen for the thermo-structural analysis
After completing the 2D models thermal-structural analysis studies the 3D models were analyzed for possible crack propagation condition. A few different structural BC scheme were selected and analyzed based on 2D models study for the boundary condition sensitivity study. The final thermal field distribution is shown on Figure 12. For the thermal-structural analysis the 3D model with simplified mechanical loading conditions was selected. To BC scheme is implemented by one node fixed in most applicable location an internal rib fixed in space for all three directions, and one other node at the same internal rib is fixed in the <010> axis or y-direction, the bottom plane fixed in the direction of the blade stacking axis, the <001> axis or the z-direction. The final model is plotted for the start-up case with thermal loading and BC applied. Figure 13. After thermal structural analysis was completed the expected crack propagation zone were defined. The magnitudes and directions of stress indicate that the component has significantly high stresses in the locations of expected cracks and with the principal stresses suitably aligned. It can be observed that the highest stresses occur on the internal surfaces of the blade.

5. SUB-MODELING APPROACH

The ANSYS is capable to build a sub-model and interpolate temperatures and loads. Usually the size of a crack is small relative to the size of the structure. Confining the remeshing for crack growth to the sub-model greatly reduces the amount of data that needs to be transferred to, and processed by. It also allows depart undamaged portions of a model with different structural modelling, complex boundary conditions and are meshed with another elements.

Sub-modeling is used for mesh modification only; it does not affect the analysis strategy. The remeshed local sub-model is inserted back into the global model and the stress and deformation analysis is performed for the full combined model. The sub-model can be redefined at any step of a crack growth analysis.

The two ANSYS mesh models (.cdb files) have built. The smaller portion of the 3D airfoil span was extracted for fracture analysis. This is not necessary but it illustrates the process that will be useful for larger models.
Also the altered full model was built. Each element component was archived as a separate model, writing the DB information to .cdb files, which consists of the exterior elements and the boundary conditions, as a regular ANSYS. The global and local models have shown in Figures 14 and 15. The Ansys options used to create node components. The node component on the local portion of airfoil should be the same as node component on the outer blade model.

5.1 Crack growth results
Prediction of 3D crack propagation was conducted with thermal-mechanical stresses induced and boundary condition applied for comparison with experimental and failure results. The corner crack growth predictions linked well with the experimental and failure results for similar material, temperature and load conditions [10], [11], [4], [7], [9], [14], [5], [6].
Prediction of crack growth in the presence of the complex stress field that results from various temperature fields on geometries that imitate features in actual blade was achieved. Considerable decrease in crack growth life due to crack propagation from the cooling hole was successfully predicted using the 3D fracture mechanics code. The model predicts the propagation of the crack front assuming linear elastic behaviour without the effect of possible residual stresses.

Several criteria have been proposed to describe the mixed-mode crack growth. Among them, one of the most commonly used is based on the maximum stress criterion at the crack tip. The maximum stress criterion postulates that the growth of the crack will occur in a direction perpendicular to the maximum principal stress. Thus, the local crack-growth direction is determined by the condition that the local shear stress is zero. In practice this requirement gives a unique direction irrespective of the length of the crack extension increment. Therefore the procedure adopted in the system is to use a predictor corrector (the subroutine embedded in Franc3D/NG) technique to ensure the crack path is unique and independent of the crack extension increment used.

The results obtained from an incremental crack-extension analysis are a crack path definition, individual crack shapes displacements, and stress intensity factors for different stages of crack growth and/or stress intensity factor histories and life predictions. Figures 16, 17, 18 and 19. Results of the linear elastic (LE) Franc3D/NG analysis are shown in Figures 16 and 17 includes the maximum stress intensity factors, plotted against crack length.

Figure 16 The normalized KI and KII along the final crack front under analyzed stresses
The calculated stress intensity factors indicate a strong mode I (KI) and mode III (KIII) interaction and a weak mode II (KII) interaction on the contact surface. However, on the free surface it is primarily a crack opening (KI) condition only.

Figure 17 The normalized KIII along the final crack front under analyzed stresses.

The plots of mode I, II Ks (the vertical axes of Figure 16) were based on the geometric calculation points along the crack front. The horizontal axes of these plots represented a location along the crack front with a scalar, unit less, value that varied from zero to one. Zero represented one end of the crack front and one represented the other end, both of which were on the free surface (surfaces inside hole and adjusted wall surface) of the FRANC3D model. The mode I Ks were two to three orders of magnitude greater than both the mode II and mode III Ks. These mode I dominant K findings confirmed crack installation and shape were nearly ideal because energy release rates are highest from mode I cracks in local tension fields. The calculated stress intensity factors indicate that only KI play a strong role in propagation, this is of course expected since the stresses were perpendicular to crack area. The plot also indicates that the average stress intensity factor along the crack front exceeds the critical SIF could be occurred.
Figure 18 Detailed evaluations crack size or shape and crack path geometry

This means mode I $K$ values should be greater than modes II and III $K$ values. A corollary to this, whenever mode I $K$ values were not dominant then crack front shape and orientations were not ideal. Therefore, future crack front advances would alter the crack front shape and or orientation. The mode I through III $K$ plots show the greatest changes in $K$ values near the free surfaces of the crack front. This typical behaviour was due to the singularity associated with the end of the crack front on the free surface of the model. Thus, $K$ values near the free surface contained the greatest degree of variation and uncertainty.

For the remaining life analysis, a $K_{eff}$ versus $a$ plot was constructed after completing crack growth iterations using the Franc3D Stress Intensity Factor History mode Figure 18. The stress intensity calculations in center of crack front were used, crack growth is locally perpendicular to the crack front. All points along a given crack front occur at the same life, $N$ thus, the $\Delta a$’s were calculated for each step as each local $K_{eff}$ as well. Figure 19.
The predicted fatigue life was preliminary estimated using the SURCK (UTC Pratt & Whitney lifting prediction code) Figure 20. The life prediction mode is available in Franc3D V 2.6. Crack lengths versus cycle count data are shown.
As expected the number of cycles increases as crack grows is reduced. Crack arrest develops before approaching compressive stress zone in airfoil wall. The crack size was changed from 0.010” to 0.040”. The shape of crack was mostly defined by local stress distribution.

This work shows that it is possible to predict crack growth for a penny shaped surface crack subjected to mixed-mode loading in general agreement with results obtained from published observations. The differences between the experimental results and the numerical predictions may partly depend on the material scatter and partly be due to deficiencies in the physical model. For instance crack closure may be developed in different ways for 3D surface cracks than for the 2D CT-specimens. Furthermore, with the implementation of fracture criteria, crack growth can be also directly analysed with a fracture mechanics approach. No convergence difficulty has been encountered during the crack growth analyses.

6. CONCLUSIONS AND RECOMMENDATIONS

A new appropriate approach to the phenomenological modelling of fatigue damage behaviour based on the well-known concepts of continuum damage mechanics is developed.

The article show how CAD modelling, finite element analysis, computational fracture mechanics, sub-modelling, meshing capabilities have been combined to create a methodology that provides an analyst with the capability to model realistically shaped cracks in existent turbine blades[24] subjected to realistic loads.

For our task we analysed one of the worst load cases based on sensitivity studies of temperature distribution and boundary conditions at cooling hole location. The thermal cycle for our study is simplified to Cycle II, or in-phase TMF, that occurs when the maximum strain is directly in phase with the maximum temperature.

The general thermal–stress problem separated into two distinct problems to be solved consecutively. The first is a problem (thermal analysis) in what is generally the theory of heat conduction and requires the solution of a boundary-value problem. When the temperature distribution has been found, the determination of the resulting stress distribution (thermal-stress analysis) is a problem in what is termed the nonlinear uncoupled quasi-static theory of thermoelasticity.

This article outlines a framework for damage tolerance assessment using computational mechanics software. The approach is presented through the methodology for simulating the growth of through cracks in the airfoil walls of turbine blade structures. It is based on the available thermal mechanical fatigue experimental studies and micro structural observations for advanced nickel based aunts the features, which are important for the comprehensive TMF and crack propagation modelling for structural analysis of turbine blades components.

Comprehensive knowledge of the crack propagation characteristics Comprehensive of nickel based supper alloys is essential for the development of structural integrity. For critical turbine blades application potential improvement in fatigue life, performance, structural efficiency and maintenance offer incentives for the selection and development of material with improved crack propagation resistance. In the aerospace industry, a fundamental understanding of the growth of long or macroscopic fatigue cracks under more realistic types of in-service loading is essential for the design, analysis, development and inspection of fail-safe structures. The methodology currently being used in design and analysis is the defect-tolerant approach, where the fatigue lifetime is evaluated in terms of the time, or number of
cycles, required to propagate the largest undetected crack to failure (defined by fracture
toughness, limit load or allowable strain criterion). This approach relies on an integration of
the crack growth expression, representing a fracture mechanics characterization of relevant
data on fatigue crack propagation. In the current study, as in [1], LEFM theories were used
for fatigue crack growth predictions. Fatigue crack growth rates were determined using a
modified Paris model accounting for crack closure. A crack is assumed to advance when its
SIF is large enough to overcome closure and is larger than the SIF of the previous load step.

7. THE FUTURE WORK

The knowledge obtained during this first work has shown the major interest crack
propagation methodology that involves usage 3D finite element and fracture mechanics
numerical tools. Results are promising and the perspectives are numerous to describe
durability issues of turbine blades. This thesis has also underlined the great complexity of the
material. To continue the work the crack propagation simulations for the different initial
flaws and crack-extension criteria need to be reviewed and compared. The dimension and
crack aspect ratios from the different simulations and the actual cracked blades are planned
for evaluation. The contribution of KIII/KI and KII/KI interactions to the crack propagation
needs to be defined. The incorporation/simulation of typical and overspeed mission cycles
under real life centrifugal, aerodynamic, thermal and thermal-mechanical loading conditions
need to be introduced. Vibration modes also influence the crack growth rate. Other aspects of
feature work are the initiation of crack inside the wall from a flaw, the creation of multi
cracks, the coupling of damage and crack evolution, the possible evolution of nodes in 3D.
The LEFM crack propagation model disregarded the effect of residual stresses. The creep
deformation behavior of nickel-based single crystal superalloys also controls the service
life of turbine blades used in modern turbine blades. The creep phenomenon takes place in
general at high temperatures and is characterized by the fact that under constant stress and
temperature, the material deforms visco plastically. This time-dependent plastic deformation
is governed by a changing in creep velocity which represents the response of the
material to loading.

A few models for the creep deformation behavior of single crystal superalloys were
presented in latest publications. Constitutive equations are constructed for single-crystal
nickel-based superalloys[15]. The model allows the following features of superalloy creep to
be recovered: dependence upon microstructure and its scale, effect of lattice misfit, internal
stress relaxation, incubation phenomena, the interrelationship of tertiary and primary creep,
and vacancy condensation leading to damage accumulation. In [16] an extension of the
Cailletaud single crystal plasticity model to include modelling of tertiary creep was discussed.
In [17] a general framework for advanced creep damage modelling was discussed.
The proposed approach consists in deriving a constitutive model at the continuum scale, where
state variables and effects can be homogenized, based on macrostructural features and
deformation mechanisms. A time-independent formulation has been derived for creep damage
and the procedure for identifying the material model parameters has been briefly indicated.
The creep involved crack propagation will be accomplished by performing anelastic-plastic
stress analysis of the model without the crack local model. For the creep analyses the residual
stresses will be computed in ANSYS or ABAQUS [18] prior to executing the crack growth
analysis. Separate analyses will be performed incorporating bulk residual stresses that result
from local yielding at the crack tip and by thermal-mechanical fatigue.
Each set of analyses will be conducted using the applied investigational conditions, and incorporated measured material properties including plastic deformation at elevated temperature, fatigue crack growth rates for varying stress ratios and measured residual stress profiles, where applicable.

In the case where bulk residual stresses only will be incorporated, the residual stress calculation should include one full loading cycle at elevated temperature. Residual stresses will be present after unloading due to yielding at the cooling hole/or another location. The results of [8] study successfully demonstrated the potential to predict the effect of compressive residual stresses on crack growth retardation at corner cracks; elevated temperature corner crack growth experiments on notched Rene 88DT specimens were performed. The development of methodology for the damage-tolerant approach based on finite element and fracture mechanics numerical crack propagation models can’t be successful using the current numerical codes. The implementation in numerical modelling concepts of local microstructural features like the grain size and geometry, the crystallographic orientation relationship, and the grain boundary structure will be excellent approach.

8. REFERENCES

8. A. L. Hutson; M. Huelsman; D. Buchanan; R. John1; S. Haering: Corner Crack Propagation in the Presence of Residual Stresses, AFRL-ML-WP-TP-2006-439

175
14. C.M. Branco and J. Byrne: Elevated Temperature Fatigue on IN718 Effects of Stress Ratio and Frequency, Proceedings of the 81st Meeting of the AGARD/SMP.
21. Lucjan Witek, Crack propagation analysis of mechanically damaged compressor blades subjected to high cycle fatigue, Engineering Failure Analysis Volume 18, Issue 4, June 2011, Pages 1223–1232
22. Lucjan Witek, Numerical stress and crack initiation analysis of the compressor blades after foreign object damage subjected to high-cycle fatigue, Engineering Failure Analysis Volume 18, Issue 8, December 2011, Pages 2111–2125
23. Daniel Leidermarka, David Aspenberga, David Gustafssona, Johan Moverareb, c, Kjell Simonssona, The effect of random grain distributions on fatigue crack initiation in a notched coarse grained superalloy specimen, Computational Materials Science Volume 51, Issue 1, January 2012, Pages 273–280
24. Tomasz Sadowski, Przemyslaw Golewski, Detection and numerical analysis of the most efforted places in turbine blades under real working conditions, Computational Materials Science Volume 64, November 2012, Pages 285–288