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The Inadequacy of Safe-Life Prediction: Aero-Engine Fan and Compressor Disk Cracking

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Abstract

The use of a safe-life methodology to ascribe a replacement interval to gas turbine engine components has been used extensively for over 40 years. However there are inherent limitations in the methodology, resulting in significant under-utilisation of component lives, and an inability to account for rogue flaws and other non-representative factors. This paper will present three examples where the safe-life approach was inadequate in predicting the safe working life of critical engine components. These examples illustrate the complexity of the processes that have to be taken into account to produce realistic life estimates.

1. Introduction

Critical gas turbine rotating components, such as compressor disks, spacers, cooling plates and turbine disks, are subjected to cyclic stresses caused by engine start-up and shutdown, as well as by major throttle excursions during flight manoeuvres. These cyclic stresses can exceed the yield strength of the material at stress-concentration sites, such as bolt holes, bores, blade dovetail slots and rim serrations and can thus lead to low cycle fatigue cracking.

A safe life method is conventionally used to determine the in-service life of rotating gas turbine components subject to low cycle fatigue. In this procedure a safe service life for the component is obtained from component and specimen tests of the appropriate material under representative loading conditions. The component life is calculated by fitting a statistical model to the fatigue results, and the life is determined based upon the probability of crack initiation after a period of engine usage, calculated using mathematical models that take into consideration mission profiles and mission mixes. Component usage is then normally restricted to the number of flight hours which are calculated to produce a 0.8mm surface crack in one component out of an assumed population of 1000 identical parts under the same usage This represents approximately three standard deviations from the mean (-3σ). This crack size is considered detectable with high reliability by the most commonly used inspection technique - liquid penetrant inspection.

The consequence of this criterion is that the bulk of component lives lie above the -3σ limit and all of these lives are discarded. Furthermore, when a component contains a rogue flaw, the safe-life procedure cannot accurately predict the life, as the flaw is not considered in the original probability distribution function of the LCF database.

This paper will present three examples where the safe-life approach was inadequate in predicting the working life, and illustrate the inability of the safe life methodology to take account of defects not considered in the original probability distribution.

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In the first example a severely deformed surface microstructure was caused by abusive machining of a tie-bolt hole in a fan disk. As a consequence the life of this component fell outside the original probability distribution function (PDF) upon which the safe-life predictions were made, resulting in premature cracking. Cracks formed within this microstructure around the perimeter of the hole and once the component was placed in service those cracks perpendicular to the hoop stress began to grow as low cycle fatigue cracks.

In the second case, the manufacture of a disk with an abnormal microstructure resulted in cracks emanating from a tie bolt hole when that disk was placed in service. Once again the PDF upon which the original safe-life estimates was based is not applicable and consequently an erroneous life prediction was made. However in this case an appropriate PDF can be determined retrospectively so that other uncracked disks with this abnormal microstructure could be appropriately lifed.

In the third case the life of a low-pressure compressor disk was based on the stresses at a particular circumferential structural feature with an acute radius of curvature. As the safe-life is defined as the time to initiation of a 0.8 mm flaw size, no consideration is given to the behaviour of the crack after initiation. Detailed modelling and simple experiments indicated that in this case the crack is expected to grow in an orientation such that it would not affect the performance of the component nor compromise safety for a considerable period of time after initiation.

The paper presents the view that safe-life analysis alone represents only a partial view of all the processes that should be taken into account in determining overall component replacement intervals.

In this paper the prediction of remanent life was based on the use of stress, thermal, metallographic and fractographic analyses, as well as risk assessments using probabilistic rather than deterministic parameters to achieve more realistic life assessments. Mission profile analyses were also carried out to assess the severity of engine usage.

2. An Abusively Machined Tie-Bolt Hole

Following the detection of a crack emanating from a bolt-hole in an engine disk, an investigation was undertaken to determine the subsequent crack growth behaviour. The disk geometry and observed crack direction are shown in Figure 1. The radial crack emanating from the bolt-hole was cut from the disk and opened, revealing the crack face shown in Figure. 2. The cracking was found to be due to fatigue which had started within the bore of the hole and away from the corner. The crack markings were examined using both optical and scanning microscopy and the crack growth rate was predicted using both numerical and analytical methods and compared to the measured growth rate.

The metallographic studies indicated the presence of a surface deformed layer, with a depth of approximately 0.6 mm, and the crack growth progression measurements on the fracture surface showed rapid crack growth through the deformed layer from multiple surface cracks all around perimeter of the hole. Furthermore the presence of tungsten carbide was detected at the surface, presumably from a piece of tooling.

The fatigue cracks originated in alpha case particles in the microstructure of the hole surface, indicative of localised overheating. It was concluded from these observations that an abusive hole drilling or reaming operation caused overheating and localised damage.

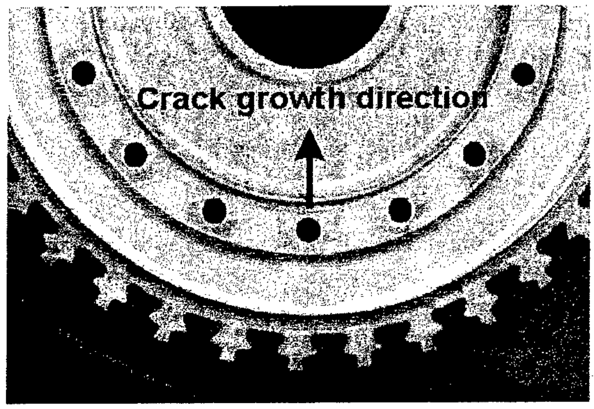

Figure 1: Disk geometry and crack growth direction.

Figure 2: Radial bolt-hole crack using optical microscopy.

The material of the disk and adjacent components was Ti-8Al-1Mo-1V. The nominal operating temperature at the bolt-hole region of the disk was determined by analysis and measurement to be approximately 200°C. Crack growth data for various stress ratios was obtained from the published literature and interpolated to the operating temperature.

A 3D cyclic FE assembly model (22.5° sector) was created, consisting of three fan disks, spacers and air seals to determine the global behaviour, as shown in Figure. 3. These components were meshed using 20-noded brick elements. The applied loading includes the centrifugal and thermal loads at maximum power setting (1, 2) Appropriate boundary conditions were applied to the end surfaces of the assembly model. Stress analysis was carried out using ABAQUS software (3) and displacement solutions were obtained.

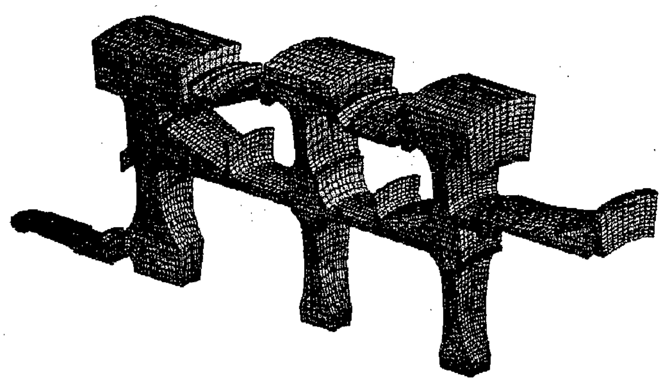

Figure 3: 3D FE model of the assembly.

A 3D FE sub-model (22.5° sector), including all the local geometry features, was created for the disk. The solutions from the 3D FE assembly model were transferred to the cutting boundaries in the sub-model and the stress distribution of the disk were determined, as shown in Figure. 4. The maximum principle stress of 435 MPa occurs under maximum power settings at the bore-side of the bolt-hole, indicating the region where a crack is most likely to form, and in fact where it was observed.

Furthermore, from fractographic analysis it was determined that crack propagation rates through the deformed microstructure were twice as fast as through the non deformed microstructures, with the cracks perpendicular to the maximum principal stress becoming propagating cracks. The crack growth analyses carried out as part of the FE analysis corresponded very closely with the fractographic measurements, indicating that failure of the disk was likely within the scheduled safe life.

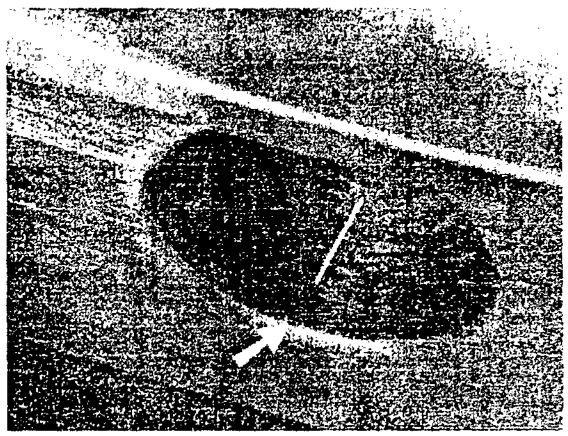

Figure 5. Indication of the crack direction in the bolt hole

It was concluded that machining of the tie-bolt holes was done in such a way that a deformed surface layer of approximate depth 0.6mm was produced. This layer either had micro-cracks form all around the perimeter of the hole during the machining operation or shortly thereafter. Once in service the cracks were readily propagated due to the stresses caused by start stop start cycling, leading to premature cracking and a life considerably shorter than the safe life predicted from the standard database.

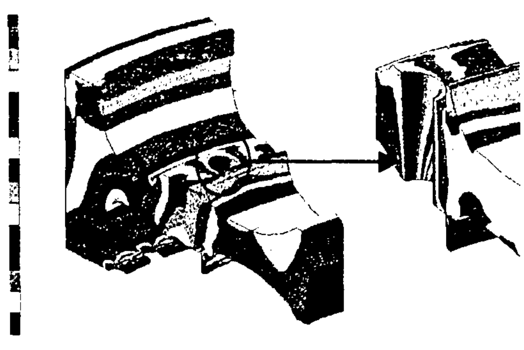

Figure 4: Maximum principal stress distribution for the disk with detailed view of the critical location.

3. A Disk With An Abnormal Microstructure

A crack was found in the tie-rod hole of a second stage compressor disk. No other cracks of this type had been seen previously. This hole was believed to experience relatively low stresses, and hence was not expected to be life-limiting in terms of low cycle fatigue. An indication of the orientation of the crack is shown in Figure 5.

The single longitudinal crack on the inner surface of the tie rod hole showed extremely faint markings consistent with fatigue progression marks. The crack was very deep with a short surface length and is shown schematically in Figure 6. The material of the disk and adjacent components was Ti-8Al-1Mo-1V.

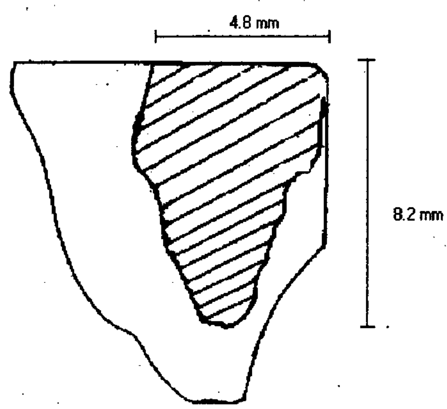

Figure 6. Schematic of the shape of the crack

The crack was difficult to observe visually as it did not extend to the outer edge of the hole, appearing to start about 0.8 mm inside the bore of the hole from the front face of the disk.

The crack was noted to be very deep and narrow in relation to its length on the bore surface with a length of about 4.8 mm and a depth of about 8.2 mm.

The microstructure of this disk was found to contain significant banding of the α phase. This was probably due to incorrect processing or perhaps segregation in the original ingot. This microstructure has been described previously for this alloy (4)

SEM examination of the crack fracture face revealed that fracture appeared to have occurred transgranularly. The nature of the fracture changed within different bands of the material. Some bands displayed elongated facets with a fairly consistent direction of crack propagation evident from the markings on the facets. Other bands displayed more equiaxed facets in which the crack direction as indicated on each facet appeared to be almost random. In all cases faint markings could be observed consistent with fatigue at low stress intensities.

The crack initiated within the hole at a location coincident with the maximum principal stress (σ_{hoop}). The propagation behaviour of the crack was determined by the presence of α-phase bands which tended to constrain the crack growth in the through-disk direction, as a result of preferential crack growth along the α-bands compared to growth in the normal titanium $\alpha + (\alpha+\beta)$ microstructure (5).

In this case the prediction of a safe life analysis is possible if the probability density functions were to be based upon a data base derived from LCF properties of the α-rich banded material. The promulgated safe life was in fact based on an inadequate database and hence cracking occurred in service much earlier in the life than expected. The promulgated safe life for this type of microstructure is thus very un-conservative.

4. Benign Crack Growth

A finite element (FE) method was utilised to analyse the mechanical and thermal stress in a 4th stage Low Pressure Compressor (4th LPC) disk assembly in an aircraft gas turbine engine(6). This FE analysis indicated that the critical region for fatigue is at a front snap radius. The geometry of the disk is shown in Figure 7.

It was found that the maximum principal stress at the front snap radius dropped rapidly from 800 MPa at the free surface to 350 MPa at a depth of 0.5 mm.

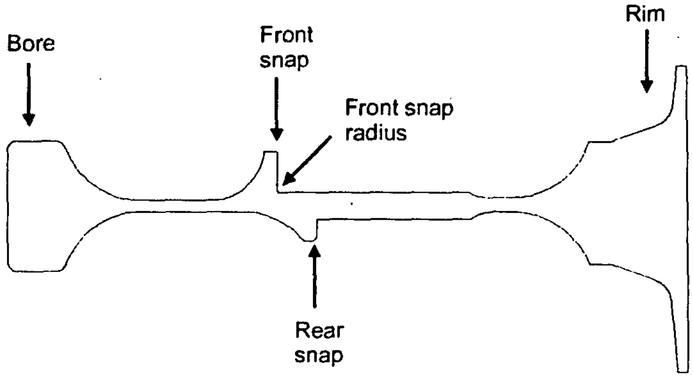

Figure 7: Schematic cross-section of a compressor disk.

Based on the calculated stresses and the available mechanical property data it was possible to determine a safe life for this location which was consistent with the safe life derived by the OEM. However further analyses and experiment were carried out to determine the consequences of cracking in order to assess the significance of the safe life concept.

Traditionally a FE crack profile has to be created manually and this can be very time consuming, especially for the 3D case (7). The process involves the collapse of normal elements to crack tip elements and the translation of the mid-side nodes of the crack tip elements to quarter points towards the crack tip. These features have been automated in the code ZENCRACK (8), which is interfaced with the FE code ABAQUS. A crack block can be re-meshed so that this block is replaced with a crack front comprising of crack tip elements. The crack front can be either semi-circular/semi-elliptical or straight, within a crack block. Therefore, by combining blocks with various embedded crack fronts, both surface and through-thickness cracks can be generated easily.

In ZENCRACK, the direction of crack growth is governed by the direction of the maximum strain energy release rate. The amount of crack growth is determined by the magnitude of the energy release rate (9, 10).

The crack growth procedure starts with the generation of an initial crack and the calculation of the stress intensity factors. The crack growth direction and the amount of growth are then determined by the virtual extension method and the crack front is updated after a nominated increment of crack growth. This process is repeated until the required crack size or number of cycles is reached.

Semi-circular and semi-elliptical surface cracks with a depth of 0.2 mm were inserted perpendicular to the front snap radius at the peak stress location, 25 degrees from the radius runout (Figure 8). Stress intensity factors (SIF's) were then calculated using the J-integral method. The SIF values at the both free surface ends increase with crack length whilst the crack depth remains constant (Figure 9). Therefore, a crack initiated at the front snap radius is expected to grow preferentially in the circumferential direction and to grow at a slower rate in the radial direction.

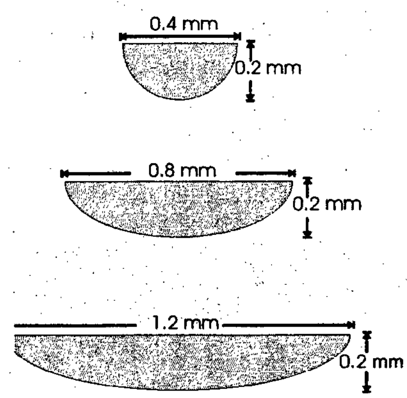

Figure 8 Initial crack profiles used in the analysis

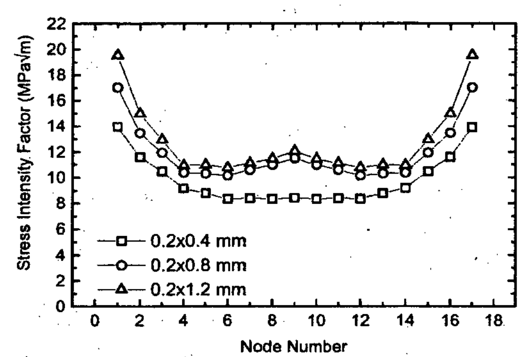

Figure 9: Stress Intensity Function distributions for initial crack profiles.

A typical load spectrum was obtained for the disk and ZENCRACK was used to transform the spectrum into an equivalent constant amplitude spectrum using a weighting function (defined by the occurrence of each load pair), and a scaling factor was used in order to convert the number of cycles to engine flight hours.

The crack profile derived from this crack growth procedure changed from a planar semi-circular to a non-planar elliptical shape with a 12° deviation from the original crack plane. The amount of crack growth in the circumferential direction was more than twice that in the radial direction, resulting in a reduction of the aspect ratio of depth to length from 1 to 0.6. It is therefore expected that a crack starting from semi-circular shape will grow in both circumferential and radial directions, evolving into an elliptical crack and becoming more elliptical with time

These analyses showed that a planar semi-circular crack could be expected to evolve into a non-planar semi-elliptical crack because propagation is predicted to be faster in the circumferential than in the radial direction. The extreme case of radial propagation from a 360° circumferential crack produces the shortest propagation life and hence provides the most conservative disk life prediction. With this very conservative assumption the crack growth life is indicated to be in excess of 5500 hours beyond the 6000 hours initiation life, and is very likely to be very considerably longer.

The results of these analyses have been confirmed by experimental studies which have found that cracks generated in the front snap radius of samples cut from the parent disk grow preferentially in the circumferential direction. The tests in these studies produced a stress-state in the front snap radius that was similar to, but not fully representative of, the service conditions. The shape of the crack obtained in these test conditions is shown in Figure 10.

Since no in-service cracks have been seen to-date this prediction has not been fully validated. It is intended to carry out full-scale spin pit tests of 4th LPC engine disks with implanted flaws in the front snap radius to fully validate these predictions.

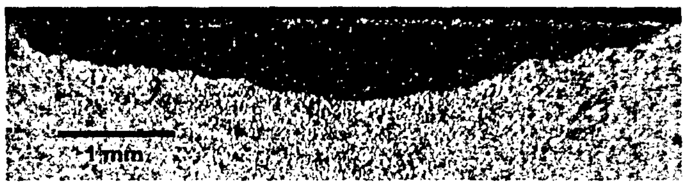

Figure 10 Crack Configuration in an experimental test replicating the engine conditions

5. Conclusions

The cases presented here indicate that the traditional LCF safe life analysis represents only a partial view of all the processes that contribute to defining and determining component replacement intervals. The fact that the LCF statistical data base omits to include other contributing factors such as the ones described in this paper, i.e. non-representative microstructures and the possibility of manufacturing and re-work flaws, leads to a non-conservative estimate of component replacement intervals. However, if no account is taken of the behaviour of cracks subsequent to reaching the assumed size of 0.8mm the assessment of replacement intervals may be excessively conservative.

The cases presented here illustrate the complex processes which have to be taken into account in determining replacement and overhaul intervals for critical components. The LCF analysis carried out by the OEM is only part of the analysis. A more detailed analysis, including a risk analysis needs often to be carried out retrospectively, including all the possible failure mechanisms.

The use of a 0.8 mm detectable crack as the criterion for a safe life was originally based on what could be reliably detected with NDI equipment at the time of the development of safe-life methodology. Modern automated NDI equipment can detect much smaller crack sizes with a very high degree of confidence, and safe-life estimates could therefore be adjusted to take advantage of this extra sensitivity without a commensurate increase in risk.

Conventional safe life methodology is founded on the assumption of nominal material and manufacturing conditions, and under these conditions the methodology provides a structured process for design and life management of high energy rotors. However undetected material and manufacturing anomalies represent a departure from the assumed nominal conditions and have resulted in the service incidents described in this paper.

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Paper 22: Discussion

Question from H Pfoertner – MTU, Germany

Would you comment on the relationship between numerical crack-growth predictions and the necessity to perform spin testing?

Presenter's Reply

Each case has to be taken on its merits. In probably a few cases with simple geometries, an analytical solution alone may be sufficient. However, most cases will involve a combination of analytical solutions and tailored validation tests, ranging from simple tests, through multi-axial loading tests, up to full-scale component tests and spin tests. Each method has strengths and weaknesses, and these need to be understood.