Physics of Failure Modelling at the Microstructural Level for Prognostics of Creep Failure in an Engine Turbine Blade

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ABSTRACT

The paper presents the results of a probabilistic creep life study on RRA 501 KB turbine blades and demonstrates the importance of using physics based probabilistic damage modeling techniques to deal with life prediction uncertainty in cast equiaxed components. It is shown that physics based damage analysis yields accurate results and considerably less mechanical properties data is needed for life prediction of cast components. In physics based damage analysis, it is also easy to quickly assess the life limiting damage modes and to establish fracture critical locations in components. In physics based modeling, the influence of individual microstructural or thermal-mechanical loading factors on metallurgical crack nucleation can also be studied with relative ease. Residual life of service exposed parts and effectiveness of life extension techniques can also be predicted because the state of microstructure due to prior service and repair can be taken into account.

In this study, Life Prediction Technologies Inc.'s (LPTi's) prognosis tool known as XactLIFE^{TM} was successfully used to establish the fracture critical location of RRA 501KB first stage gas turbine blades under steady state loads. Deterministic analysis was first used to compute the lower bound airfoil nodal creep life of the various finite element nodes and this was followed by probabilistic creep life analysis to take into account the variability of microstructure from one blade to another. The analysis used typical engine operating data from the field in terms of engine speed and average turbine inlet temperature (TIT). The primary objectives of the case study are to show how prognosis can allow a user to predict component fracture critical locations, establish inspection intervals to avoid failures and establish fleet reliability for engine specific operating conditions.

1.0 INTRODUCTION

The ability to forecast remaining life of equipment appears simple enough, particularly if a log of usage in hours is kept which can be compared to a ceiling number of hours, or if a graph of operating characteristics can be compared to threshold values. But this is simplistic, and invokes certain questionable assumptions. One assumption is that the components fail according to a wear-out schedule, e.g., at x hours of usage. This may not be the case. A ceiling usage based on hours does not factor in stresses that can prevent realization of these hours. The notion of stresses that significantly diminish mean time between failures (MTBF) is not new. Professional logistics, maintenance and manufacturing engineers are familiar with the distinction between calculated MTBF and operational MTBF (actual usage with real operating data), in which operational MTBF may be a factor of 20 different to the calculated MTBF [1].

The determination of predicted MTBF requires the development of prognosis expert systems that consider the specific stress and temperature histories of each major component on an individual basis and factor them into the physics based damage accumulation models formulated at the microstructural/nanostructural level. A schematic of a typical prognosis system for analyzing hot section components is presented in Figure 1. The solution integrates combustor modeling, off design engine modeling, thermodynamic analysis, and finite element modeling including a non-linear finite element solver, operational data filter and microstructural damage models on a single platform. The system provides a choice of damage models, for steam as well as gas turbine applications such as creep, Low Cycle Fatigue (LCF), stress corrosion, corrosion fatigue, cyclic oxidation and Thermal Mechanical Fatigue (TMF) analysis. The XactLIFE™ is also capable of predicting safe inspection intervals (SIIs) for other critical parts such as discs, spacers, cooling plates and shafts. The system flow diagram further indicates that the expert system is capable of anticipating the risk of future failures, based on variability of microstructure and assumed operating conditions, using probabilistic analysis techniques.

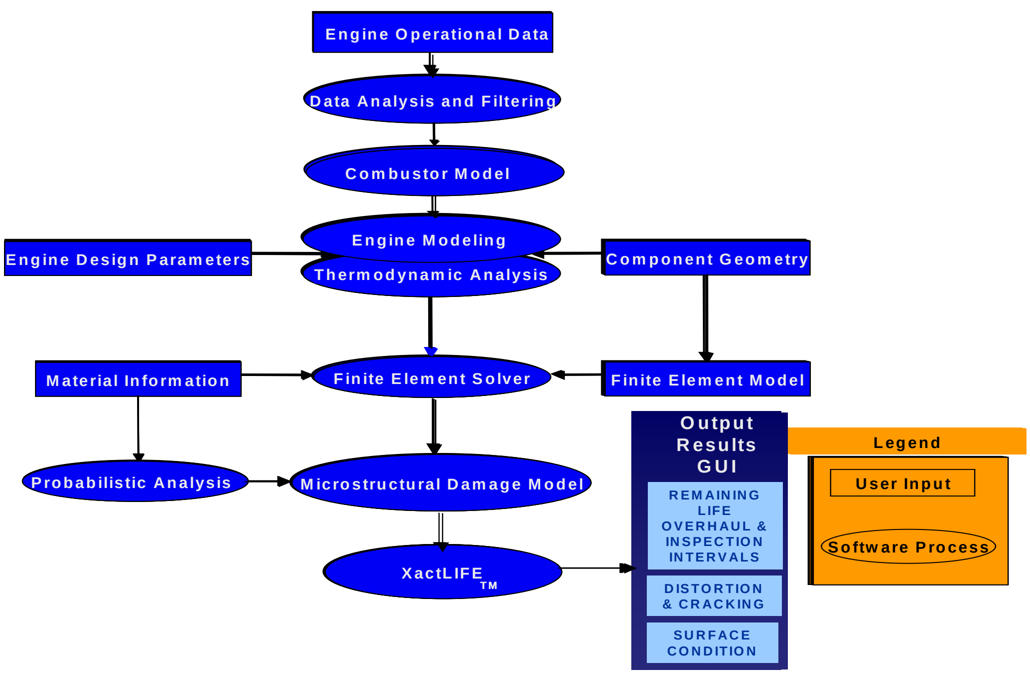


Figure 1: Engineering flow diagram for the prognosis system designed and implemented by Life Predictions Technology Inc. (Patent Pending).

At present, the original equipment manufacturers (OEMs), users as well as repair and overhaul (R&O) communities use failure modes effects criticality analysis (FMECA) to assess the engine fleet reliability. However, OEMs, R&Os and users continually end up revising their reliability predictions based on actual operating experience as it is accumulated. This is because statistically significant amount of service experience is required to make reliability predictions and obviously such experience is always missing when new engine designs are introduced to the market. Often OEMs use past experience with similar engine designs to make reliability predictions and users must wait a few years before enough failure data is accumulated to make reliable predictions. It is precisely this ambiguity in FMECA type technologies that can be easily addressed by physics based prognosis technology.

This paper presents the result of a probabilistic case study carried out in collaboration with Standard Aero Limited, on the Rolls Royce Allison (RRA) 501KB first stage gas turbine blades, where the value proposition of using prognosis in conjunction with physics based microstructural damage analysis for reliability assessment is clearly demonstrated.

2.0 TURBINE BLADE CASE STUDY

In this study, the prognosis system was used to conduct probabilistic blade creep life analysis of RRA 501KB first stage turbine blades under steady state conditions. Typical engine operating data from the field in terms of engine speed and average turbine inlet temperature (TIT) was used in the analysis, Figure 2. The subject RRA 501KB blades is made out of conventionally cast Mar-M246 material and the airfoil is internally convection cooled using compressor discharge air.

Cumulative Time	RPM	Temperature (^{o}C)
0:00:00	0	15
0:00:10	14,250	1,035
21:00:10	14,250	1,035
21:05:10	0	15

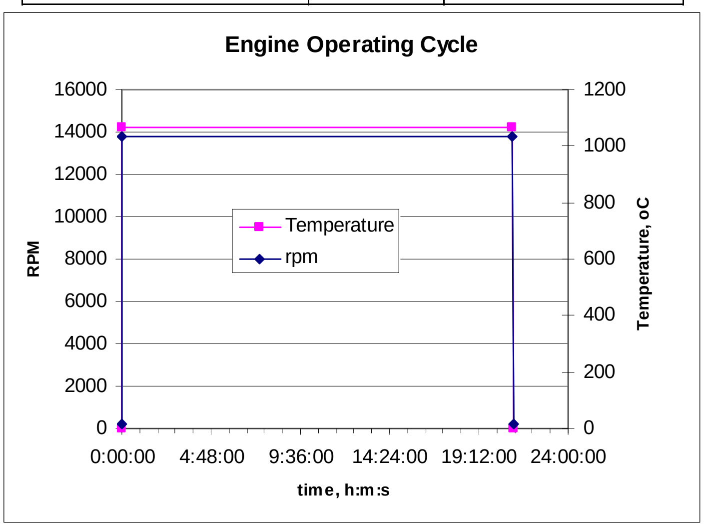


Figure 2: Typical engine profile in terms of turbine inlet temperature and speed.

2.1 Mechanical Structural Analysis Requirements

The first step involved in the prognosis is the creation of the blade geometry using the geometry analyzer software and this is followed by the creation of a fully meshed finite element model of the blade, Figure 3.

The temperature dependent material properties data such as elastic modulus, Poisson ratio, yield strength and work hardening coefficients are also required for non-linear finite element analysis. These data were also collected prior to performing the thermal-mechanical stress analysis [2], Table 1 and Table 2. A constant Poisson ratio of 0.28 was assumed.

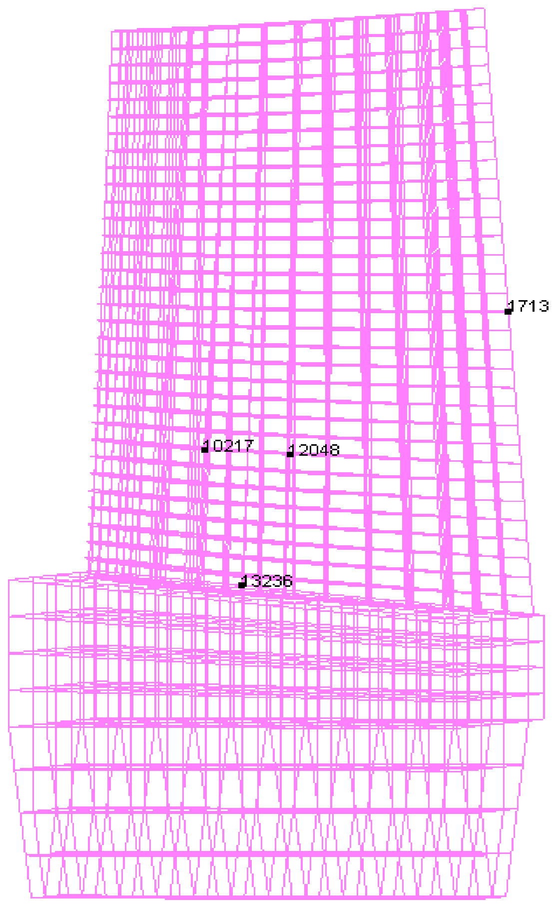


Figure 3: Finite element model of the blade with some life-limiting nodes displayed.

Table 1: Dynamic modulus of elasticity and shear modulus for Mar M246 alloy [2].

Temperature (K)	Elastic Modulus (GPa)	Shear Modulus (GPa)
288	210	82
317	208	81.4
995	168	65.7
1,020	166	64.8
1,053	163	63.7
1,083	160	62.6
1,116	157	61.2
1,258	139	54.2
1,269	137	53.5

Table 2: Tensile properties of Mar M246 alloy [2].

Temperature (K)	351	473	569	1073
Yield Strength (MPa)	844	845	841	748
UT Strength (MPa)	986	990	994	986
Elongation (%)	4.3	4.23	4.23	4.36

2.2 Engine Modeling and Thermal Boundary Conditions

The prognosis system uses the actual average TIT or exit gas temperature (EGT) or power for the specific engine. Known on-design engine parameters such as rpm, mass flow, exhaust pressure ratio, generator efficiency, mechanical efficiency, etc are used to compute the pitch line airfoil temperatures at different stages of the turbine under off-design (changing ambient temperature and pressure) engine operating conditions. To account for off-design engine parameters, compressor and turbine maps were generated for the RRA 501KB engine and these maps form a standard input into the prognosis system. Convection cooling effects are also considered in the thermodynamic analysis of the blade airfoil. Another important input into the system is the TIT profile and this profile is computed using the average TIT or EGT in conjunction with semi-empirical or computational fluid dynamics (CFD) combustor modeling procedures. The computed TIT profile is shown in Figure 4. These inputs are used in the advanced thermodynamic module to compute the blade metal temperatures in both the radial as well as the chord-wise directions. The metal surface temperatures are then estimated along each cross section of the blade including the leading and trailing edges, Figure 5, and this output of the thermodynamic module defines the temperature boundary conditions for thermal-mechanical stress analysis.

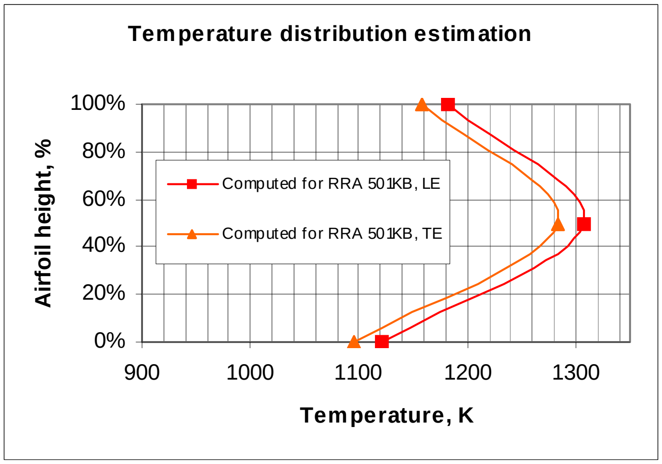


Figure 4: Computed leading and trailing edge temperature distributions.

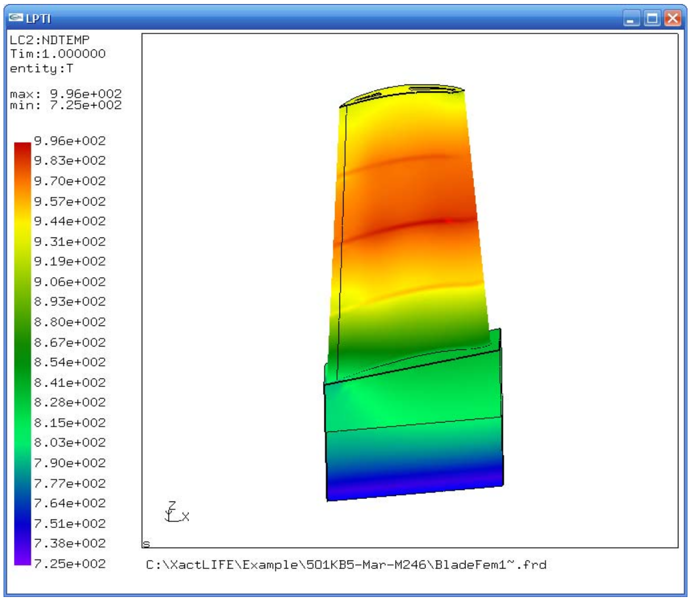


Figure 5: Temperature profile for RRA 501 KB.

2.3 Thermal Mechanical Stress Analysis

The built-in FEA solver in the prognosis system automatically carries out the thermal-mechanical stress analysis using the nodal temperature distributions and the maximum engine rotational speed as boundary conditions for FEA. It is noteworthy that the 501KB blade is shrouded and the mass of the blade shroud was taken into consideration while calculating the centrifugal loads on the blade airfoil by adjusting the density of the blade tip nodes. The computed thermal-mechanical stress distributions along the blade are shown in Figure 6. The non-linear FEA revealed that none of the blade airfoil regions had undergone any plastic deformation under the influence of the loading conditions examined. This is significant, because only time dependent deformation would thus be expected to occur during service. The stress distribution was generally quite uniform along the airfoil although, as expected, higher stresses were prevalent in the blade root section.

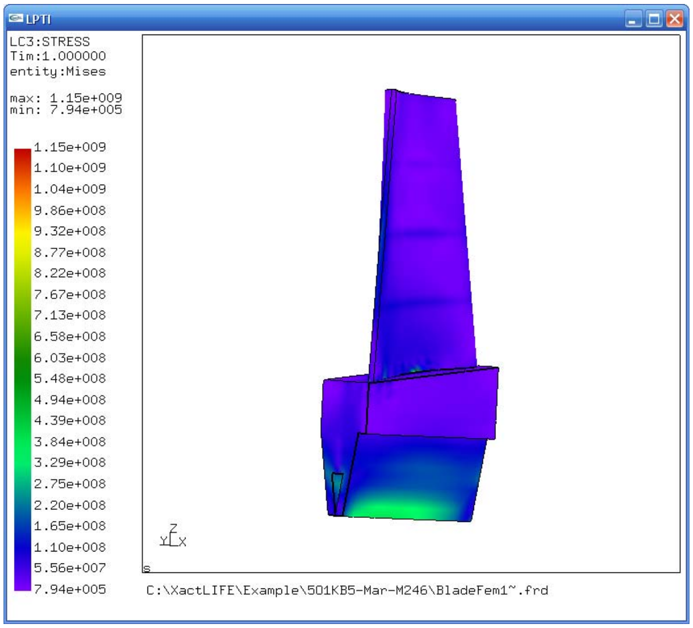


Figure 6: Von Mises stress profile of the blade.

2.4 Probabilistic Creep Damage Analysis

Prior to conducting a detailed probabilistic analysis, a deterministic analysis was carried out to establish the probabilistic analysis of the critical nodes by introducing microstructural variability. Deterministic life depicts the lower bound nodal life and details of the methodology used can be found elsewhere [3]. Essentially, deterministic nodal life is computed by assuming worst case assumptions for all variables. In deterministic analysis, a combined creep deformation model that considers deformation along grain boundaries and within the grain interiors together with the oxidation damage accumulation along the boundaries was used to take the FEA solver input at maximum rotational speeds to compute the creep lives of all nodes and to establish the primary fracture critical location of the blade. The fracture critical location of the blade was defined as the lowest creep life location in the airfoil. The quantitative microstructural information required to execute the damage analysis was collected up-front and this included microstructural variables such as the grain size, grain boundary microstructural parameters, intragranular microstructural parameters etc. A combination of deformation mechanisms such as the intragranular dislocation movement and multiplication, grain boundary sliding accommodated by a number of deformation processes, creep cavitation and a variety of dislocation-precipitate interactions including the evolution of microstructure due to deformation are considered in the overall creep deformation process.

In keeping with the bulk material deformation rationale, the nodal creep strain at failure was set at 5%. It is recognized that the failure strain in the case of cast alloys is dependent on the soundness and the size of a casting.

Table 3 provides the creep life of four life limiting nodes in the airfoil section along with the respective temperatures and stresses operating at these locations. It is evident that the primary fracture critical location lies along one third of the airfoil height on the suction side of the blade (see FEM model in Figure 3). The average blade creep life of blades is then calculated by averaging the lives of nodes in the immediate vicinity of the fracture critical location within a finite volume of the material. This life is in the range of 70,000 hours. According to this analysis, conventionally cast Mar-M246 blades should be inspected after 35,000 hours, the MTBF interval was predicted by using a safety factor of 2 [3]. The untwist data available for service exposed subject blades indicate that the blades start bulk creep deformation at approximately 60,000 operating hours. Some internal oxidation of cooling passages is also observed during service. If this effect is taken into account in prognostics analysis, then the predicted usable life of blades would be slightly lower than 70,000 hours. Prognosis based numbers thus match favorably with the field experience.

Table 3: Nodal creep life prediction results of subject RRA 501KB turbine blade.

Node	Stress (MPa)	Temp (K)	Life (Hrs)
13236	367.4	855	53,297
10217	173.5	950	45,097
12048	151.2	945	61,496
1713	166.7	975	33,823

In the case of cast equiaxed blades, grain boundary deformation and oxidation plays a dominant role in the creep crack initiation process. As a result, grain size (d), grain boundary precipitate size (r) and interparticle spacing (λ) also play a major role in the creep deformation process. Typical probabilistic distributions of these microstructural features, that take into account the variability of these features from one blade to another, are shown in Figure 7, Figure 8, and Figure 9. Most microstructural features possess a lognormal probabilistic distribution, [4, 5, 6] that can be written as:

$$\text{Log}\,(d, r, \lambda) = \text{Gau}\,(\mu'_{(d,r,\lambda)}, s_{(d,r,\lambda)}) \quad (1)$$

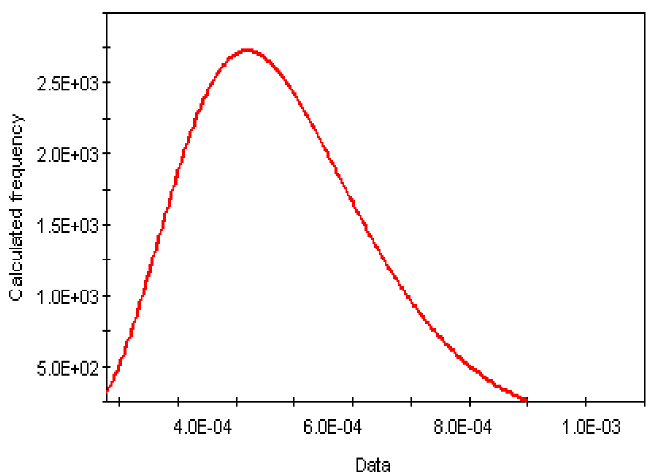


Figure 7: Grain size variation in MAR M246 blades.

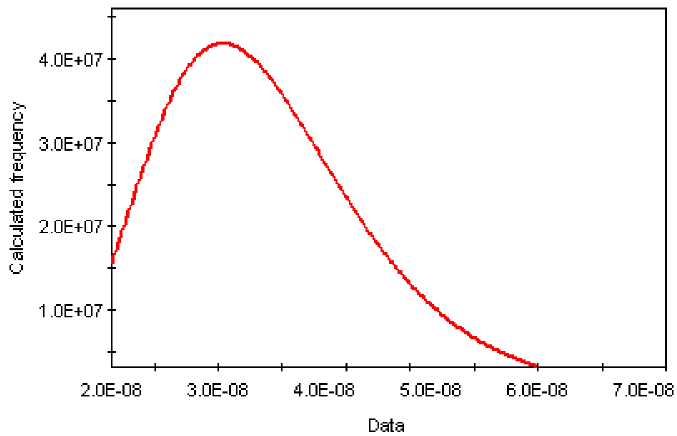


Figure 8: Grain boundary carbide particle dradius variation in MAR M246 blades.

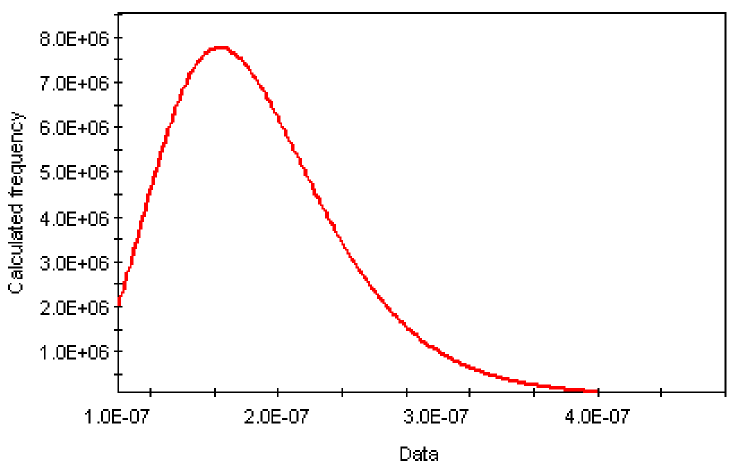


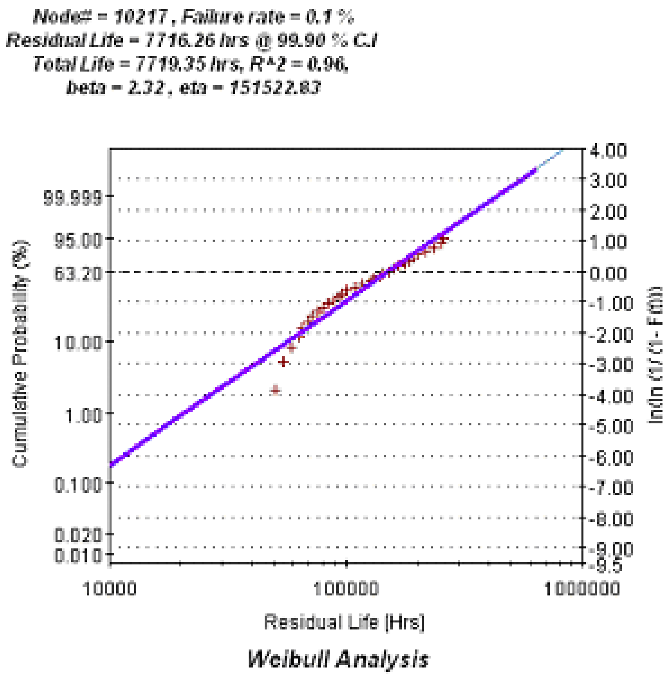
Figure 9: Grain boundary carbide interparticle spacing variation in MAR M246 blades.

Where μ' depicts the mean of the microstructural feature and s is the standard deviation of the variable. Upon randomizing these microstructural variables, probabilistic life calculations were carried out under steady state operating conditions. Two parameter Weibull creep life distributions were computed for the four critical airfoil nodes given in Table 3. A two parameter Weibull distribution is described by:

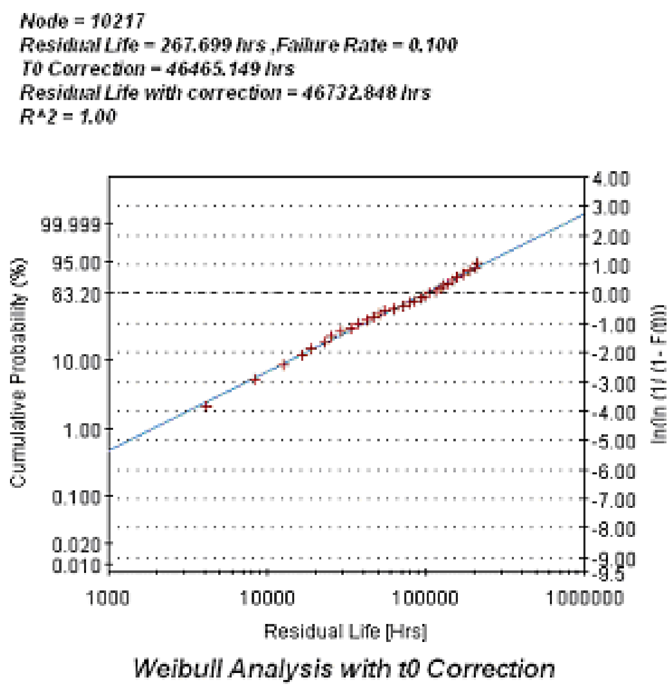
$$F(t) = 1 - \exp -(t/\eta)^{\beta} \tag{2}$$

Where F(t) is the cumulative probability of failure, t is the creep life, η is the characteristic life and β is the Weibull modulus. The probabilistic distribution of creep life of node number 10217 (see Figure 3) is plotted in Figure 10(a) in the form of two-parameter Weibull distribution. It is evident from Figure 10(a) that a threshold value of creep life exists and a three-parameter Weibull distribution, that uses t_0 correction to account for the threshold life, is required for accurate representation of the probabilistic creep life data. The three-parameter Weibull distribution is represented by:

$$F(t) = 1 - \exp - [(t-t_0)/\eta)]^{\beta} \tag{3}$$



(a) Two-parameter Weibull distribution.



(b) Three-parameter Weibull distribution.

Figure 10: Weibull distributions of creep life for node number 10217.

Where t_0 is the threshold value obtained from the two-parameter Weibull plots. All four critical nodes analyzed revealed a similar life pattern. The t_0 corrections were thus applied to all four cases and the resultant creep life distributions of the four nodes were plotted. The corrected Weibull distribution for node number 10217 is shown in Figure 10(b). A correlation coefficient of greater than 0.99 indicates was obtained in all cases.

The creep lives of all four nodes at a cumulative probability of failure of 0.1%F (approximately 1 in 1000 chance of crack nucleation at the node) are shown in Table 4. Deterministic nodal life values are also presented for comparison with the 0.1% F probabilistic analysis results in Table 4. In all cases, the lower bound deterministic values match favorably with the 0.1% F probabilistic data. These data indicate that the deterministic crack initiation life values or microstructural variability based 0.1% F probabilistic analysis results can be used as a guide for predicting MTBF for new blades. Therefore, in light of these findings, FMECA-based reliability predictions are not necessary for fleet maintenance if prognostics tools are available for life prediction. However, it is necessary to conduct physics based prognosis for accurate MTBF prediction. Previous investigations have shown that empirical creep life prediction approaches such the Larson-Miller parameter based calculations can be off by as much as a factor of 20 relative to observed field experience [7].

Table 4: Probabilistic distribution of nodal creep life.

Node	Two parameter Weibull life (hr)	Three parameter Weibull life (hr)	Deterministic life (hr)
10217	7,719	46,732	45,097
13236	13,133	57,323	53,297
12048	19,144	59,595	61,496
1713	4,870	33,643	33,823

The microstructure based prognostics analysis can also be used to assess the effects of repairs and refurbishment processes simply by assessing any changes in the key microstructural features such as the grain size, precipitate size etc. to quantify the MTBF of repaired or refurbished parts rather than waiting for field experience to accumulate to judge the reliability of repairs. The microstructural information is easy to generate and once the case is set in the XactLIFE™ system, scenario analysis can also be carried out to assess the cost effectiveness of the repairs from a usage perspective.

3.0 CONCLUSION

Prognosis based deterministic and probabilistic creep life analysis was carried out on the subject RRA 501 KB first stage turbine blades at maximum operational speeds and turbine inlet temperature. The deterministic analysis was used to predict the fracture critical location in these blades and the primary fracture critical location was predicted to lie along one third of the airfoil height on the suction side.

Probabilistic creep life analysis was carried out on the four fracture critical nodes in the airfoil section by taking into account the variability of grain size and grain boundary microstructural features such as the grain boundary precipitate size and inter-particle spacing. The average blade creep life of conventionally cast Mar-M246 blades was computed to be over 70,000 hours yielding a lower bound deterministic MTBF of over 35,000 hours. Internal oxidation effects were not considered in the present analysis and this would reduce the predicted creep life and MTBF for the blade.

At 0.1%F, the probabilistic nodal creep life values match favorably with the deterministic nodal creep life values. These data can be used to establish blade reliability and to make decisions about MTBF for fleet maintenance. Microstructure based prognosis can also be used to establish the reliability of repairs by generating the relevant microstructural information and conducting future usage based scenario analysis.

4.0 REFERENCES

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