EXPERIMENTAL METHODS FOR THERMOMECHANICAL FATIGUE IN GAS TURBINE MATERIALS

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Abstract

In order to improve life prediction models the understanding of the physical mechanisms active during various types of fatigue cycle conditions have to be understood. To that end, in-situ observations in an environmental scanning electron microscope have been performed. To produce the thermo-mechanical fatigue (TMF) cycle, a test equipment have been developed able to provide thermal cycles up to 900°C. An experimental series to analyze the differences between TMF in-phase and out-of-phase mechanical loading with respect to the temperature cycles has been performed of Inconel 718.

Three different fatigue experiments, in-phase with temperature cycle 300-550°C, out-of-phase with temperature cycle 300-550°C and out-of-phase with temperature cycle 300-625°C, have been performed. Generally it was found that the fastest crack growth rate was obtained for in-phase loading. The choice of temperature in the out-of-phase type of cycling did not influence the crack propagation rate significantly, but the change in crack mechanism from transgranular to intergranular was obvious form the ESEM observation.

Introduction

In gas turbine applications, nickel based superalloys are used for the blades to withstand the high temperatures during service. The high temperatures make air-cooling of the blades necessary, but also induce high temperature gradients in the material. These gradients generate stresses and during service the effect variation results in thermo-mechanical fatigue (TMF). For flying and stationary turbines different operation characteristics appear. The impact from temperature, strain, stress, environment and the rate of the variation of these variables are vital for life assessment analysis, as well as is the understanding of the mechanisms that influence the crack propagation.

There are several articles published concerning the phenomena occurring in different materials during thermo-mechanical fatigue. Gayda *et al*. [1] compare isothermal and bithermal thermo-mechanical fatigue behaviour of a NiCoCrAlY-coated single crystal superalloy, PWA 1480, where the failure is shown dependent on the coating protecting the superalloy. Mughrabi *et al*. [2] show the specific aspects and the fundamental differences of isothermal and anisothermal fatigue of the mono-crystalline nickel base superalloy CMSX-6. Zauter *et al*. [3] have studied isothermal and thermo-mechanical fatigue of the austenitic stainless steel AISI 304L, and observed structural changes and differences between cycles. Castelli *et al*. [4] identify the effects of dynamic strain aging and metallurgical instabilities under isothermal and thermo-mechanical loading conditions in Hastelloy X. Kraft and Mughrabi [5] have studied the effects of thermo-mechanical fatigue of the mono-crystalline nickel base superalloy CMSX-6.

The material used in this study, Inconel 718, has been examined in several articles through the years. Fatigue crack growth behaviour has been studied in-situ within a SEM by Andersson and Persson [6]. During LCF tests at elevated temperatures and different load conditions Chen et al. [7] evaluated the fatigue crack growth rate to construct a life model. Mercer et al. [8] use both polycrystalline and single crystal Inconel 718 to investigate the micro-mechanisms of fatigue crack growth.

In this article, a series of crack growth experiments on Inconel 718, at thermo-mechanical fatigue in-phase and out-of-phase, have been performed and analysed. The load cycle is force controlled with load ratio R=0.05. The thermal load cycles covered the temperature ranges 300-550°C and 300-625°C. The period of the cycles was about 55-75 seconds in total. The tests were made within an environmental scanning electron microscope (ESEM) in order to facilitate observation of crack propagation.

Experiments

In this study, a fatigue test equipment, designed to work within the ESEM, has been used. The test equipment design is constrained by the limited space within the ESEM. The ESEM is used to make in-situ observations of the crack propagation during load and temperature cycling, and to study the specific mechanisms occurring close to the crack tip.

The ESEM load stage is driven with an electrical engine with screws that generate the tensile force on the test specimen. To create the temperatures needed to obtain the desired TMF cycle, relatively fast heating and cooling of the test specimen is needed. The heating is created through a heating wire that is wind around the test specimen and isolated with aluminium oxide, which also keeps the wire in place. When current is passed through the heating wire it will heat the test specimen locally, giving a homogenous temperature in the centre of the test specimen where the crack is situated. To prevent heating of the load stage, and to create faster cooling in the TMF cycle, water cooled copper pieces are attached to the test specimen, cf. Fig 1.

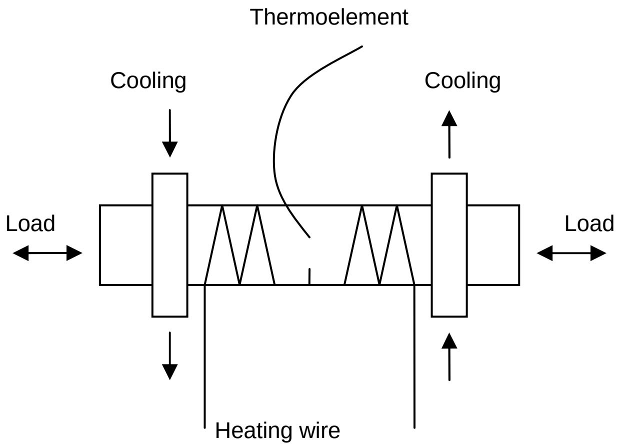

FIGURE 1. The test specimen where heating, cooling, temperature measurement and mechanical loading are indicated.

For this study a typical nickel base gas turbine material, Inconel 718, was used. Test specimens were made out of 0.25 mm foil, and with dimensions of 70x10 mm as a single edge notched tension specimen. They were solution heat-treated at 980°C in furnace, quenched in water, and age-hardened for 8 hours at 720°C, furnace cooled, age-hardened for 8 hours at 620°C and, finally, air cooled. An initial crack of length a=1.0-1.5 mm was introduced by pre-cracking in a servo hydraulic MTS-frame at 30 Hz, with maximum stresses σ=600-760 MPa, and load ratio R=0.05. The specimen surface was ground to produce a smooth surface suitable for the ESEM observations. The heating wire was wound around the specimen and a thermo-element was welded on the test specimen for temperature control. The load and temperature cycles were controlled by a control system implemented in LabView [9].

In this series of experiments the purpose was to compare TMF in-phase and out-of-phase cycles, with the case of two different maximum temperatures in the thermal cycle. One that are recommended as maximum usage temperature and the other, where essential creep are expected. Three TMF experiments were performed and the cycle specifications are shown in table 1 together with crack lengths at the start and at the end of the experiments. Throughout the experiments images were taken that were used to measure crack propagation rate, crack shape and to observe the mechanisms occurring during crack propagation.

TABLE 1. The specific test parameters.

TMF cycle	Temperature	Δσ (MPa)	Cycle time (s)	Crack length (mm)
In-phase	300-550°C	20-760	55	0.8-1.9
Out-of-phase	300-550°C	20-720	55	1.0-3.0
Out-of-phase	300-625°C	20-640	75	1.4-3.5

Results and discussion

The crack is not continuously propagating through the test specimen as seen in Figs. 2 a-c. The zero propagation rates depend on the microstructure in the material. When the crack propagates along a slip band and reaches a grain boundary or when the crack merges with a micro crack in front of the main crack, the crack stops for some cycles and the crack tip blunts. When these types of situations appear, the crack has a tendency to branch. The crack propagation path becomes very irregular which makes the crack surfaces stick together leading to unloading of the crack tip. Such phenomenon have in other test specimens been seen to lead to sudden crack tip overloads when these forces have released. It is commonly observed that one single micro-crack in front of the main crack grow because of an irregularity in the material and then merge with the main crack. This leads to a jump in the a-N curve and probably affects the propagation for a large portion of the crack path. The crack propagation rate versus the stress intensity factor for the three experiments are shown in Fig. 3. First order polynomial curve fits of the calculated test results are also shown in the graph to visualise the differences in growth rate.

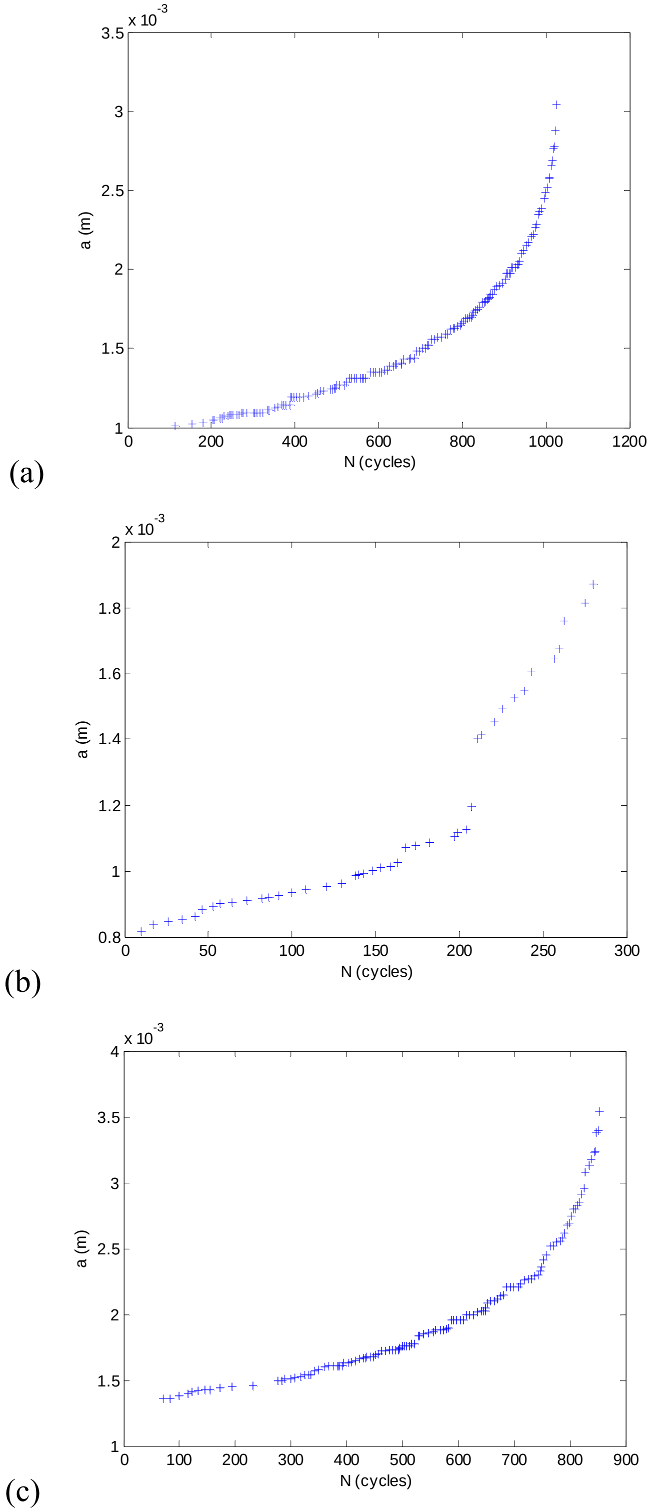

FIGURE 2. Crack length *a* verses number of cycles *N* for: (a) TMF in-phase, 300-550°C; (b) TMF out-of-phase, 300-550°C; (c) TMF out-of-phase, 300-625°C.

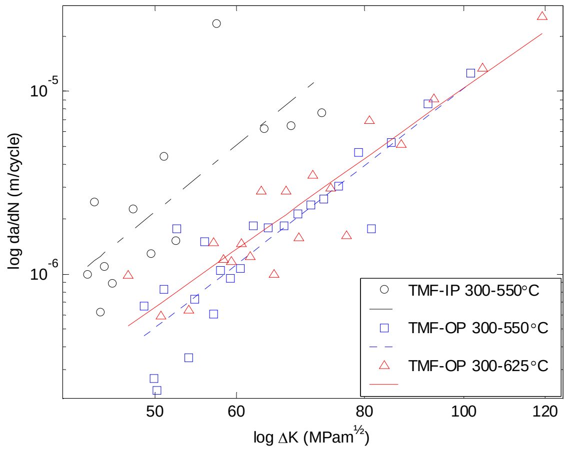

FIGURE 3. Crack propagation rate *da/dN* versus stress intensity factor range *⊿K* for the three experiments with a curve fit for each test results. IP denotes in-phase and OP denotes out-of-phase.

The experiment with in-phase cycle shows higher crack propagation rate than both the out-of-phase cycle experiments, cf. Fig. 3. In Figs. 4-6, the cracks are depictured form the different TMF cycles during the last parts of the experiments, where the crack propagation rates are high. In the in-phase 300-550°C experiment, the crack is propagating alternating along slip bands and along the grain boundaries, and some micro cracks appear in front of the crack, cf. Fig. 4. For the experiment with out-of-phase loading and temperature range 300-550°C, the propagation is inter-granular, and a lot of slip bands are present through which the crack propagates, cf. Fig. 5. When the thermal cycle is 300-625°C out of-phase, the growth of micro-cracks in the grain boundaries are substantial, cf. Fig. 6. This leads to inter-granular crack growth when the main crack merges with the micro-cracks. This change in crack mechanism, with more creep, do not significantly affect the propagation rate.

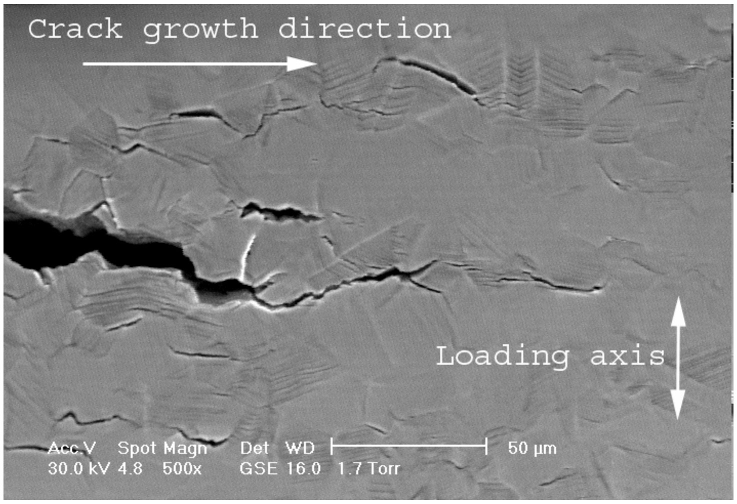

FIGURE 4. ESEM picture from the TMF in-phase 300-550°C experiment after 263 cycles and load ratio 20-760 MPa. Current load is 760 Mpa and the crack length is 1.8 mm.

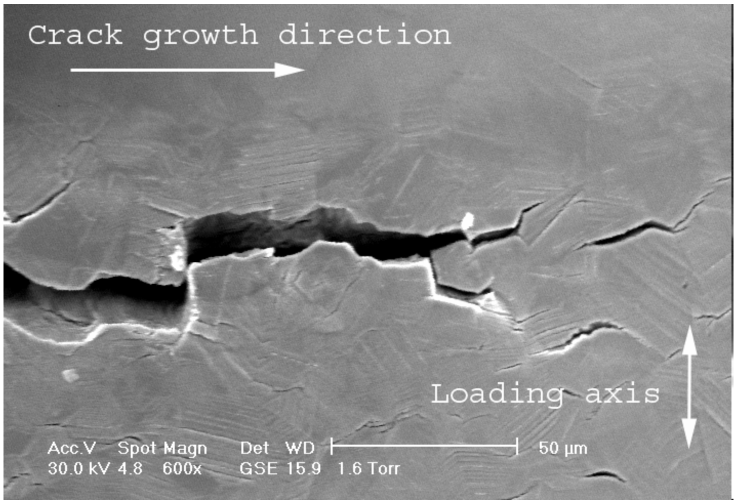

FIGURE 5. ESEM picture from the TMF out-of-phase 300-550°C experiment after 946 cycles and load ratio 20-720 MPa. Current load is 720 MPa and the crack length is 2.1 mm.

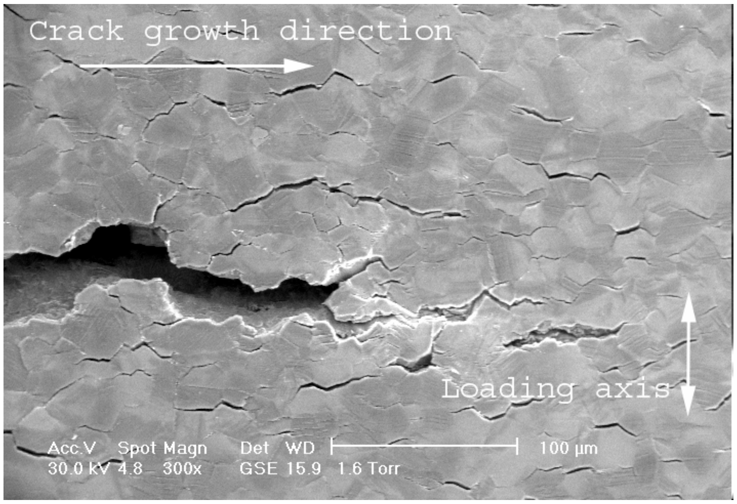

FIGURE 6. ESEM picture from the TMF out-of-phase 300-550°C experiment after 848 cycles and load ratio 20-640 MPa. Current load is 640 Mpa and the crack length is 3.4 mm.

Conclusions

An experimental method to examine in-situ thermo-mechanical fatigue crack growth within an ESEM has been demonstrated. The test equipment delivers temperature cycles in the range 300-625°C with a period of 75 seconds to specimens 0.25 mm thick. The high temperatures are produced without vital image disturbances. Such thin test specimens are sensitive for variations in thermal distribution through the cross section near the crack tip. This will affect micromechanical events close the crack tip in an evident manner.

Three different thermo-mechanical cycles are analyzed in this study and during crack propagation various mechanisms are observed. The experiment with thermo-mechanical in-phase cycling imposes higher crack propagation rate than out-of-phase observed for the same temperature interval. An increase of maximum temperature within a cycle do not increase the crack propagation rate significantly, but the crack growth mechanisms change.

Acknowledgements

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