Title: Aero Engine Life Usage Monitoring Including Safe Crack Propagation

Authors: Juergen Broede
Manfred Koehl

1 ABSTRACT

The safe crack initiation life concept is generally used to predict and monitor the service life of aero engine parts. This concept, which declares a structural part's life as exhausted if a small crack of a predefined depth has been initiated with a given probability, leaves the question of the remaining crack propagation life up to a catastrophic failure unanswered. If the crack initiation is followed by a long crack propagation life before the onset of unstable crack growth, the structural part will be replaced too early, causing higher costs than necessary. On the other hand, if the remaining life to dysfunction is very short, a possible safety problem may be left unnoticed. Therefore, a modern lifing concept for fracture critical parts should include the safe crack initiation life as well as the safe crack propagation life. Considering a safety margin up to dysfunction, it is expected that the crack propagation life could partly be utilized to extend the usage period beyond the limits set by the safe crack initiation life concept. In the present contribution it will be shown how the calculations of fracture mechanics parameters and the resulting crack propagation process are integrated into the algorithms of on-board life usage monitoring software. Crack propagation monitoring software is in use in the German OLMOS system of the TORNADO engine RB199 since 1996. Experience gained with this application and earned benefits will be presented.

2 INTRODUCTION

Aero engine fracture critical parts undergo cyclic loading during their operational usage. Due to the nature of this loading, the material experiences fatigue at some highly stressed areas, what leads to initiation and propagation of fatigue cracks.

Fatigue is the life limiting damage mechanism for most of the fracture critical parts, since growth of cracks beyond a certain stage of their development (i.e., beyond a certain crack depth) increases the probability of part failure. To maintain the structural integrity of the engine in accordance with the required safety standards, it is necessary to retire a part before an accepted risk level is exceeded.

MTU Motoren- und Turbinen-Union Muenchen GmbH, Dept. TPKF,
P.O. Box 50 06 40, 80976 Muenchen, Germany.

Fatigue life of a part is defined as the number of cycles (with a given stress range at given temperature conditions) that the life limiting critical area of that part is able to endure until a crack with specified properties has developed.

The classical method to treat fatigue life is the concept of safe crack initiation life (frequently just called: the safe life concept). 'Safe' means in this context that the scatter of material strength is considered and the life of the weakest part of the whole population declared as the life of each member of this population. The consequence of this concept is that only the fewest parts will have generated a small fatigue crack when they all are taken from service. The majority of the parts will be crackfree. And even parts which have developed an initial crack will still have a remarkable portion of remaining life, since in most of the cases the crack can be allowed to grow to some certain crack depth before the engine integrity will be jeopardised.

This behaviour led to the idea to safely utilise some portion of the crack propagation phase. The underlying lifing concept is called the concept of safe crack propagation life. This concept is equivalent to that of the safe crack initiation life, but allows instead of roughly 0.4 mm depth a fatigue crack to grow until dysfunction. The dysfunction criterion may include different cases which all could reduce the structural integrity (e.g. the onset of unstable crack growth). Of course - the concept does not accept that the dysfunction condition will be really reached, but provides a well defined safety margin. Due to this real safety margin, the concept of safe crack propagation may be judged as 'safer' than the classical safe (crack initiation) life concept.

3 SAFE CRACK INITIATION AND CRACK PROPAGATION LIFE

The basic idea for the concept of safe crack initiation life is that a new part is free of defects, a defect (in this case a fatigue crack) is generated in service, and the part's life is expired, when the defect has been created. The criterion for 'existence' of a crack is that the crack has been initiated and grown to a certain depth. A commonly used value for this crack depth is 0.4 mm. This criterion is a little arbitrary, although sensibly based on long experience.

The concept of safe crack propagation life is based on the idea that the part contains an initial defect at the beginning of the crack propagation phase (where the defect behaves like a crack of a certain depth), that the crack propagates under service loading, and that the part's life is expired when the crack enters the phase of part dysfunction. In contrast to the crack initiation criterion, the dysfunction criterion really determines the end of the part's life. This enables us to define a measurable safety margin. Thus, the part will be taken from service when a certain portion (e.g. two third) of the number of load cycles to dysfunction have been accumulated. If the concept of safe crack propagation life is used for life extension, the number of cycles to dysfunction encompasses both the crack initiation and the crack propagation phase. The safety factor of two third will then be applied to the total number of cycles.

While the safe crack initiation life is established as the number of stress cycles to reach an accepted statistical probability for the existence of a crack with the depth of 0.4 mm, the safe crack propagation life is established as 2/3 of the number of cycles to reach an accepted statistical probability for the presence of the dysfunction condition. The statistical probability takes into account that material strength and crack growth properties exhibit some scatter. For the weakest individual of the part's population, the structural integrity must be ensured. Generally accepted statistical probabilities for that weakest part are in the range of 1 out of 750 to 1 out of 1000.

Parts lifed under either of these lifing concepts are not inspected for cracks when they are retired. Re-use of the parts beyond the safe crack initiation respectively propagation life is not considered, although most of the parts will not contain a crack grown to the depth which is correlated with the respective criterion.

Note that the safe crack initiation life concept cannot provide a measure for the real safety of the critical part, since it is unable to predict a value for the failure margin. In most of the applications there will be sufficient margin for a crack to grow to part dysfunction, but it is also possible that the dysfunction life is very close to the crack initiation life. In such very rare cases the crack initiation life cannot be considered as really safe, in contrast to the safe crack propagation life where a safety margin is defined.

4 LIFE USAGE MONITORING

Fracture critical parts in aero engines are released only for limited life and must be retired when their life limits are reached. Life usage monitoring serves to identify the proper time. How long a critical part can be kept in service, depends on both the released life at the critical areas and their life consumption due to operational usage. Different methods for life usage monitoring have been established.

The traditional method is to count the engine flight time and to multiply it with a cyclic exchange rate. The cyclic exchange rate provides a relationship between the flight time and the life consumed at a critical area. As the correlation between flight time and cyclic life consumption is very weak, conservatism needs to be incorporated into the cyclic exchange rate, what in turn leads to overestimation of life consumption for most of the parts.

In reality, the life consumed during an engine run or flight is based on stresses and temperatures at the critical areas of the components. These parameters depend obviously on the actual mission profiles. Thus, better exploitation of the released life is achieved with individual monitoring, where life consumption of each part is individually calculated using actually measured engine parameters.

The procedures for individual monitoring consist of effective algorithms for use in real time, able to calculate the consumed life directly from measured engine signals. The algorithms allow for fast processing of the input signals as they appear under real aircraft and engine manoeuvring. Results are available immediately after the end of a flight. Life usage is measured in damage related physical or technical units rather than in engine flying hours. Normally, the most damaging cycle of the design mission is declared as the reference cycle for the considered critical area and used as the unit for damage.

Details of the method have been published at several occasions [1-5]. Here only a summary is given. The method determines the thermal and mechanical boundary conditions for the engine components on the basis of measured time histories of engine operating parameters (such as spool speeds, intake conditions and gas path temperatures). Based on these boundary conditions, the transient temperature development within the components is calculated. Stresses at critical areas are computed, which are then used together with the corresponding temperature histories to predict the related damage. Critical area damage is accumulated over all engine runs, so to build up complete life consumption records for all monitored parts of an engine.

The procedures for individual life usage monitoring outlined here (which are basically also applied in the process of determining cyclic exchange rates for traditional life usage tracking) are closely related to the life prediction process which is part of the entire engine development process [12].

For most of the critical areas, the concept of safe crack initiation life is employed. Under this concept, the number of reference cycles needs to be predicted, which the critical area can undergo until a fatigue crack will have been generated and grown to the predicted depth of 0.4 mm. Material *SN*-curves are used which describe the relationship between applied stress range and the corresponding number of cycles to crack initiation. Mean stress and temperature effects are covered as well.

For critical areas where the original safe crack initiation life is extended into the safe crack growth regime, additionally the safe crack propagation life needs to be predicted. For this prediction, typically the methods of linear elastic fracture mechanics are used. Two things are required, namely the stress intensity factor range of the most damaging cycle accompanied by *R*-ratio (stress intensity factor ratio of cycle minimum to cycle maximum value) and temperature, and the crack propagation law relevant for the used material. The crack propagation law describes the crack propagation rate as function of the stress intensity factor range, considering also *R*-ratio and temperature. The accumulating crack growth process is simulated by integration of the crack propagation rate from the initial crack depth to the onset of instability under reference cycle loading. From the number of cycles necessary to propagate the crack up to the dysfunction criterion, one can derive the safe crack propagation life.

5 STRESS INTENSITY FACTOR

For prediction of the safe crack propagation life and also for life usage monitoring in the crack propagation regime, it is necessary to determine the stress intensity factor. The stress intensity factor depends on the geometry of the component, on the stress field around the critical area, and on the current shape of the crack. As these quantities in aero engine components are very complex, text book solutions for the stress intensity factors are generally not available. Thus, they are calculated by finite element analyses (or on the basis of experimental results, see [12]).

The crack shape is given by the crack surface (which in many cases may be considered as a plane) and the crack front. It is essential to consider the crack as a whole. In particular, it should be noticed that the stress intensity factor varies along the crack front, so that the crack growth velocity is different at different points of the crack front.

A 3D finite element model is used, where the crack surface and the crack front are introduced. As an example, in Figure 1 a modelled crack front at a critical area in the rim slot fillet of a turbine disc is shown. An automated procedure has been established which allows to simulate the development of the crack using finite element calculations in combination with an appropriate crack growth law. Details of this technique were already published in [6-11].

The procedure starts with an initial crack. The initial crack shape is either taken from test experience with real parts or simply assumed as a half or quarter elliptical front at a plane perpendicular to the direction of the maximum principal stress. The

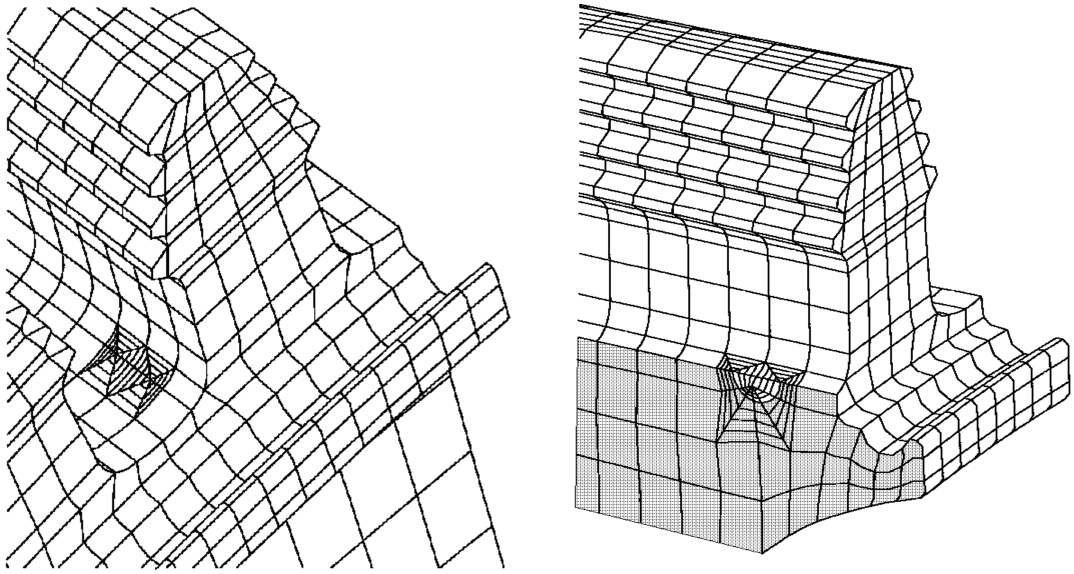

FIGURE 1. REMESHED FE-MODEL OF A TURBINE DISC IN THE VICINITY OF AN INTRODUCED CRACK. LEFT: VIEW AT DISC SURFACE. RIGHT: VIEW AT CRACK PLANE.

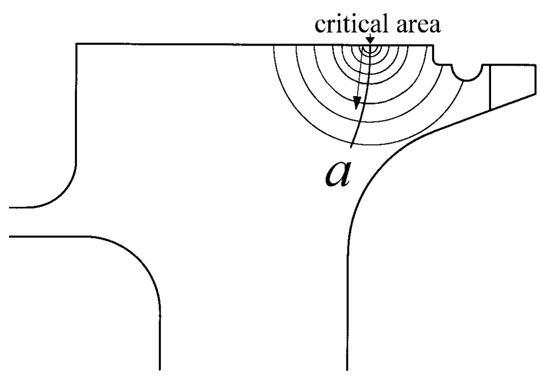

FIGURE 2. ANALYSED CRACK FRONTS AND CRACK PATH ***a***

exact shape of the initial crack is not so important as the crack will develop into a balanced shape anyway.

For the part containing this initial crack, the stress intensity factor along the crack front is calculated. Typically, the load case belonging to the maximum stress of the reference cycle is used. All relevant loads (as centrifugal and thermal loads) contributing to the stress field around the critical area are included. With the stress intensity factor range and the crack propagation law, the crack growth increment at each point of the crack front is calculated and a new crack shape predicted. Since the crack grows slowly, the stress intensity factor will not change significantly during a small number of cycles. Thus the crack growth for a number of cycles can be computed with the same stress intensity factor distribution. But when the grown crack is distinctly different from the original one, a new stress intensity factor calculation becomes necessary. This process (calculation of the stress intensity factor, determination of the according crack growth rate and prediction of the new crack shape) is repeated several times building up a complete crack growth history over the number of applied cycles. This crack growth history ranges from an initial crack (which is usually smaller than or equal to that for the crack initiation criterion) to the onset of unstable crack growth.

Now, one can choose a path at the crack surface from the point where the crack has originated (the critical area) into the depth of the considered structure, as shown in Figure 2. Along this path the crack depth $\boldsymbol{a}$ is measured. For the path, a relationship between the crack depth $\boldsymbol{a}$ and the corresponding stress intensity factor $\boldsymbol{K(a)}$ can be established. Dividing the stress intensity factor by the monitored stress $\boldsymbol{\sigma(0)}$ present at the uncracked critical area $\boldsymbol{a=0}$ itself, defines a so called geometry function $\boldsymbol{g(a)}$. This geometry function provides the relationship between the stress at the critical area and the stress intensity factor at the crack front for each value of the crack depth and enables us to calculate the time history of the stress intensity factor from the time history of the stress at the critical area including the effect of increasing crack depth.

For this procedure it is assumed that the stress fields around the critical area are proportional for all load cases of the mission. In fact, this is not the case. But the error is considered negligible as long as the stress intensity factors for the higher stress levels are modelled correctly. Deviations for sub-cycle stress intensity factor ranges are acceptable as their contribution to the overall damage is small.

Currently only a correction for residual stresses is made. The basic idea for this correction is that during the first load cycles some local plastification occurs, what causes some redistribution of the stress fields, as illustrated in Figure 3. After initial plastification, the component is assumed to behave linearly, so that the application of linear elastic fracture mechanics methods appear adequate. This redistribution is accounted for by an additional additive term $\boldsymbol{K_{add}(a)}$ in the formula for the stress intensity factor. The aim is to find a representation of $\boldsymbol{K(a)}$ as a function of the known (since monitored) elastic stress $\boldsymbol{\sigma_{elastic}(0)}$ at the critical area ($\boldsymbol{a=0}$) :

$$\boldsymbol{K(a) \;=\; g(a) \cdot \sigma_{elastic}(0) \;+\; K_{add}(a)} . \tag{1}$$

The just verbally described procedure to determine the geometry function $\boldsymbol{g(a)}$ and the additional additive term $\boldsymbol{K_{add}(a)}$ as a function of the crack depth $\boldsymbol{a}$ is now stated more precisely :

<u>Firstly</u>, a couple of linear-elastic 3D finite element analyses of the structure containing cracks of different depths according to Figures 1 and 2 is performed under reference load conditions (assumed as extreme load case also in operational usage), yielding the stress intensity factor $\boldsymbol{K^*_{ref}(a)}$ as a function of the chosen crack path $\boldsymbol{a}$.

<u>Secondly</u>, a 3D finite element analysis of the uncracked structure under reference load conditions is performed, linear-elastically as well as elastic-plastically, in order to determine the linear-elastic stress $\boldsymbol{\sigma_{elastic,ref}(a)}$ and the elastic-plastic stress $\boldsymbol{\sigma_{plastic,ref}(a)}$ along the crack path $\boldsymbol{a}$.

The difference defines the residual stress

$$\boldsymbol{\sigma_{residual,ref}(a) \;:=\; \sigma_{plastic,ref}(a) \;-\; \sigma_{elastic,ref}(a)} . \tag{2}$$

Therefore, after an initial plastification has occured, the effective stress $\boldsymbol{\sigma(a)}$ in the uncracked structure under arbitrary load conditions can be formulated as

$$\boldsymbol{\sigma(a) \;=\; \sigma_{elastic}(a) \;+\; \sigma_{residual,ref}(a)} , \tag{3}$$

where $\boldsymbol{\sigma_{elastic}(a)}$ is approximated by the monitored elastic stress $\boldsymbol{\sigma_{elastic}(0)}$ at the critical area ($\boldsymbol{a=0}$), scaled by the respective stresses produced under reference load

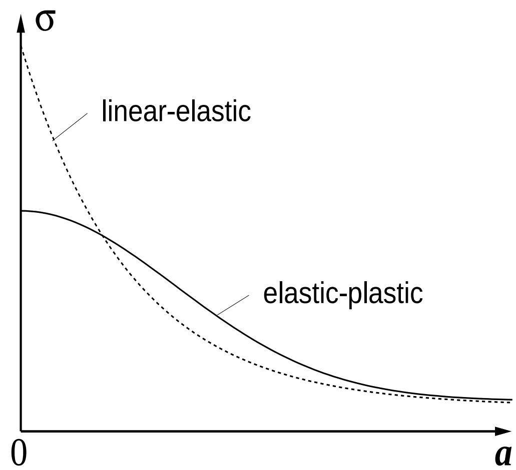

FIGURE 3. STRESS REDISTRIBUTION DUE TO PLASTIFICATION

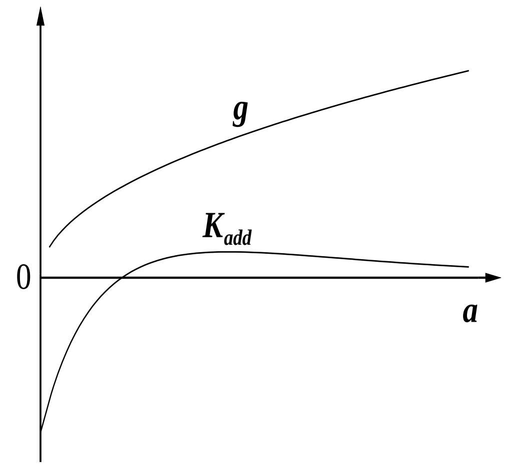

FIGURE 4. GEOMETRY FUNCTION AND ADDITIVE TERM

conditions:

$$\sigma_{elastic}(a) \ := \ \sigma_{elastic}(0) \ \cdot \ \sigma_{elastic,ref}(a) \, / \, \sigma_{elastic,ref}(0) \, . \tag{4}$$

Since the stress intensity factor $K^*_{ref}(a)$ can be represented as the product of the local linear-elastic stress $\sigma_{elastic,ref}(a)$ in the uncracked structure and a geometry factor $g^*(a)$, this geometry factor is defined by

$$g^*(a) \ := \ K^*_{ref}(a) \, / \, \sigma_{elastic,ref}(a) \, . \tag{5}$$

Making use of this geometry factor, the effective stress intensity factor $K(a)$ for arbitrary load conditions can be written as

$$K(a) \ = \ g^*(a) \ \cdot \ \sigma(a) \, . \tag{6}$$

Comparison of (1) and (6) defines the desired geometry function $g(a)$ as well as the additional additive term $K_{add}(a)$ due to residual stresses, after substituting equations (3), (4) and (5) into equation (6) :

$$g(a) \ := \ K^*_{ref}(a) \, / \, \sigma_{elastic,ref}(0) \ , \tag{7}$$

$$K_{add}(a) \ := \ \sigma_{residual,ref}(a) \ \cdot \ K^*_{ref}(a) \, / \, \sigma_{elastic,ref}(a) \ . \tag{8}$$

Figure 4 shows a sketch of these quantities as functions of a. The geometry function g increases usually monotonically with the depth a. The additive correction K_{add} starts with a negative value at the critical area ($a=0$), increases with increasing depth a, and becomes slightly positive. This behaviour of $K_{add}(a)$ is caused by a stress redistribution after plastification as already illustrated in Figure 3. In the chosen example, the highest plastification occurs at the critical area ($a=0$), reducing the stress intensity factor, while - as a static balance - in deeper, not plastified regions the level is greater compared to purely elastic results. Up to what depth values a the level of the stress intensity factor is increased depends on the size of the plastified region and on the amount of plastification.

For given reference conditions and a given initial crack depth, there exists a direct correlation between the accumulated number of applied cycles N_{ref} and the crack depth a (to be obtained by integration of the crack propagation law). This means that the geometry function g and K_{add} can be interpreted either as a function of the crack depth a (as above) or as a function of the number of reference cycles N_{ref} applied. Both depictions are equivalent.

Nevertheless, for the purpose of life usage monitoring it is preferred to formulate the geometry function as a function of the number of accumulated reference cycles.

6 RELATIVE CYCLIC DAMAGE

Since in life usage monitoring the released life of an engine component is formulated in terms of the maximum allowed number of reference cycles, it is convenient to define the relative cyclic damage D_{cycle} of an arbitrarily given stress cycle (characterized by its stress range and temperature conditions) by the ratio of the damage of the cycle to the damage due to one reference cycle :

$$D_{cycle} := \textit{(damage of cycle)} \,/\, \textit{(damage of reference cycle)}. \tag{9}$$

Thus, the relative cyclic damage is expressed in units of *one reference cycle.* The evaluation of the relative cyclic damage D_{cycle} differs between the crack initiation phase and the crack propagation regime.

If $N_{cycle,init}$ denotes the number of repeated applications of the considered stress cycle leading to crack initiation, a measure for the damage due to one cycle is introduced by its inverse $1/N_{cycle,init}$. In particular, the damage of one reference cycle is denoted by $1/N_{ref,init}$. The relative cyclic damage for the crack initiation phase is

$$D_{cycle} = N_{ref,init} / N_{cycle,init} \qquad \text{(for crack initiation).} \tag{10}$$

For the crack propagation phase, the damage of an arbitrary cycle can be quantified by the crack propagation rate $(da/dN)_{cycle}$. Particularly, the damage of the reference cycle is $(da/dN)_{ref}$. We obtain for the relative cyclic damage

$$D_{cycle} = (da/dN)_{cycle} / (da/dN)_{ref} \qquad \text{(for crack propagation).} \tag{11}$$

7 DAMAGE ACCUMULATION

7.1 Crack Initiation

Under the concept of crack initiation life, the damage accumulation process is assumed to be a linear process. The damage increments are independent from the current state of accumulated damage and the Miner's Rule is used, i.e. the relative cyclic damage values of each extracted cycle are added up.

7.2 Crack Propagation

The damage accumulation process in the crack propagation regime - in contrast - is a non-linear one. The damage increment depends additionally on the currently accumulated stage of damage. The physical representation of the accumulated damage is the crack depth a, but in the terminology of life usage the number of consumed reference cycles N_{ref} is preferred. The current stage of damage determines on one hand the value of the geometry function $g(a)$ (see above in equation (7))and on the other hand the crack growth increment of the reference cycle $(da/dN)_{ref}$ which is internally used as reference.

If the concept of safe crack propagation life is used to extend the life beyond the safe crack initiation life, then it is necessary that the algorithm switches from one procedure to the other controlled by the current stage of cumulated damage. To distinguish between both procedures, it is checked if the already consumed number of cycles is below or above the released number of cycles to crack initiation. If it is below, then the crack initiation damage process applies, otherwise the crack propagation process.

We know that the life usage monitoring process for aero engines is strongly related to the history of an engine run [1]. In particular, each engine run is treated separately and at its end all cycles are closed and the damage accounts are updated. Since an engine run can be considered as short compared to the life of fracture critical parts and the cracks at critical areas grow slowly, we can assume that the current state of damage is nearly constant during one engine run. This allows us to determine the values of the damage dependent parameters only once per engine run, namely at the beginning of each engine run. The procedure of the flight damage calculation for crack propagation can be specified as follows:

- The geometry function $g(a)$, the term $K_{add}(a)$ representing the residual stress, and the reference cycle crack propagation increment $(da/dN)_{ref}$ are given as functions of the accumulated number of cycles. Usually a representation in form of tables is used where the current values are obtained by linear interpolation.
- As part of system and algorithm initiation at the beginning of an engine run, it is checked for the respective critical areas whether the crack propagation regime has been entered. If yes, then the values $g(a)$, $K_{add}(a)$ and $(da/dN)_{ref}$ are determined. They are kept constant for the whole engine run.
- During the main calculation steps and also within the final calculation, all extracted stress cycles are converted into stress intensity factor cycles using the geometry function $g(a)$ and the term $K_{add}(a)$. The corresponding crack propagation increments $(da/dN)_{cycle}$ are calculated by evaluation of the crack propagation law according to stress intensity factor range ΔK , R-ratio and temperature. Dividing the respective crack propagation increments $(da/dN)_{cycle}$ by the reference cycle crack propagation $(da/dN)_{ref}$ yields (see equation (11)) the damage of the considered cycle in terms of the relevant life consumption units (i.e. multiples of reference cycles N_{ref}). Damage increments are accumulated over the whole engine run.
- In the final calculation phase - i.e. after the engine has been switched off - the damage accumulated over this engine run is added to the damage accounts.

With this procedure it is ensured that life usage monitoring in the crack propagation phase is completely equivalent to that of the crack initiation regime, and that both lifing concepts can be commonly applied.

8 EXAMPLE CALCULATIONS

In the German OLMOS system of the TORNADO engine RB199 the concepts of crack initiation and crack propagation life are combined, where the safe crack propagation life is used to extend the initially released crack initiation life.

The cyclic damage accumulated over all cycles and subcycles of an individual flight can be expected to be higher in the crack propagation regime than in the crack initiation phase because of the different effect of the subcycles. The subcycle damage in the crack propagation regime is higher due to different slopes of SN-curve and crack propagation law, and more damaging subcycles exist in the crack propagation regime since the crack propagation threshold is relatively lower than the endurance limit in the crack initiation phase. Therefore, the ratio of cyclic damage of crack initiation to crack propagation might strongly depend on the flight profile. Considering these effects, one may expect higher scatter in flight to flight damage for the crack propagation phase.

A main frame computer simulation of the damage calculation procedure described in section 7 was applied to the critical area in the rim slot fillet of a turbine disc according to Figure 1 for a representative number of recorded real flight missions. Figure 5 shows the statistical distribution of the damage ratios. Each data point represents the ratio between crack propagation damage and crack initiation damage for an individual flight. It can be seen that scatter reaches from nearly 1 (for flights with virtually no subcycle damage) to about 3.5 (for flights with a significant number of damaging subcycles). This figure clearly demonstrates that there does not exist a fixed ratio between crack propagation and crack initiation damage, but that this ratio is significantly influenced by operational usage profiles. As a result, for the crack propagation the average damage per flight time turned out to be greater by a factor between 1.5 and 2.0 compared with the crack initiation. This effect was expected.

Finally, the question on the benefit gained by the introduction of the safe crack propagation life concept can be treated by comparing the crack initiation life consumption with the crack propagation life consumption over a representative number of flight missions.

To quantify the benefit due to the extension of the safe crack initiation life concept to the safe crack propagation life, we refer to the introduction of the 2/3 dysfunction life (cf. section 3) which is equal to 2/3 of the number of reference cycles up to the dysfunction criterion (e.g. unstable crack growth), including crack initiation and propagation phase. If we refer the numbers of reference cycles in the crack initiation phase and those in the crack propagation phase to the respective damage per flight time, the respective life times are obtained. Thus, we are able to compare the flight time in the crack propagation phase with the flight time in the crack initiation phase. The ratio

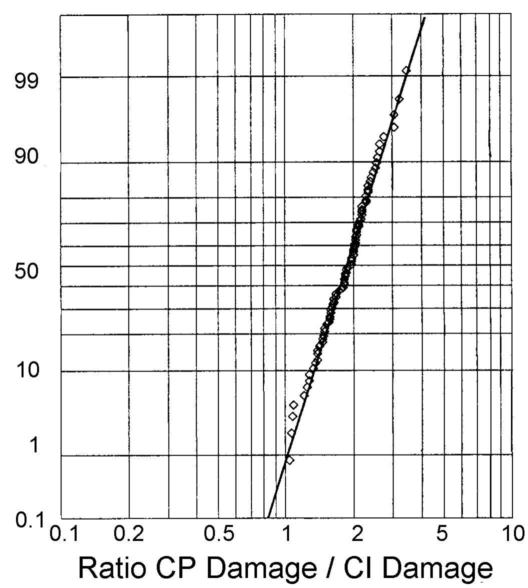

FIGURE 5. PROBABILITY FUNCTION OF DAMAGE RATIOS FOR THE ANALYSED FLIGHTS

yields a measure for the benefit gained by the inclusion of the crack propagation regime.

In the example shown in Figure 1 (rim slot fillet of a turbine disc) the service period in terms of engine flight time can be increased by about 40%, if in addition to the crack initiation regime a safe percentage of the crack propagation regime is utilised.

9 CONCLUSION

Algorithms to monitor life consumption in the crack initiation phase as well as in the crack propagation regime have been developed. The algorithms for crack propagation are formulated in such a way that they are compatible with the formulas for crack initiation monitoring, in particular they are also formulated on the basis of reference cycles rather than on crack dimensions. The example of a critical area in the rim slot fillet of a turbine disc shows that the service period in terms of engine flying hours can be increased by about 40% if in addition to the crack initiation regime a safe percentage of the crack propagation regime is utilised.

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