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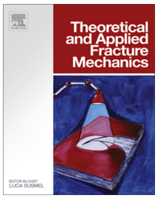

Three-dimensional crack growth modelling of a Ni-based superalloy at elevated temperature and sustained loading

Erik Storgårds *, Kjell Simonsson, Sören Sjöström

Division of Solid Mechanics, Department of Management and Engineering, Linköping University, SE-58183 Linköping, Sweden

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ABSTRACT

High temperature materials subjected to elevated temperature have been shown to be sensitive to dwell times, giving an increased crack growth rate. The interaction between these dwell times and rapid cyclic loads have been shown to constitute a complex problem. Many models have been developed for 1D conditions, but the application to general 3D conditions has seldom been seen, although this is the most common case in most structures. In this paper a model for taking care of the interaction between these load modes in general 3D crack growth has been developed. The model uses 1D results for extension to general 3D, thus providing for local crack front evolution with a minimum of numerical simulations. Consequently, a history dependent crack growth law in 3D is given in this paper, which is capable of tracking the damage from the sustained load, and the interaction with rapid cyclic loading. The model has been implemented for usage with finite element calculations and several different tests are simulated and compared with experimental results for the nickel based superalloy Inconel 718 at 550 °C. The simulation results show crack shapes in agreement with experimental fracture surfaces and time to failure.

1. Introduction

Life prediction in gas turbine applications presents a challenging task as high temperatures in combination with severe thermo-mechanical loads push the materials to their degradation limit. Load cycles that a gas turbine is exposed to typically include a start-up phase with long and strong thermal transients, followed by a block of constant power at which the turbine may be subjected to various cyclic loads, e.g. caused by turbulence or fluctuations on the power grid. After this, a shutdown phase is usually initiated with slow ramp-down to idle condition. The interaction between rapid cyclic and sustained load, either at constant power or during long start-up and shut-down phases, can exert a major impact on crack growth rates, and thus on the life of critical components.

In order to handle load cycles of the type discussed above, a number of different models have been developed, which are either linear superposition models of the two load modes, see e.g. [1,2], or models with interactive behaviour, cf. [3]. Independently of the choice of model the underlying foundation is, in the majority of cases, based on physical observations from crack paths. Cracks exposed to sustained load have been seen to fracture in an intergranular mode rather than the common transgranular cracking, see e.g. [4–6]. The different observations have developed into two damage mechanism theories of how the grain boundaries are affected. These are, stress accelerated grain boundary oxidation (SAGBO) and dynamic embrittlement (DE), see e.g. [7,8]. In tests in vacuum the effect of sustained load damage was not observed, see e.g. [8], by which it may be concluded that grain boundary damage is in need of some kind of embrittling element e.g. oxygen to function.

Sustained load damage has also been paid more quantitative attention to, e.g. [9,10] where Inconel 718 corner cracks were investigated. The findings on these fracture surfaces show another important behaviour which is also seen for cyclic loads, namely crack tunnelling (more growth in the depth than on the surface). It is, as concluded by numerous authors for the case of cyclic load, closely related to the crack constraint over the front, see e.g. [11] and for some more recent findings, see e.g. [12–14], where it is shown how plane strain and plane stress conditions will have a pronounced effect on the crack shape. Crack tunnelling with cyclic loads may therefore be related to the amount of crack closure present, as higher closure values will be associated with more pronounced plane stress conditions and thus give a lower propagation rate [15,16]. Tunnelling related to sustained load damage on the other hand, cannot for obvious reasons be related to crack closure but must still be dependent on constraint level, cf. [9,17].

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* Corresponding author. Tel.: +46 (0)13282475.
E-mail address: erik.storgards@liu.se (E. Storgårds).

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Nomenclature

A	fitting parameter
B	fitting parameter
C	power law constant
D	damaged zone length
DCPD	direct current potential drop
DE	dynamic embrittlement
E	fitting parameter
EDM	electro discharge machining
K	stress intensity factor
S	scale function
SAGBO	stress accelerated grain boundary oxidation
SIF	stress intensity factor
a	crack length
$\dot{m}$	damage mechanism based growth rate
n	power law constant
α	constraint parameter
ΔK	stress intensity factor range
σ	stress
R	load ratio
Subscripts	
c	cyclic value
t	time dependent value

Many authors have developed models to describe the tunnelling, e.g. in [18] where the SIF value was scaled by a factor depending on the load ratio, in [19] where the constant C in Paris law is reduced over the crack front, and in [20] where a minimisation of errors of the growth rates are used to produce the correct crack shape. Studies of the actual constraint along the crack front have also been carried out by numerous authors. These simulations are usually based on dissolving the stress at the crack tip along the crack front to, e.g., determine the triaxial stress values along the front, see e.g. [21] or to simulate 3D crack closure, see e.g. [22]. Examples such as these show the difficulty of describing a correct constraint relation; the latter alternative [21,22] suffering from heavy mesh dependence when trying to dissolve the behaviour at the crack tip, but providing for more freedom in crack shape, and loads; the former alternative [18–20] being restricted to specified analytical cases, but on the other hand providing for rapid prediction results. Finding a method between these two should therefore be of high interest, especially for use in an industrial context.

Exploring the possibilities to describe the correct crack shape evolution during sustained load with interaction of cyclic load, will be of great interest. In this paper a modelling approach for describing crack shape evolution under these load modes is developed for 3D crack growth applications, and is validated for in-plane loaded surface crack test specimens of the Ni-based superalloy Inconel 718 at 550 °C. The model developed takes its form from the damage evolution (embrittling of grain boundaries) for sustained load and interaction with cyclic load. By using the already developed damaged zone model [3,23] for 1D, and extending it further into full 3D, an efficient load history dependence can be reached. Detailed numerical simulations have been carried out for both cyclic loads and sustained loads, as well as for mixed cyclic and dwell time loading.

2. Experiments

The fatigue crack growth tests were performed in load control, at 550 °C on bars of Inconel 718, heat treated according to AMS 5663 standard, and with an approximate grain size of 10 μm, using Kb-type (surface crack) specimens with rectangular cross sections of 4.3 × 10.2 mm, see Fig. 1. The initial notch was created by electro discharge machining (EDM), and the subsequent pre-cracking was done at room temperature using a 10 Hz sine wave with a max load of 650 MPa and $R_\sigma = 0.05$. Crack growth was monitored by direct current potential drop (DCPD), whilst the subsequent stress intensity factor (SIF) evaluation [24] was done by assuming a semi-circular crack front. In all tests the point of consideration was the deepest point of the crack geometry, for which the cracked area was evaluated through a pre-defined calibration curve. The latter was based on temperature induced beach marks for cyclic load of 0.5 Hz, for which measurements of crack length and PD values were correlated with each other. For additional description about the experiments see also [3,25].

A list of the tests simulated here is found in Table 1, where the initial and final equivalent crack lengths are shown with the loading condition for each test. The three different test types consist of cyclic load (no environmentally associated damage), sustained load (cracking by environmentally-based damage), and finally a mix of both. The mixed test contains a block of cyclic load (to a crack length of 0.55 mm) followed by a sustained load block (to a crack length of 1.8 mm), and is finally ended by another cyclic block. Note that the PD method has an accuracy of only 0.01 mm, which has been considered when evaluating the different tests, and that all load reversals were performed using a sine wave of 0.5 Hz and a max load of 650 MPa. The pre-defined calibration curve is derived for a relatively fast load (0.5 Hz), which generates time-independent behaviour for which only transgranular cracking is found. It is important to note that the considered load-bearing zone of each test specimen is the area *not* indicated by the PD reading. Likewise, the crack length that is used to derive the SIF in all the analyses below is defined by the area interpreted by PD.

2.1. Experimental results

The crack growth rate results of the cyclic tests are seen in Fig. 2, whilst the results of the sustained load test and mixed test are seen in Figs. 3 and 4.

The cyclic tests have, as expected, more crack closure for the $R = 0.05$ test than for $R = 0.6$. Please note that the $R = 0.05$ test was initiated with a short initial crack length, which gives the distinct ramp to the linear Paris region.

For the sustained load test and the mixed test it is noted an initial transient of the time dependent crack growth rate $\mathrm{d}a/\mathrm{d}t$ in Fig. 3, which indicates the build up of the damaged zone length, i.e. the length of weakened and cracked grain boundaries. When the stabilized crack growth rates are reached, the damaged zone has reached its stabilized level, at which it will be kept by the triaxial stress state of the test specimen. Investigation of the length of the damaged zone, which will be used for the modelling part of the paper is shown in Fig. 4, where data from the second block of the mixed test is used. The damaged zone, consisting of weakened and cracked grain boundaries is broken through as the rapid cyclic loading is applied, thus increasing the crack growth rate significantly. More details about the damaged zone concept and experimental findings including fracture surface investigations regarding the same can be found in e.g. [25].