On the link between long and short cracks: influence of the T-stress

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MOTS CLES : fatigue, crack propagation, short crack, T-stress

Abstract

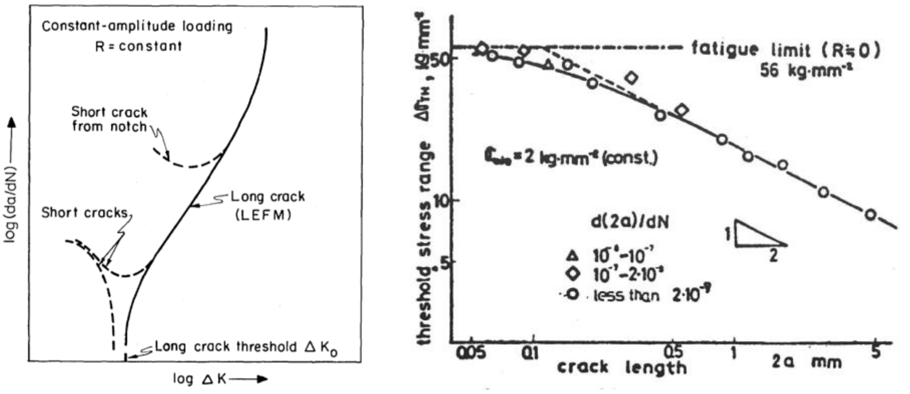
An entire experimental methodology is developed in order to link the T-stress effect to the short crack effect. The T-stress can be determined and controlled when modifying the biaxiality of the loading depending on the crack length. For the short crack effect, a “real” short crack is needed to follow its evolution under a fatigue loading. The idea is to apply a loading on a long crack that creates a loading at the crack tip which is representative of the one “seen” by a short crack. And this can be achieved by applying a specific T-stress depending on the short crack length studied. Here, two experimental campaigns are presented, one that shows the influence of the T-stress on the crack propagation, the second is intended for highlighting the short crack effect and will allow to weave the link with the T-stress.

Introduction

Turbine disks are the most critical components of the aircraft engine and are subjected to very strict certification stages in fatigue. Moreover during their service operation, more specifically during maintenance operations, they are exposed to the creation of surface anomalies such as dents or scratches. Other than the fact that it creates a stress concentration, it introduces a residual stress field at the vicinity of the surface anomaly. The latter is strongly multiaxial and with steep gradients. All this combined to the complex and severe thermo-mechanical fatigue loading the turbine disk experiences, may lead to a short crack developing in a residual stress field that will influence the first crack propagation stages. Nowadays, surface anomalies are considered as initiated cracks of similar depth and propagating from the first cycle. This gives shorter propagation life compared to experimental data and therefore introduces an important conservatism in the design methods and in the tools for in service problems. In order to predict the fatigue life of components containing surface anomalies, it is necessary to understand the physical phenomena induced by their introduction. The crack initiation leading to the short crack regime needs to be studied. Also, the influence of the residual stress field on the crack propagation needs to be taken into account. This study focuses on the short crack regime and on the link that may be weaved with the T-stress.

The short crack problem is well known but there is no clear answer on how to deal with it in the design methods. Linking it to the T-stress would allow to integrate it in a crack propagation model and then account for the short crack effect.

The short crack growth rate is greater than the one for the long crack, the linear elastic fracture mechanic is no more valid and the fatigue limit tends to be constant [1,2].



(a) (b)

Figure 1: (a) Schematic representation of the different crack propagation regimes [Suresh et Ritchie, 1984] (b) Short crack effect on the fatigue limit [Kitagawa et Takahashi, 1976]

When adding the T-stress to the stress functions that comes from the linear elastic fracture mechanics, the previous effects are represented. Irwin proposed the solution by superposition to the problem of a biaxial loading based on Westergaard's stress functions [3,4]:

$$\begin{aligned}
\sigma_{XX}(r,\theta) &= \frac{S_{YY}\sqrt{\pi a}}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\left(1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)+S_{XX}-S_{YY}\\
\sigma_{YY}(r,\theta) &= \frac{S_{YY}\sqrt{\pi a}}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\left(1+\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)\\
\sigma_{XY}(r,\theta) &= \frac{S_{YY}\sqrt{\pi a}}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\sin\frac{\theta}{2}\cos\frac{3\theta}{2}
\end{aligned} \tag{1}$$

Where the T-stress:

$$T = S_{XX} - S_{YY} \tag{2}$$

Is an independent degree of freedom representing the loading along the crack propagation direction. At fixed r and for a given loading, with a short crack the first singular term tends toward zero letting the T-stress become predominant meaning an influence of the T-stress on short cracks. The T-stress is usually and reasonably neglected when a long crack is considered. On the one hand, the short crack growth rate is greater than the one for the long crack, on the other hand, the T-stress is predominant in the presence of a short crack. Thus, our hypothesis is that the short crack effect underlies in the T-stress. It implies two statements: first, for the same loading (K, T) applied to a crack it will have the same crack growth rate. Second, the T-stress has an influence on the crack growth rate. The goal is then to determine

the T-stress effect on the crack growth rate and characterize the short crack effect with respect to what is done concerning the T-stress effect. The idea is to apply a loading which would be the same seen by either a long crack or a short crack. It means that a long crack subjected to this loading would behave the same way as a short crack and inversely, thanks to the T-stress. In the context of short cracks propagating from surface anomalies, attention will be paid to the loading so that it is possible to study short cracks shorter than 400µm.
First, the experimental method to determine the T-stress will be developed and then the short crack effect will be studied. The study has been carried out considering mode I fatigue crack propagation only.

1. Influence of the T-stress on the crack growth rate

This study aims at highlighting the T-stress effect on the crack growth rate. For that, an experimental method is set based on the work done by Brugier [4]. To create a T-stress, the biaxial state of the loading needs to be modified. So biaxial tests are mandatory knowing that, the study is carried out on the tough Inconel 718 DA, the fatigue crack propagation can be studied when working above the threshold and on top of that, a quantifiable T-stress has to be created. The challenge has been accepted by the hydraulic triaxial compression-traction machine ASTREE available at the LMT, ENS-Paris-Saclay. A model of a 150µm short crack has been used to determine the (K_I, T) to apply on the long crack contained in the cruciform specimen for the biaxial tests. For this case, K = 9 MPa√m and T = ~ -250MPa. The stress intensity factor is close to the threshold in order to “reproduce” the threshold regime a short crack would experience at its first propagation stages.
Knowing the (K_I, T) loading to reproduce on that long crack, the two loadings F_1 and F_2 have been expressed as functions of desired (K_I, T) and combined to numerical models, their evolutions with the crack length have been determined. Previous work [4] showed that the T-stress is transient so T-stress transient loadings have been applied:

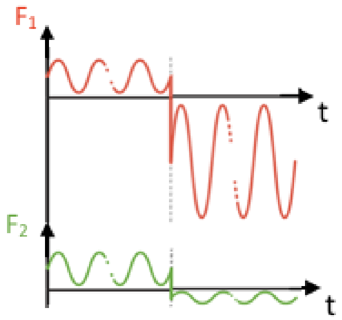


Figure 2: T-stress transient loading

It’s a sequence composed of two blocks of the same length, one block where an equibiaxial loading is applied meaning no T-stress followed by another block where a biaxial loading is applied. Here, for a given crack length and to create the T-stress associated to a 150µm short crack, a strong compressive loading (~80kN) along the crack propagation direction is needed. Between the two blocks, only the T-stress changes. All the others, including the stress intensity factor, remain the same. To follow the crack propagation, the potential drop method has been used. Also, Digital Image Correlation (DIC) has been used to keep track of the mode I crack propagation. As a sequence is applied for one crack length, it is possible to carry on the tests on the same specimen provided that the crack length is measured and the loadings re-calculated before applying a new sequence.

The fracture surfaces have been observed with Scanning Election Microscope (SEM) in order to calibrate our measurements from the potential drop method and they are really convenient for the calibration:

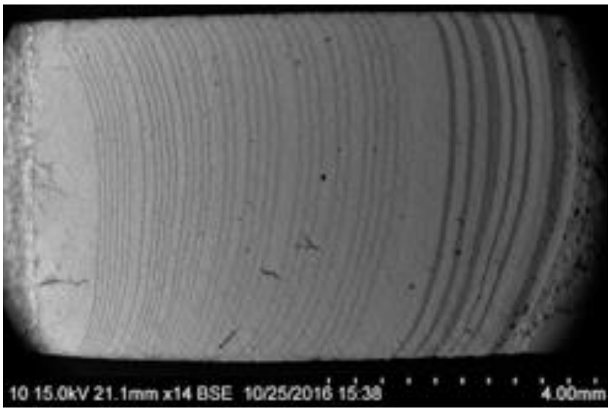


Figure 3: Fracture surface of a specimen containing many transient T-stress loadings

Many bands of different contrasts are observed and thanks to the test protocol, one band corresponds to a block of a sequence. A profilometry study has been carried out to determine whether it is a direction change or plastic blunting:

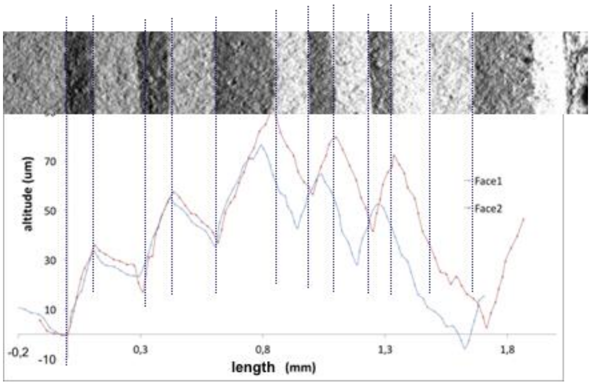


Figure 4: Profilometry on the two faces and identification with SEM observations

First it is a change of direction but it is still mode I crack propagation: the altitude is plotted in micrometer versus millimeter, the goal was only to highlight and show the identification with SEM observations. It seems that there is a cumulation of the plastic blunting with the blocks resulting in a discrepancy between the two faces. The calibration law can be then used to access the crack propagation:

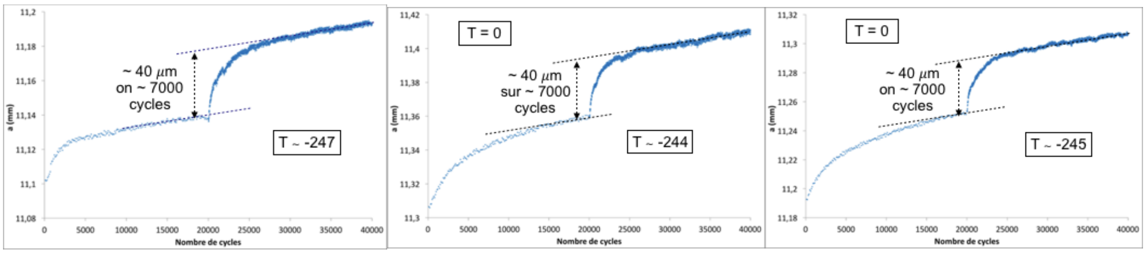
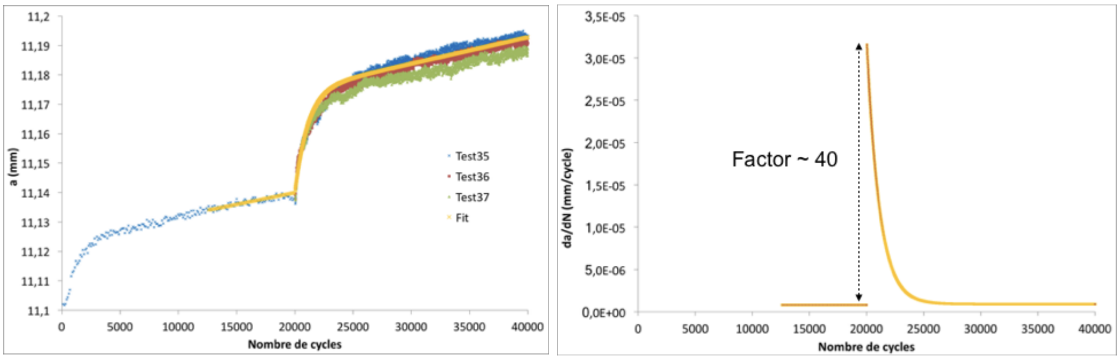


Figure 5: Crack length versus time for three similar T-stress transient loadings

The results show a major increase of the crack length at the transition from a "T=0" block to a "T=~-250" block, over 40µm spread on 7000 cycles. Also, we can notice a good reproducibility of the results obtained for the same kind of T-stress transient loading:



(a) (b)

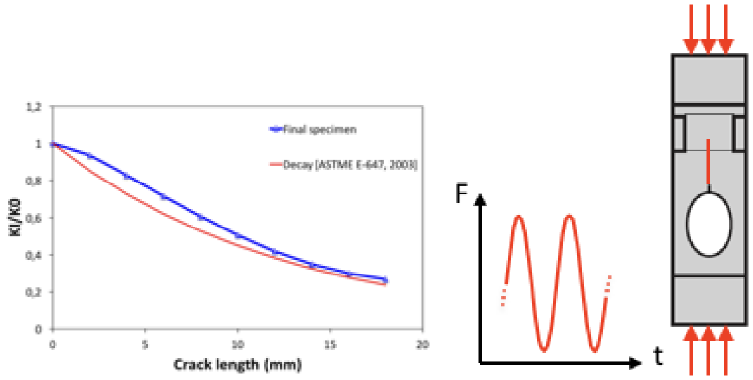
Figure 6: (a) Superposition of the previous loadings and fit (b) Crack growth rate calculated

The transient nature of the T-stress effect is also shown as the evolution retrieves the same one as at the end of the first block. A huge increase of a factor ~40 of the crack growth rate is then measured. The T-stress has an important effect on the crack propagation, the goal is now to weave the link with the short crack effect.

2. Link with the short cracks

Now that the T-stress effect has been shown, the study focuses on the short crack effect. Originally, the loadings have been calculated on short cracks before determining the loadings to apply to the long crack. But now, this (K_I, T) loading that has been applied before needs to be applied on the corresponding short crack, in this case, 150µm. Here is presented the experimental method to obtain the short crack needed in the right conditions and the tests to perform that will allow us to link the previous results to the short crack effect

The challenge here is to obtain a residual stress free short crack, in order to "reproduce" with accuracy the threshold regime, representing the short crack. In the previous work [5], a notched specimen has been designed so that the stress intensity factor K_I decreases with the crack length and the fatigue crack propagation stops when K_I reaches the threshold. The loading is calculated so that the crack stops at a specific location that is called the "stub":



(a) (b)

Figure 7: (a) K_I evolution versus crack length in the notched specimen (b) Notched specimen with fatigue loading

After that the stub is extracted from the notched specimen by Electrical Discharge Machining (EDM). The edge is then carefully polished until obtaining the need short crack. Knowing the geometry of the stub and the crack length, the idea is to determine the loading so that the right (K_I, T) loading is induced at the crack tip. The potential drop method will be used to follow the crack propagation. A rise of the crack growth rate is expected that will allow us to link the short crack effect to the T-stress effect.

3. Conclusions

An experimental protocol is proposed for the characterization of the short crack effect and to link it to the T-stress. An experimental methodology has been set in order to link the short crack effect to the T-stress effect. The T-stress effect has been shown representing a huge increase of crack growth rate of a factor ~ 40 for a $\Delta T \sim -250$ MPa.

The comparison of the results obtained on short and long cracks will allow us to validate the assumption and if confirmed, it will be possible to measure short crack growth using tests on long cracks, and bring more experimental data on this domain.

Moreover, the residual stress field created by the introduction of the surface anomaly is multiaxial. Meaning that there is probably an important stress along the crack propagation direction and as showed before, the T-stress has an important influence on the crack growth rate so it will be possible to take into account this phenomenon via the T-stress.

References

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