Methodology for Lifing Turbine Disk Bores Under Multiaxial States of Stress

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ABSTRACT

A methodology is described for determining the minimum low cycle fatigue (LCF) life of turbine disk bores under multiaxial states of stress. The empirical data used to establish the methodology were generated from a set of six mini disks designed to simulate the same biaxial stress ratio as in an actual turbine disk bore. The mini disks, made of DP-718, were tested at 600°F (589°K) by cycling between 5,000 and 52,000 rpm in a spin pit. The testing was interrupted to check for fatigue crack initiation in the bore, which occurred only in one of the disks. Crack initiation life, defined as the number of cycles required to initiate a crack of 0.015 inch (381 μm) depth, was derived through subsequent striation counting. An approach was developed for estimating lives of turbine disk bores using principal stress range with its associated stress ratio as the lifing parameters. Statistical and probability analyses of both the spin pit results and uniaxial LCF data were conducted. A unique probability density function was used for minimum life estimation. Fractographic observations of crack initiation modes are brought in to support the methodology.

INTRODUCTION

Aircraft engine components are in general subjected to multiaxial states of stress. Both thermal and centrifugal components contribute to the stress state at any instant. For turbine disk bores, in general, the contribution is predominantly from the centrifugal. This makes it easier to simulate the stress state of a disk bore by spin testing sub size or mini disks. Many theories [1] have been proposed in the past to account for multiaxial stress state in life estimation. They are stress, strain or energy based. The stress and strain based methods were formulations involving principal, von-Mises' (also referred to below as effective) or shear components of stress and strain respectively. Often in these models, known also as the critical plane models [2,3], a stress term to take into account the influence of mean stress acting across crack plane had to be incorporated. It is worth mentioning that in most of the work published on multiaxial lifing models the major objective seems to have been the development of a life prediction parameter which will encompass a very large spectrum of multiaxial stress states from the pure tension all the way to pure torsion.

There is a general recognition that stress based models are relevant to lives in the so called "high cycle fatigue" regime and that the strain based models are applicable primarily to regimes of lower lives. For turbine engine components the certification lives are in the range 10,000 to 25,000 cycles, which puts the corresponding average lives in the 100,000 cycle range or higher. This would tend to put the right methodologies for disk bore lifing in the stress-based class.

Two stress-based parameters are considered in this effort, (i) principal stress range and its associated stress ratio, and (ii) effective stress range with the stress ratio associated with the max principal stress range.

MATERIAL

Both the turbine and mini disks were made from delta-processed Inconel 718 (DP-718). It has the same chemistry and heat treatment parameters as the normal wrought IN-718 except that the delta processing [4] prior to final forging imparts a very uniform grain size of ASTM 9 or finer across the entire disk. The grains are hardened primarily by precipitation of gamma double-prime. A distribution of fine MC (M for N_b or T_i) type carbides, which have an average size of about 0.001 inch (25 μm), is present throughout the microstructure. A large database of tensile, LCF and cyclic crack growth was generated for this material using standard ASTM recommended specimens. The LCF database consisted of 366 unixial specimens machined from turbine disk forgings and tested at temperatures between 75°F (297°K) and 1200°F (922°K) at various strain ratios (min/max) ranging from -1.0 to 0.7. This spectrum of strain ratios produced stress ratios ranging from -1.0 to 0.5. A design curve (LCF model) was constructed through multilinear regression that describes the average and minimum LCF strength as a function of temperature, stress ratio (min/max) and desired cycles across the whole temperature range. The design model describes a family of curves, in which log of stress is expressed as a function of log of cycles giving the typical bilinear shape, along with a stress ratio formulation and a temperature function. Fractography was conducted on the broken LCF specimens. Failure initiations observed in DP-718 LCF specimens were of two types. At low temperatures, from 75°F (297°K) to approximately 400°F (477°K), the initiations occurred at the surface in Stage-I (crystallographic) mode on slip planes. As the temperature was increased the initiations occured either at the surface in Stage-II (non-crystallographic) mode (perpendicular to the axial stress) at carbides, or in Stage-I (crystallographic) mode at sub-surface or internal locations, thus creating a bimodal distribution at elevated temperatures.

TESTING

The specific turbine disk whose life had to be certified had an estimated bore temperature of 600°F (589°K) at full speed. The elastic stresses were 153, (1055), and -48 (-331) ksi (MPa) respectively in the hoop and axial directions which gives a biaxial stress ratio of -3.2. At these stresses, the average lives could go into hundreds of thousands of cycles. As the cycle time in a spin pit test is approximately 5 minutes the cost of spin pit LCF simulation precluded running to such high lives to obtain a failure. Hence it was decided to increase the test stress by 16 percent thereby reducing the average failure cycle to an acceptable number. In fact, depending on whether principal stress or effective stress controlled crack initiation, the spin test parameters could be so defined to differentiate between the two. At the higher bore stresses chosen for the spin tests the LCF model would predict failure in a more reasonable time. If the failure was controlled by the effective stress criterion as defined above, the lower 99.9% of the lives would fall within 70,000 cycles. A much lower 0.8% of the lives only would fall within 70,000 cycles if the failure was controlled by the principal stress. Hence, very few failures would be expected for the latter case. Simultaneously, if there was a correlation between fractographic details and the life distribution at a specific temperature, then all possibilities of crack initiation, both Stage I and Stage II would manifest in the failures encompassing the lower 99.9%. On the other hand, if only 0.8% of the failures were captured, the mini disk crack initiation characteristics would follow those specimens that skirt the minimum behavior at the test temperature. The latter is associated with Stage-II type initiating from carbide particles. The maximum number of test cycles, therefore, was chosen to be 70,000 at which all tests would be terminated.

Six mini spin disks (Fig. 1) were machined from DP-718 turbine disk forgings. The bore was ground with the same procedure as employed in manufacturing of the actual disk bores. The spin pit was heated to 600°F (589°K) and the disks were cycled between 5,000 and 52,000 rpm. A proprietary vibration monitor was used at the vendor for crack detection in the spin pit. Florescent penetrant and eddy current inspections were performed in the bore on all disks to verify presence or absence of cracks at regular intervals. After testing to 70,000 cycles, the sixth mini disk was further used to determine cyclic crack growth rate in the bore stress field for the purpose of calibrating crack propagation life from a depth of 0.015 inch (381 μm) to beyond.

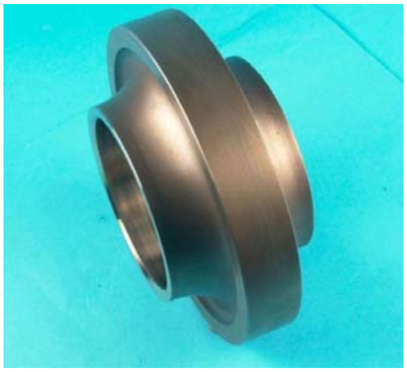

Figure 1. Shape of the Minidisk.

Test Results

Spin pit test results are shown Table 1. The first disk was spun to 112,123 cycles before testing was stopped. No cracks were found in the bore. The second disk failed from a machining-induced defect at a location adjacent to the bore at 29,980 cycles. This was an area that was turned rather than ground and the location indicated abusive machining. Failure of disk #2 was therefore declared non-valid or “suspension” from a lifing standpoint as the stresses peak maximum at the center of the bore, always in ground condition, in the actual disk. Striation counting was conducted on the fracture surface of disk #2 and the cycles to propagate the crack from 0.015 inch (381 μm) depth to failure were estimated to be 8,500. Cracking was detected in disk #3 at 54,765 cycles. No cracking was detected in disks 4 through 6 when they were retired at 70,000 cycles.

Table 1. Spin Pit Mini Disk Test Results.

Disk #	**Total # of LCF Cycles on Disk**	**Crack Indication**	**Crack Location**	**Cycles to grow from 0.015 inch (381 μm) deep crack**
1	112,123	No	N/A	N/A
2	29,980	Yes, a single crack, Fracture	Not in the bore (adjacent turned surface)	8,500 to fracture
3	54,765	Yes, Two Cracks, No fracture	Central Portion of the bore (ground)	3500 to 0.068 in (1.73 mm) depth for the smaller crack
4	70,000	No	N/A	N/A
5	70,000	No	N/A	N/A
6	70,000	No	N/A	N/A

When disk #3 was examined, two surface cracks were found located approximately diametrically opposite near the center of the bore. Both cracks had initiated from carbides of approximately 0.001 inch (25 μm) in size (Fig. 2). Each crack, after initiating from a carbide particle propagated for a short distance maintaining an aspect ratio (depth to surface length) of half and with the crack orientation perpendicular to the max principal (hoop) stress. After reaching a total length of 0.010 inch (250 μm) each crack propagated in an oblique mode inclined at approximately 45 degrees. In the oblique mode, the crack still maintained an aspect ratio of about 0.5. Incidentally this unique propagation behavior is identical to that observed in uniaxial specimens of this and other high strength materials such as U720-LI, DA-718 and Rene 95. One of the cracks had propagated more than the other. The length/depth dimensions of these two cracks were 1.1/0.5 and 0.140/0.068 inches (27.9/12.7 and 3.6/1.7 mm) respectively. Striation counting could not be conducted on the larger crack since its surfaces appeared to be in a smeared condition. No smearing interfered with striation counting on the smaller crack for which propagation cycles from 0.015 inch (381 μm) to 0.068 inch (1.7 mm) crack depth were estimated to be 3,500.

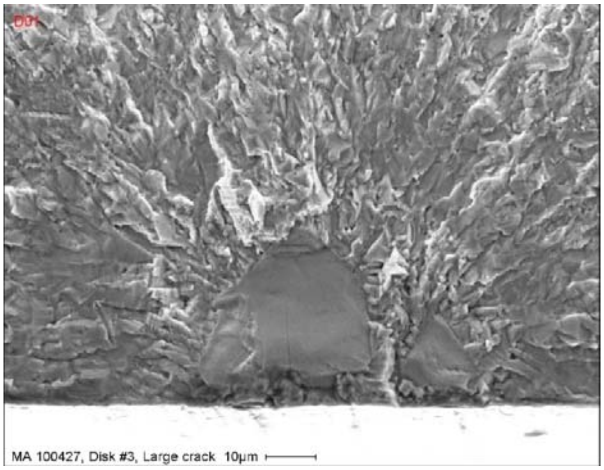

Figure 2. SEM Image of Crack Initiation Location of the Larger Crack in Disk #3.

Since the crack initiation life of the disk had to be based on the larger crack and striation counting could not be conducted on its fracture surface, disk #6 was used for ascertaining the crack propagation rate under the spin test stresses up to a depth of 0.5 inch (12.7 mm). This disk had sustained 70,000 cycles without cracking. Four starting notches, A, B, C and D, each 0.020 inch (508 μm) long and 0.010 inch (254 μm) deep, were electro-discharge machined (EDM) in the bore at the center, equally spaced hoop wise. The disk was spun to a total of 7,500 cycles. Crack replication was conducted at 3,307, 5,500, 6,500 and 7,500 cycles. Oblique propagation mode was observed on all four cracks. Table 2 shows the crack growth measurements, which are plotted as red symbols in Figure 3.

NASCRAC software was used to estimate crack propagation rates. Crack growth rate data were available for DP-718 from testing of surface cracked tension (Kb-Bar) bars [5]. These in conjunction with the disk stresses were used to estimate propagation cycles from 0.015 inch (381 μm) to 0.5 inch (12.7 mm) depth for the larger crack in disk #3. The crack length versus cycles data from this analysis were then adjusted to go through the mean of the measurements in Table 2 for the four EDM notches. The adjusted curve is also plotted in Figure 3. The propagation cycles for the larger crack in mini disk #3 to advance from 0.015 inch (381 μm) to 0.5 inch (12.7 mm) depth were thus estimated to be 5,396. The crack initiation life of disk #3 to

0.015 inch (381 μm) crack depth could then be equated to the difference, 54,765 -5,396, or 49,369 cycles.

Table 2. Spin Pit Crack Growth Results for the 6th Disk.

Cycles	**Total Surface Length in inches (of two legs + 0.020 inch (508 μm) EDM notch) At Cycle [Values in brackets are in mm]**			
	A	**B**	**C**	**D**
3307	0.0328 [0.83]	0.0312 [0.79]	0.0304 [0.77]	0.0320 [0.81]
5500	0.0675 [1.71]	0.0578 [1.47]	0.0580 [1.47]	0.0755 [1.92]
6500	0.1031 [2.62]	0.0764 [1.94]	0.0848 [2.15]	0.1054 [2.68]
7500	0.1785 [4.53]	0.1351 [3.43]	0.1515 [3.85]	0.1804 [4.58]

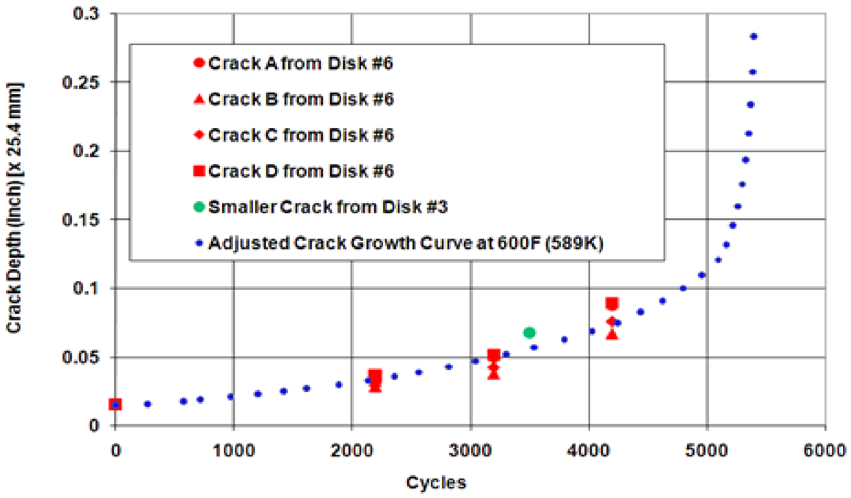

Figure 3. Crack Growth Estimations and Observations on Mini Disks.

CALCULATION OF MINIMUM LIFE FOR MINI DISKS

Let us first note that a designer is interested in estimating the "minimum" life of components to which a "risk" value can be attached. What follows is the description of a unique procedure which was developed for estimating the minimum life of the mini disks at 0.135 % failure probability. First the probability for crack initiation in disk #3 which was the lone disk that had cracked had to be estimated using a statistical analysis of the mini disk test results. Once this was known, the minimum life of mini disks was calculated using the uniaxial LCF data and use of a unique probability function.

Ranking of the Single Failure

As shown in Table 3, given the five suspensions, the adjusted rank for disk #3 is 1.2, which corresponds to a median probability of occurrence of 13.54% using Benard's equation [6]. This means that the probability of crack initiation for the mini disks at 49,369 cycles was 13.54%.

Table 3. Ranking of Spin Disks.

Mini Disk Cycles	**21,480**	**49,369**	**70,000**	**70,000**	**70,000**	**112,123**
Rank	1	2	3	4	5	6
Failure/Suspension	S	F	S	S	S	S
Reverse Rank	6	5	4	3	2	1
Adjusted Rank	N/A	1.2	N/A	N/A	N/A	N/A
Median Rank	N/A	13.54%	N/A	N/A	N/A	N/A

Comparison to LCF Database and Model

LCF data for DP718 at 600°F (589°K) is plotted in Figure 4 as the ratio of measured cycles (for each specimen) to the minimum cycles at the -3 sigma level estimated from the LCF model. The data were then fit to a 3-parameter log-normal distribution. The value of 1.0 in the abscissa represents the LCF model minimum, i.e., if any specimen life fell on the minus-three sigma line, that datum point would lie at the ratio of 1.0. All the data generated at 600°F (589°K) for DP-718 are shown in this plot. At 0.135% probability of failure, a ratio of 1.2098 can be obtained from the curve fit. In other words, minus-three sigma value for this ratio is higher than that assumed by the LCF model.

Since this uniaxial database forms the basis of the current LCF life estimation system, this plot can be taken as providing probability of failure of a specimen provided this ratio for that specimen is known, or vice versa. Furthermore, it is assumed that the plot is applicable to multiaxial life estimations as well. Therefore, if the crack initiation life of the spin disk (49,369) is known and also its probability of crack initiation (13.54%) can be independently estimated, then its minimum life can be estimated from this plot. Since 13.54% probability of occurrence at the initiation life of 49,369 cycles translates to a ratio of 2.3001, estimated life at 0.135% probability would be equal to 49,369 multiplied by the ratio ({1.2098/2.3001} = 0.526) or 25,967 cycles. Table 4 shows that, for the spin disks, the above calculated minimum life of 25,967 cycles is much closer to that estimated (from the LCF model at disk stresses) based on principal stress criterion (28,116 cycles) than that based on effective stress criterion (7,713 cycles). The ratio of the minimum life predicted by this method to that predicted by the LCF model is (25,967/28,116) or 0.9236. This correction could be incorporated in component life calculations.

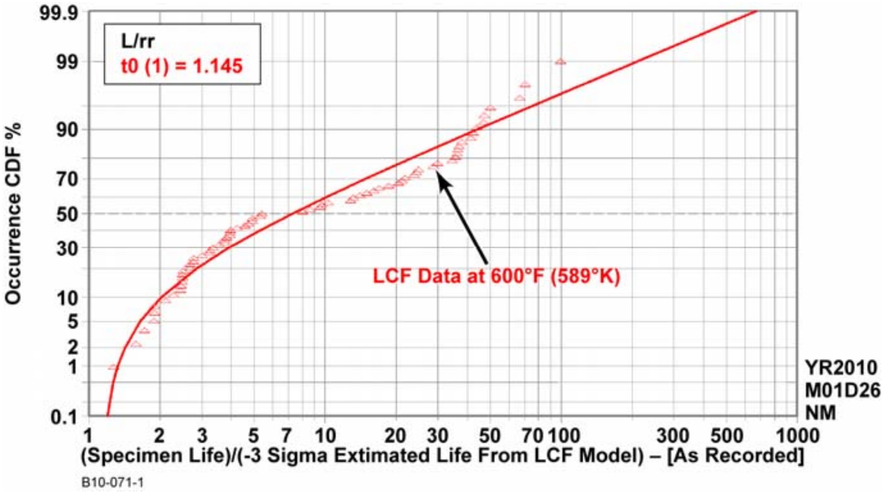

Figure 4. LCF Specimen Data at 600°F (589°K) Plotted as the Ratio of Specimen Life to the Life at -3 Sigma Level Estimated from the LCF Model.

Table 4. Lives Based on Principal and Effective Stress Criteria.

Disk Bore	Criterion	T (°K)	Stress Range (MPa)	Stress Ratio (min/max)	Minimum Life from uniaxial LCF Model	Average Life from uniaxial LCF model	Minimum Life predicted by this method
Spin Disk	**Principal**	589	1216	-0.3086	**28,116**	2,145,717	**25,967**
Spin Disk	Effective	589	1420	-0.3086	7,713	23,051	N/A

DISCUSSION

This method shows that the use of principal stress criterion as defined above in conjunction with the LCF model is closer to estimating the minimum lives of mini disk bores. Note the underlying assumption that once the LCF model has been developed by specimen testing and declared as the design curve for all life estimations, which is a procedure employed by the engine companies, that is the primary information to which all multiaxial test results need to be compared statistically and related to in developing life estimation methodologies. Most of the well known stress and strain-based multiaxial models [1] have a shear stress or shear strain term acting on the plane of cracking along with a stress component acting normal to the shear plane. A characteristic of these models, also known also as critical plane models, is that a crack forms on a unique plane with respect to the stress tensor on which the crack propagates initially. None of these models would apply in the present case since the plane of cracking was perpendicular to the principal stress in the bore. The plane of initial crack propagation was perpendicular to the principal stress. This leaves only models based on principal stress or von Mises' stress to consider for the present case.

If the principal stress controlled crack initiation, it would be consistent to expect failure to occur on a plane macroscopically perpendicular to the maximum principal stress direction. The method can take into account the mean stress effect explicitly by resorting to the stress ratio formulation which can be deduced from the uniaxial specimen data. There is no ambiguity in the geometrical relations between the crack plane and the principal stress direction. Hence failure is deemed to be associated with the largest principal stress range in conjunction with its stress ratio and as predicted by the uniaxial LCF model with its validated stress ratio correction factor. On the other hand, the effective stress has no directionality. The justification for use of von-Mises' stress in multiaxial lifing problems is that fatigue cracking is believed to be preceded by dislocation motion and cracking on slip planes. Note also that when at very high cyclic lives the crack initiation mode changes to crystallographic the macroscopic crack propagation plane, which is the discriminating characteristic in critical plane models, is still perpendicular to the principal stress. If we ignore the mean stress effect, the estimated average and the minimum lives by the effective stress criterion would be 3.8627E+07 and 4.1068E+05 cycles respectively. The stress-ratio-based adjustment to the effective stress range, which would match the minimum life prediction from the spin pit results, would be more negative and equal to -0.7. Thus, a comparison between the two methods points to the advantage of using a principal stress-based method over that based on von Mises' stress for life estimation of turbine disk bores.

CONCLUSIONS

The mini disk results reported above show that principal stress criterion is the most favored approach for estimating minimum LCF lives of disk bores of DP-718. The method is elegant and involves the use of a lifing parameter that is consistent with the crack initiation mode in DP-718. Let us note first that for uniaxial cases the procedure is simple and the data from uniaxial LCF tests, which typically form the larger part of LCF databases, are perfectly appropriate to use. For multiaxial life prediction more complex parameters or procedures are needed. However, the present exercise shows that if the application is limited to a “restricted” multiaxial field, such as the bore of a turbine disk, simpler parameters can be employed and the results made more relevant and robust to the case considered. This also results in the least variance. It points to the need to consider restricting development of a multiaxial life estimation model to a smaller spectrum of multiaxial states than typically entertained because, although fatigue originates from dislocation movement, the “causal” parameters which dictate crack nucleation mechanics can be expected to vary with variation in the multiaxial stress tensor and may be difficult to bring under a simple formula covering a wide spectrum of multiaxial conditions.

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