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Influence of superimposed vibrational load on dwell time crack growth in a Ni-based superalloy

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ABSTRACT

Sustained loads have for some Ni-based superalloys been shown to give rise to increased crack growth rate at elevated temperature. Such loads generate a history dependent fatigue problem due to weakening and cracking of grain boundaries during dwell times, later broken apart during subsequent load cycles. So far most studies have focused on the interaction of load cycles, overloads, and temperature. However, vibrations of different kinds are to some extent always present in engine components, and an investigation of how such loads affect the dwell time cracking, and how to incorporate them in a modelling context, is therefore of importance. In this paper a study of the most frequently used gas turbine material, Inconel 718, has been carried out. Mechanical crack propagation testing has been conducted at 550 °C for surface cracks with and without the interaction of superimposed vibrational loads. Subsequent investigation of the fracture behaviour was performed by scanning electron microscopy and the modelling work has been conducted by incorporating the vibration load description within a history dependent crack growth law. The obtained results show reasonable accuracy with respect to the mechanical test results.

1. Introduction

Crack growth in Ni-based superalloys at elevated temperature has been seen to be heavily influenced by the load mode the material it is subjected to. Depending on the loading frequency, a significant difference can be seen in the crack growth behaviour. For more rapid cyclic loading, transgranular growth is dominating (as for most other metallic materials). However, this is not the case for lower frequencies (i.e. dwell times) and sustained loads, which have been seen to cause intergranular crack growth, see e.g. [1]. The latter situation has also been shown to give rise to an increased growth rate per load cycle, see e.g. [2] where examples of this can be found for Inconel 718. Several other studies over the past decades have also shown the same phenomenon for different temperatures and alloy compositions, see e.g. [3–12].

Much resources have been put into investigating the reason behind this dwell time effect, but a complete description of the damage process has still not been found. A number of theories have been developed, the two most commonly referred to being dynamic embrittlement (DE), see [1], and stress accelerated grain boundary oxidation (SAGBO), see [13]. Models for describing the damage are either physically based ones, where an actual damage mechanism is described in order to handle the crack growth behaviour, such as in [14], or of a more phenomenological nature e.g. [15–17]. A third type has also been seen which combines the two (physical and phenomenological) for describing the history dependence. Examples of this can be found in [18,19] which partially use input from FE simulations and in [2,20] which are solely based on LEFM.

Studies of other load types than dwell time at max load have not been frequently seen. Some works have focused on overloads in combination with dwell times, see e.g. [5,21–25], load spectra with dwell times, see e.g. [20,26,27], and thermo-mechanical crack growth with dwell times, see e.g. [19,28–31]. Few studies have focused on one of the most common situations in an engine environment, namely how vibrations affect the dwell time crack growth. Such loads are present in the daily operating environment of land-based gas turbines as well as aero engines, and have been shown to be a cause of fatigue and component failure. How they

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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
EDM	electro discharge machining
K	stress intensity factor
S	scale function
SAGBO	stress accelerated grain boundary oxidation
SIF	stress intensity factor
a	crack length
$\dot{a}$	crack growth rate
$\dot{m}$	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

affect the crack growth during dwell times (or sustained load) in a high temperature environment is, however, relatively unknown.

Crack growth under vibrational load at elevated temperature has been studied in e.g. [32] for Inconel 718 and in [33] for the Ni-based single crystal alloy PWA 1484. Both showed elevated crack growth for a superimposed vibrational load on the dwell time load. Limited to only these few experimental studies, there is a need for more investigations regarding how the growth mechanism, e.g. the intergranular/transgranular relation, depends on the vibrational load, and of how to model the vibration and dwell time interaction.

To contribute to this important, but still relatively unknown subject, an investigation of how the Ni-based superalloy, Inconel 718, is affected by superimposed vibrational loads on dwell times is reported in this paper. Mechanical crack propagation experiments for various loading conditions with and without vibrational loads, the latter for comparison reasons, have been conducted at 550 °C. Following these experiments an investigation of the crack paths by scanning electron microscopy to investigate the crack growth mechanism was performed. Further, the effect of vibrational loading on dwell times has been modelled by using the physically motivated phenomenological history dependent LEFM crack growth model presented in [2,20,27,31,34].

2. Experiments

2.1. Method

Fatigue crack growth tests were performed in load control, at 550 °C on Kb-type (surface crack) specimens (rectangular cross section of 4.3 × 10.2 mm) of Inconel 718 (bar material), heat treated according to AMS 5663 standard, with an approximate grain size of 10 μm. To achieve a constant and stable temperature throughout the test a resistance furnace with 3 heating zones and thermocouples in contact with the specimen was used. 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 load with $\sigma_{max} = 650$ MPa and $R_\sigma = 0.05$ according to ASTM E647 [35]. Crack growth was monitored by direct current potential drop (DCPD), while the subsequent stress intensity factor (SIF) evaluation was done by assuming a semi-circular crack front [36]. 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 based on temperature induced beach marks under a cyclic load of 0.5 Hz for which post mortem measurements of crack length and PD values were correlated with each other.

2.1.1. Evaluation procedure

The use of a pre-defined calibration curve based on cyclic loading has been proven to be an effective method for evaluating the effect of material damage (weakening and embrittling of grain boundaries) caused by dwell times, here denoted damaged zone. Comparison between some different evaluation methods can be found in e.g. [12], where it was shown that the one used in this paper is beneficial for dwell time crack growth.

2.2. Tests

Several test types were chosen to investigate the vibrational load interaction on dwell time crack growth, where information regarding the crack growth on a microstructural scale, and growth rates for model calibration, were to be gained. The first test type consisted of a dwell time without any load reversals, i.e. sustained load, while the second one consisted of an identical sustained load with a superimposed vibrational load of constant amplitude and a frequency of 10 Hz. For these tests, centred around the same mean stress value of 650 MPa, a fixed ΔK value was chosen for a crack length of 2.5 mm (i.e. close to the end of the test), defining the constant R_σ value used throughout the tests. These were chosen to be at three levels, namely, $\Delta K = 1$, 3 and 5 MPa $\sqrt{\text{m}}$. Next, a 2160 s (1/10 of a transatlantic flight of 6 h) dwell time test was used to see the influence of larger load reversals; here a $R_\sigma = 0.05$ load reversal was applied between each cycle. Fourthly, the same 2160 s test type was used but with a superimposed vibrational load, here only 1 test of ΔK 3 MPa $\sqrt{\text{m}}$ was performed. The load reversal frequency for the major load cycles in the latter 2 test types was set to 0.5 Hz, while a load frequency of 10 Hz was used for the vibration load.

The next test type was developed in order to gain information of how the material damage is affected by a larger cyclic load with $R_\sigma = 0.05$. This test type, denoted mixed test, was initiated by a cyclic block followed by a sustained load block, and finally ended by a cyclic block. The crack lengths for when to switch block type were chosen based on experience; a more detail description about this test type can be found in [2]. A similar mixed test type was then developed to see the influence of vibrational load, e.g. the effect on the damaged zone length. This type was set up in the same way, except for the first cyclic block which was removed. On the sustained load a vibrational load was added (as previously described), here also with $\Delta K = 3$ MPa $\sqrt{\text{m}}$ to give a good comparison with the rest of the tests. Finally 1 cyclic test with $R_\sigma = 0.05$ and a load frequency of 0.5 Hz was performed.

The different test types are illustrated in Fig. 1, while all tests are summarised in Table 1. All test specimens originate from the