Physics-Based Prognostics for LCF Crack Nucleation Life of IMI 685 Aero-engine Compressor Disc

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ABSTRACT

A life cycle management-expert system (LCM-ES) framework is employed in this work for physics-based prognostics of a compressor disc. The modeling approach involves the integration of both global behavior and localized response of component at the microstructural level. This paper presents the results of a low cycle fatigue (LCF) case study for a near alpha titanium alloy (IMI 685) high pressure compressor disc using a microstructure based damage model and finite element analysis results. Both deterministic and probabilistic crack nucleation lives are determined at the two critical locations. The lognormal distributions of α-grain structure of IMI685 and hard alpha (HA) inclusions is considered in the probabilistic analysis, while the deterministic life is predicted based on their extreme values that would represent the worst life. In the LCF modeling, the plastic strain estimation assumes an empirical coefficient that has a strong dependence on the alpha grains and defect size. The proposed life prediction model is capable of capturing the effect of the grain size and hard alpha particle density variation on the LCF crack nucleation life. The worst case deterministic life corresponds well with 0.1% probability of failure and lie around 3542 and 4710 cycles respectively for the primary fracture critical location in the disc.

1. INTRODUCTION

Gas turbine engine (GTE) components are subjected to extreme cyclic loads of different nature, namely mechanical, thermal and environmental during the engine operation. The performance and remaining life of the components reduce progressively because of the structural degradation and this poses a number of challenges. During the engine start-up and shut down, low cycle fatigue (LCF) and thermal mechanical fatigue (TMF) are the two dominant damage mechanisms for materials failure (Joseph and Zuiker, 2006). High cycle fatigue (HCF) arising out of vibrations can cause additional damage thus further shortening the engine life. The HCF accounts for 56% of the major aircraft engine failures and ultimately limits the service life of the most critical rotating components (Lütjering and Williams, 2007; Lütjering, Williams, and Gysler, 2003). The fan and compressor blades in a GTE are prone to HCF failures because of the high mean operating stresses and foreign object damage (FOD) (Leyens and Peters, 2003, Metzger and Seifert, 2012). For efficient design and life estimation of the GTE components, both LCF and HCF effects need to be considered. Relatively larger amplitude, smaller frequency and lower number of load cycles are encountered in the LCF failures while higher frequency, smaller amplitude and larger number of cycles are generally present in the HCF failures. The integration of these two contrasting situations makes any performance and life prediction model complex and cumbersome. Nonetheless, highly reliable and integrated materials- mechanism(s) computational models are required for the performance and lifing analysis. The aero-industries, on the other hand, are in constant demand for improved performance of aero engines by pushing the operating variables like the temperature and structural stress to higher ranges. This trend makes the structural materials more vulnerable to early damage evolution and their faster growth resulting in shorter life and greater risks of failures.

High energy aerospace grade rotor materials are thermal-mechanically processed (TMP) following a number of critical steps within a small window of temperature and strain rate. The TMP follows various heat treatments to tailor specific microstructure and properties in the alloys (SWRI, 2008; Semiatin, Nicolaou, Thomas and Turner, 2008). In titanium alloys, the materials and manufacturing anomalies and defects are observed relating to material/metal flow and cracks/cavities. The hard alpha inclusions potentially degrade the structural integrity of high energy rotors. The life cycle management of rotors based on either the safe life approach or the damage tolerance philosophy is impacted. A damage tolerance based probabilistic fracture mechanics approach was considered by South West Research Institute (SWRI) to develop DARWIN code to enhance the life of conventional transport aero-engine rotors. The software essentially focuses on the LCF of titanium rotors/discs containing HA anomalies and considering residual stress effects (Lütjering and Williams, 2007; SWRI, 2008).

Our current on-going research focuses on the physics-based component specific technology solution for the assessment of the current damage state and the remaining useful life (RUL). The approach involves both global behavior and localized response of the material at microstructural level. The physical damage evolution and accumulation at micro level in components during operations of the GTE provide the vital inputs for life estimation. The material's response to loading and environmental conditions and experimental/ simulated damage state constitute the basis of our approach. The intended physics-based prognostics solution combines both flight usage and microstructural damage data for reliable prediction of RUL of the GTE. In this paper, our objective is to apply the material microstructure - LCF model for the assessment of deterministic and probabilistic life in titanium alloy. High temperature near alpha (α) Titanium (Ti) alloys, in general are used for demanding applications such as static and rotating gas turbine engine components. The combination of high strength-to-weight ratio, excellent mechanical properties, and corrosion resistance makes titanium the material of choice for many critical applications. The maximum operating temperature for the forged and heat treated Ti alloys in aero-engines has been raised from 300°C to 600°C in the last 50 years (Lütjering, Williams, and Gysler, 2003; Leyens and Peters, 2003). Near alpha high temperature alloy, IMI 685 is considered in this work as a test case. The LCM-ES framework employed in this work incorporates thermodynamics-based off-design engine modeling, computational fluid dynamics (CFD) and heat transfer analysis, finite element method (FEM) analysis and physics-based damage models.

2. ALLOY AND DEFECT CHARACTERIZATION

2.1. Near-α IMI685

Ti alloys with small amount of β stabilizers (< 2 wt%) offer excellent oxidation resistance rather than high temperature creep resistance. Typical applications of the alloy in aerospace industries include airframe skin components and jet engine parts (compressor casing and other parts) requiring high strength at 455°C. Nominal compositions and maximum allowable usage temperature are respectively Ti-6Al-5Zr-0.5Mo-0.25Si and 520°C. The range of microstructures for the IMI685 alloy consists of heavily deformed α–grains along with some spheroidized α to widmannstatten structure to acicular to martensitic structures (Boyer, Welsch and Collings, 1994). Quenching from beta phase fields produces laths of martensitic alpha which are delineated by thin films of beta phase. Ageing causes precipitation of fine alpha phase dispersion, while air cooling from beta phase fields gives a basket weave structure of widmannstatten structure of alpha phase delineated by beta phase (Wanhill and Barter, 2012). A large number of qualitative and quantitative models have been established describing their deformation and fracture behavior as a function of host of material parameters, including microstructure.

For the probabilistic life analysis presented in this paper, the size distribution of alpha grain size in IMI 685 alloy is assumed to be lognormal as displayed in Figure 1. The mean size of the alpha grain is considered as 55 microns (Nag, Praveen and Singh, 2006). The variance resulting from the mean and assumed distribution is assumed to be 22.5.

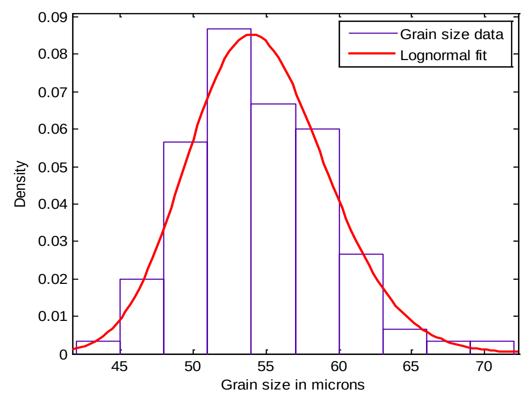

Figure 1: Lognormal distribution of grain size in IMI 685

2.2. HA Defect

Two types of defects (I and II) are known to be highly detrimental for the aircraft-grade titanium alloys. Type I or hard alpha (HA) represents the interstitially stabilized alpha phase with higher hardness and lower ductility as compared to matrix phase. The HA is characterized by excessive concentrations of elements like N (TiN), C and /or O. Type II are abnormally stabilized alpha-phase resulting from segregation of metallic alpha stabilizers, such as aluminum, contain an excessively high proportion of primary alpha and are slightly harder than the adjacent matrix (SWRI, 2008; Semiatin, Nicolaou, Thomas, and Turner, 2008; US patent 4622079). The HA inclusions tend to cause premature LCF crack nucleation. The inclusions are particularly detrimental as they are infrequently and sporadically found in ingot and finished forged products. Excellent coherency between low density HA defects and the matrix in the deformed product makes it difficult to be inspected during NDE. Microporosity as well as microcrackings are always associated with HA imperfections. SWRI has developed computer models for the prediction of the HA size and distribution as well as for diffusion zone (DZ) that correlates well with measured data (SWRI, 2008; Semiatin, Nicolaou, Thomas, and Turner, 2008; McKeighan, Perocchi, Nicholls and McClung, 1999).

For the probabilistic test case analysis presented in this paper, the size distribution of HA defects is assumed to be lognormal as displayed in Figure 2. The mean and variance for the data set are considered to be 17.7 μm and 7.5 respectively to reflect the lower values usually found in thin IMI 685 discs. The two lognormal parameter estimates are μ=2.862 for location and σ = 0.154 for scale. However, much larger HA defect sizes are also reported with much less likelihood of occurrence (Semiatin, Nicolaou, Thomas, and Turner, 2008; McKeighan, Perocchi, Nicholls and McClung, 1999).

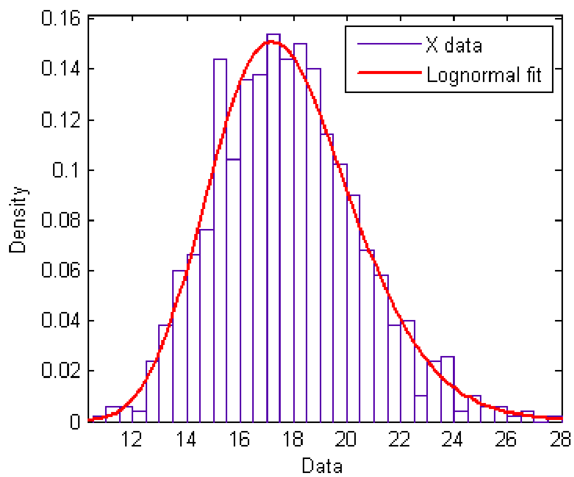

Figure 2: Lognormal distribution of hard alpha defect size in IMI 685

2.3. Alloy Property

The temperature dependent mechanical and thermal properties of IMI 685 used in this work are presented in Figure 3. As the temperature increases, the modulus and tensile strength tend to decrease while thermal conductivity and coefficient also decrease. The Low Cycle Fatigue (LCF) life data at a temperature of 500°C was also obtained from existing literature as shown in Figure 4 (Lütjering, Williams, and Gysler, 2003; Leyens and Peters, 2003). The proposed microstructure based damage model described in section 3.2 was also calibrated with this data. An average grain size of 55μm and hard alpha particle density of 0.057 per unit area was also used (Nag, Praveen and Singh, 2006; Ramachandra, Verma and Singh, 1988).

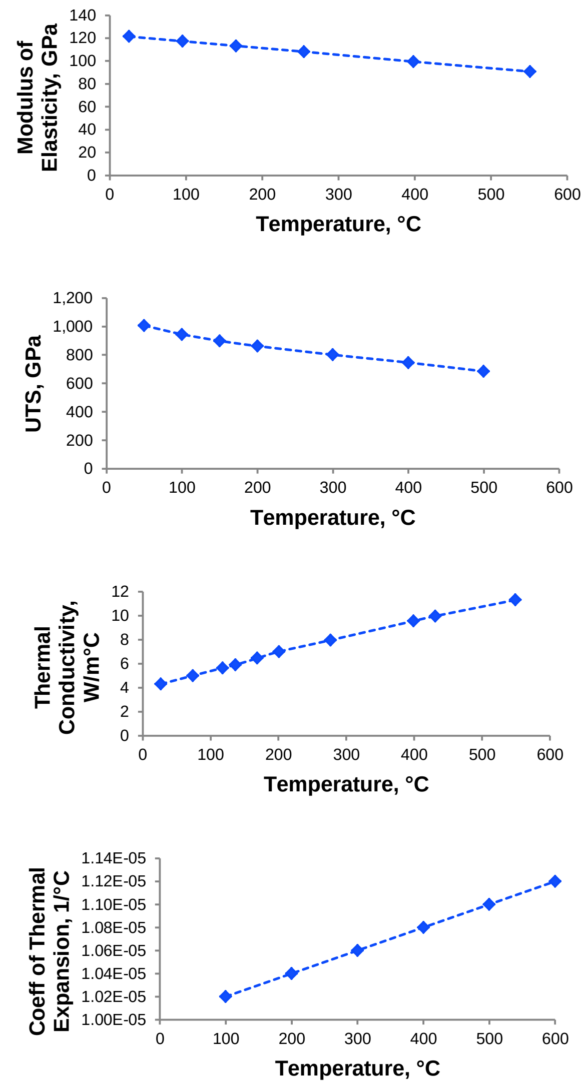

Figure 3: Temperature dependent mechanical and thermal properties

3. MODELING APPROACH

The approach here aims to integrate two levels of materials response, e.g. global and local to external stress under the influence of environmental conditions. The continuum mechanics approach for deformation and fracture is combined with localized failure and microstructural variations and dimensions (micro-mechanics). The localized behavior in the model is assumed to be controlled by two microstructural parameters, namely the alpha grain size and the inclusion size and distribution. To account for the global behavior and damage accumulation, the total strain is considered in the analysis. Following sections outline the salient features of both in the light of the prognostics and life management issues.

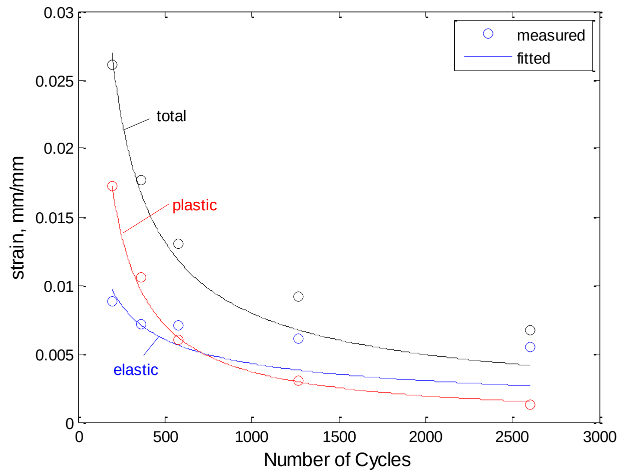

Figure 4: LCF data for IMI 685 at 500°C (Nag, Praveen and Singh, 2006)

3.1. Physics-based Prognostics

A patented Life Cycle Management-Expert System (LCM-ES) framework for true physics-based prognostics is shown in Figure 5. It incorporates the engine cycle thermodynamics analysis, computational fluid dynamics (CFD) and heat transfer analysis, finite element method (FEM) analysis, and materials science based damage models.

In this framework, the engine operational data obtained from the actual or intended usage of the engine is filtered into damage loads based on embedded metallurgical rules. The off-design engine modeling module is incorporated in the proposed system and built using the engine design parameters, this module is capable of generating the boundary conditions for heat transfer analysis for accurate temperature prediction over the engine components. A coupled thermal-structural FEA module is also included that is capable of obtaining the stress and strain states of each component that is in turn used as an input for the microstructural damage modeling module that predicts the mission profile based remaining life of each component. The same damage models can also be used to conduct probabilistic analysis that would allow the prediction of component reliability upfront as a function of the microstructure variability from one material to another. The inputs required to run the prognostics analysis include the component geometry and mesh files, material information and on-design engine design parameters. The lifing solution combines both flight usage and microstructural damage data for reliable life prediction.

3.2. Proposed Damage Model

Proposed microstructure based model is essentially strain based. The total strain ($\frac{\Delta\varepsilon_t}{2}$) based model with the elastic component ($\frac{\Delta\varepsilon_e}{2}$) modeled using Coffin-Manson equation and the plastic component ($\frac{\Delta\varepsilon_p}{2}$) modeled using the

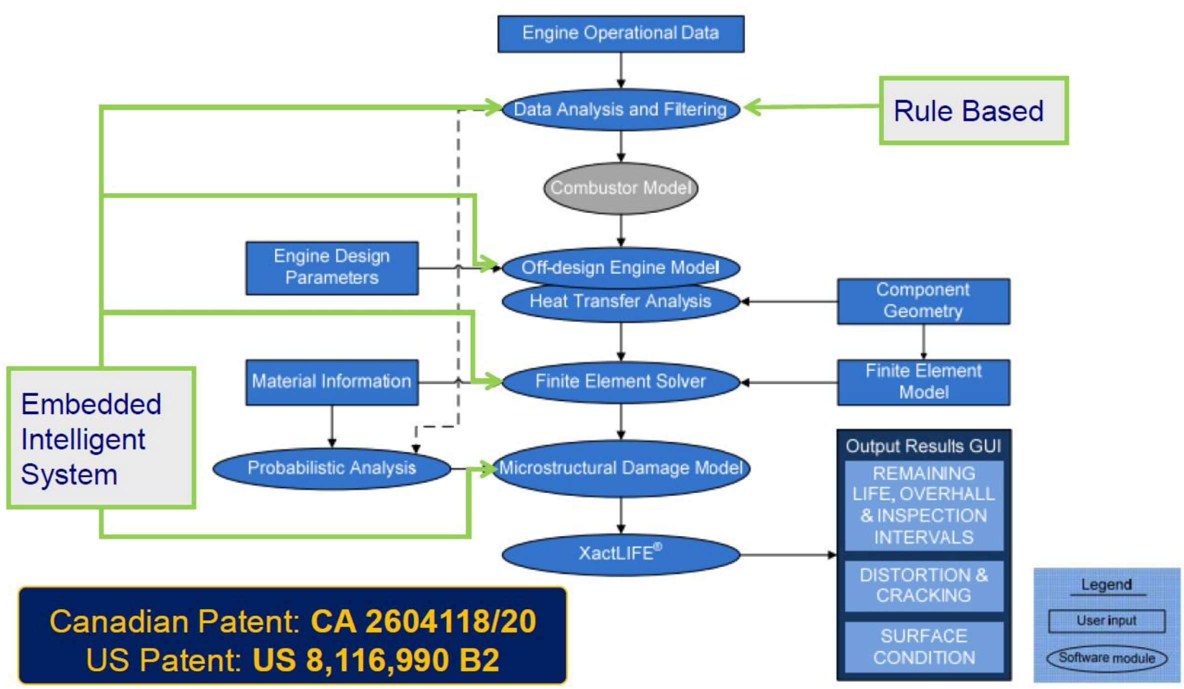

Figure 5: Life Cycle Management - Expert System for physics-based prognostics

microstructural parameters (Koul, 1998). The model is represented as below,

$$\frac{\Delta\varepsilon_t}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} \tag{1}$$

The elastic component of the stress is given below,

$$\frac{\Delta\varepsilon_e}{2} = \acute{\varepsilon}_f 2N_f{}^c \tag{2}$$

where $\acute{\varepsilon}_f$ and c are the fatigue coefficient and exponent, respectively and N_f is the number of loading cycles to crack nucleation. The plastic component is represented as below,

$$\frac{\Delta\varepsilon_p}{2} = \frac{A(n,d)}{\sqrt{2N_f}} \tag{3}$$

where d is the grain size, n is the number of hard alpha (HA) particles per unit area and A is an empirical coefficient. The probabilistic analysis will involve the variation of the microstructural parameters within their distribution range at a life limiting node identified with deterministic analysis.

4. CASE STUDY

For the purpose of a case study, a disc that is made of IMI 685 has been selected that belongs to the High Pressure Compressor (HPC) section of an aero-engine with a thrust rating of around 30kN. The LCF life was determined for a typical operating condition of the engine operation that would represent a simple mission with take off-cruise-landing. The cruise speed, altitude and the rpm (10,000 rpm) of a 30kN thrust aero-engine was taken into consideration for the off-design modeling to predict the mean-line temperature and pressure of the engine core that would serve as boundary conditions for subsequent thermal analysis. The following tasks were performed as per the LCM-ES framework requirement described earlier using a physics-based prognostics system called XactLIFE.

4.1. Geometry and Finite Element Modeling

In the first step the 3D CAD model of the compressor disc was created and its finite element model generated using structured mesh as shown in the Figure 6. A single segment model was also created and periodic symmetry to reduce the computational expense. A structured mesh with 13,280 brick elements and 60 wedge elements were generated and five single segments used for FEA with periodic constraints to reduce the computational time while preserving accuracy.

4.2. Thermal Analysis

The mean-line temperature and pressure predicted through thermodynamics based off-design model was converted into metal temperature over the five dovetail segment disc sector as shown in Figure 7. The temperature at the bore, rim and the left and right welds of the disc were computed with the help of heat transfer analysis using a bladed disc model.

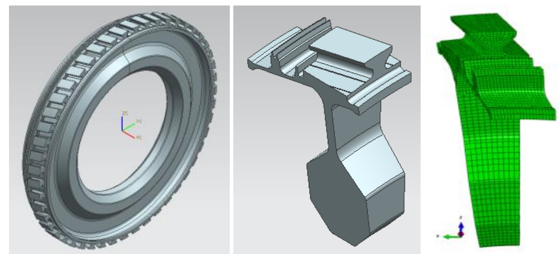

Figure 6: Geometric and finite element models

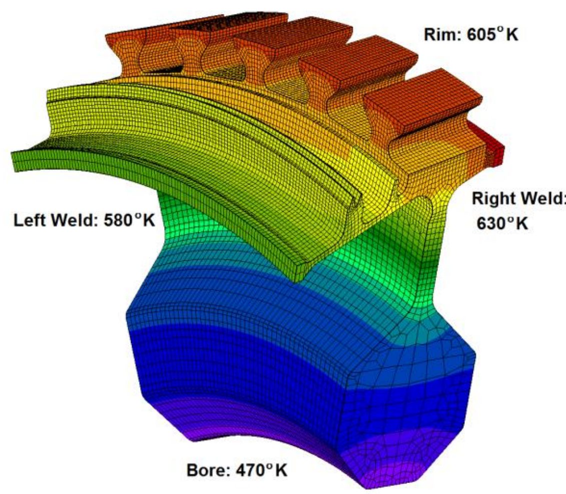

Figure 7: Predicted temperature profile

4.3. Finite Element Analysis

The finite element analysis (FEA) with a coupled steady-state thermal and structural analysis was conducted. The thermal loads obtained from the heat transfer analysis were combined with the centrifugal load and the equivalent stresses and strains of the bulk material were computed. The boundary conditions representing the actual assembly condition were applied along with temperature dependent material properties for accurate results. The predicted von Mises stress profile is shown in Figure 8 where the high stress regions at the sides are due to the boundary constraints and will be ignored while computing the LCF life.

4.4. Deterministic Life Prediction

In the final step the deterministic LCF life to crack nucleation is predicted using the proposed model and the strain result obtained from the FEA. The extreme values of the grain size and hard alpha density has been selected from the

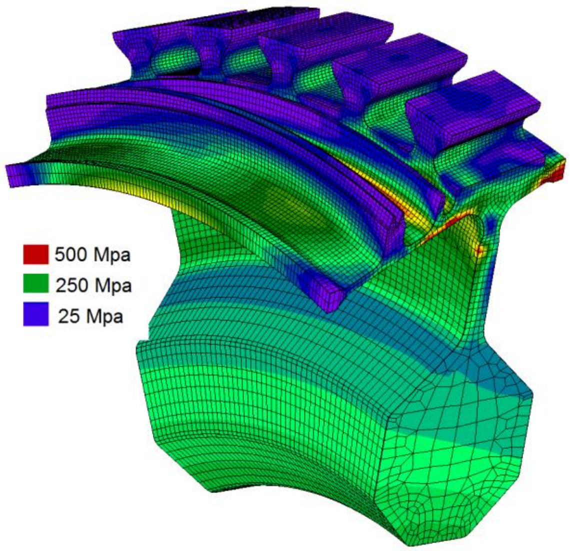

Figure 8: Predicted von Mises stress profile

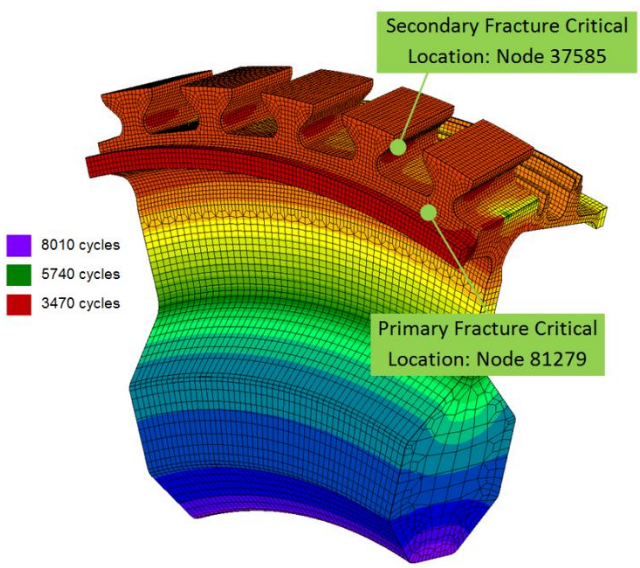

Figure 9: Predicted LCF life to crack nucleation over the disc

lognormal distribution shown in Figure 1 and 2. The distribution of the LCF crack nucleation life over the disc is shown in Figure 9.

It can be seen from the figure that apart from the boundary region corresponding to the rear right weld, the minimum life is in the serration region. At these fracture critical location, the minimum life to crack nucleation was estimated to be 3,542 and 3,639 cycles at the nodes 81279 and 37585, respectively as shown in the figure above. The location of these life limiting regions corresponds to the high stress regions at the rear right welded region and the disc serrations. In addition to the stress, the temperature may also be high due to the maximum temperature being at the disc rim.

4.5. Probabilistic Life Prediction

The grain size and the hard alpha particle density are the two microstructural parameters used in the proposed LCF damage model. A lognormal distribution of these parameters as per Figures 1 and 2 are applied on the primary fracture critical location at the primary and secondary fracture critical locations corresponding to the node numbers 81279 and 37585 respectively, and the result are shown in Figures 10 and 11. The Figure 12 also shows the variation of the life with a combined lognormal distribution of grain size and hard alpha particle distribution. The Figure 10 and Figure 11 suggest a more significant effect of variation of LCF with the distribution of the grain size compared to that of the hard alpha particle density. This observation may be true for thin discs but the distribution of the hard alpha particle density is more difficult to estimate due to the manufacturing process variability. An accurate estimation will be required for reliable probabilistic lifing analysis.

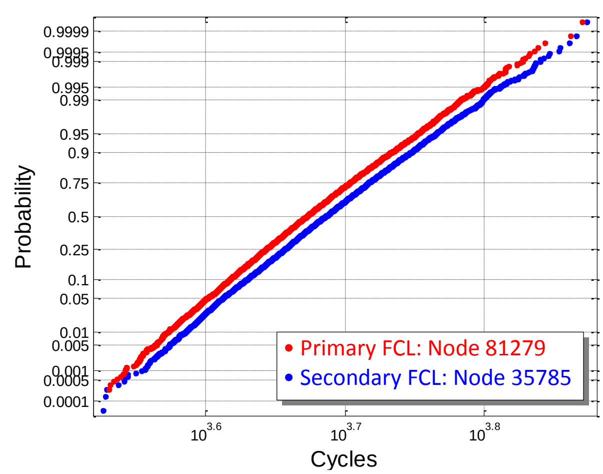

Figure 10: Lognormal probability distribution of life with variation in grain size at primary and secondary fracture critical locations (FCL)

The probability plots show that although the variation in the grain size and the hard alpha particles have different effects on the LCF crack nucleation of the IMI 685 disc, but the primary fracture critical location node has consistently lower life than the secondary fracture critical location node. To study the reliability of the life prediction approach, the deterministic crack nucleation life for the extreme combination of the grain size and the hard alpha particle density that would result in the worst life and the probabilistic life for failure of 1 in 1000 components are compared in Table 1. It can be seen that the deterministic life for both the fracture critical locations are comparable with the probabilistic life computed with the variation of both the microstructure parameters, although the effect of

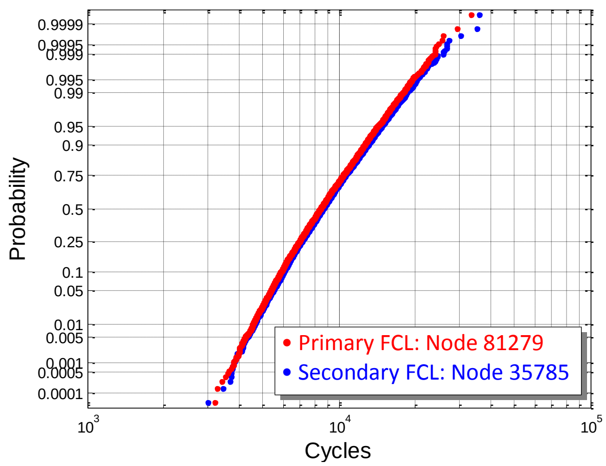

Figure 11: Lognormal probability distribution of life with variation in hard alpha particle density at primary and secondary fracture critical locations (FCL)

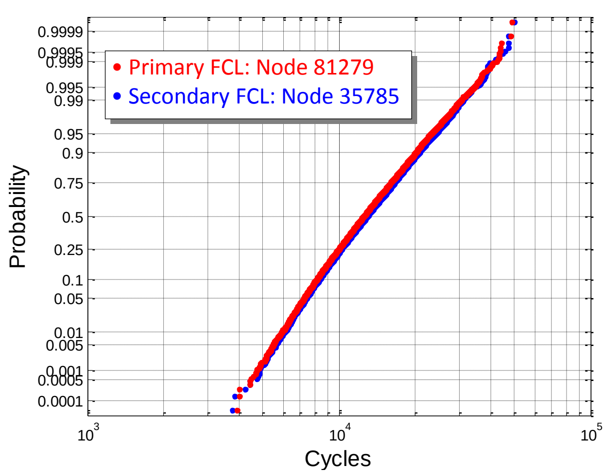

Figure 12: Lognormal probability distribution of life with variation in grain size as well as hard alpha particle density at primary and secondary fracture critical locations (FCL)

the grain size is more significant on the probabilistic LCF life prediction. But the combined effect of the variation of the grain size as well as the hard alpha particle density will provide the best result compared to the deterministic life prediction. The majority of the distributed values for the two microstructural parameters are quite different than the extreme values selected for the deterministic life prediction, making the probabilistic life consistently higher. Hence the effect of the variations in both the microstructure parameters has to be considered for computing the probabilistic life. The probability plots and the above table also suggest that the effect of the grain size and hard alpha particle density variation on the LCF crack nucleation life has been sufficiently captured through this proposed life prediction model.

Table 1: Comparison of deterministic and probabilistic life at primary and secondary fracture critical locations (FCL)

Type of Calculation	**LCF Life** Primary FCL	Secondary FCL
Deterministic	3,542	3,639
Probabilistic @ 0.001 for grain size variation	3,482	3,599
Probabilistic @ 0.001 for hard alpha density variation	3,820	3,801
Probabilistic @ 0.001 for grain size and hard alpha density variation	4,710	4,827

5. CONCLUSIONS

Physics-based prognostics approach has been applied to determine the LCF life for crack nucleation of an IMI 685 high pressure compressor (HPC) disc in a drum assembly. Thermal and structural analysis was performed on a representative disc sector to calculate the stress, strain and temperature profiles over the component. The two fracture critical locations are identified, namely the primary at the disc web and the secondary at the disc serration and LCF life analysis is reported for both.

A microstructure based damage model is proposed with grain size and hard alpha inclusions distribution as input parameters. The lognormal distributions for both these parameters are considered. Deterministic LCF life to crack nucleation computed using the extreme grain size and hard alpha particle density values that would result in the worst life is observed to be closely matching with the predicted probabilistic life at 0.001 probability of failure, suggesting the high reliability of the proposed model. This trend is also observed for both the primary and secondary fracture critical locations and also for the input microstructure parameters distributions in isolation as well as in combination. The result suggests that the grain size distribution has a stronger effect on the probabilistic LCF life in thin IMI 685 Discs.

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Dr. Ashok Koul is the President of Life Prediction Technologies Inc. (LPTi), Ottawa, ON and also acts as an overall technical advisor. He has 25 years experience in the field of materials engineering and life prediction with extensive experience in managing and supervising research and development activities in gas turbine structures, materials and life cycle management strategies. Over the years he has made key contributions in identifying and applying existing as well as emerging technologies in the field of gas turbine engineering.

Dr. Amar Kumar has more than 25 years of research and consulting experience in the fields of structural materials characterization and development, fracture mechanics, failure analysis and applications. Dr. Kumar is currently working as senior research scientist in the R&D project of diagnostics, prognostics and health management of aeroengine components. He specializes in both data driven approaches and physics-based modeling and simulations.

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