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High temperature fatigue crack propagation behaviour of Inconel 718

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Gas turbine illustration. Courtesy of Leon/Siemens.

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Preface

This dissertation has been compiled during the autumn of 2012 at the Division of Solid Mechanics, Linköping University. The research has been funded by the Swedish Energy Agency, Siemens Industrial Turbomachinery AB, GKN Aerospace Engine Systems and the Royal Institute of Technology through the Swedish research program TURBO POWER, the support of which is gratefully acknowledged.

I would like to thank my supervisors, Kjell Simonsson, Johan Moverare and Sören Sjöström, for all their help during the work on this thesis. Support and interesting discussions with all the Ph.D. colleagues at the division are highly appreciated. A special thanks also to my colleague Erik Lundström with whom I shared the work with in the last two papers. I would also like to thank Prof. Sten Johansson, Linköping University, Dr. Tomas Månsson and Dr. Magnus Hörnqvist, GKN Aerospace Engine Systems and Dr. Magnus Hasselqvist, Dr. Per Almroth and Dr. Björn Sjödin, Siemens Industrial Turbomachinery AB for valuable discussions. A special thanks to my family and girlfriend who have supported me all this way.

"Any intelligent fool can make things bigger, more complex, and more violent. It takes a touch of genius – and a lot of courage – to move in the opposite direction"

Albert Einstein

David Gustafsson

Linköping, December 2012

Abstract

The overall objective of this work has been to develop and evaluate tools for designing against fatigue in gas turbine applications, with special focus on the nickel-based superalloy Inconel 718. The fatigue crack propagation behaviour under high temperature hold times has been studied. Firstly, the main fatigue crack propagation phenomena have been investigated with the aim of setting up a basis for fatigue crack propagation modelling. Secondly, modelling of the observed behaviour has been performed. Finally, the constitutive behaviour of the material has been studied, where focus has been placed on trying to describe the mean stress relaxation and initial softening of the material under intermediate temperatures.

This thesis is divided into two parts. The first part describes the general framework, including basic observed fatigue crack propagation behaviour of the material when subjected to hold times at high temperature as well as a background for the constitutive modelling of mean stress relaxation. This framework is then used in the second part, which consists of the seven included papers.

List of Papers

In this dissertation, the following papers have been included:

- I. D. Gustafsson, J.J. Moverare, S. Johansson, M. Hörnqvist, K. Simonsson, S. Sjöström, B. Sharifimajd (2010). *Fatigue crack growth behaviour of Inconel 718 with high temperature hold times*, Procedia Engineering, Volume 2, pp. 1095-1104.
- II. D. Gustafsson, J.J. Moverare, K. Simonsson, S. Sjöström (2011). *Modelling of the Constitutive Behaviour of Inconel 718 at Intermediate Temperatures*, Journal of Engineering for Gas Turbines and Power, Volume 133, Number 9, pp. 094501.
- III. D. Gustafsson, J.J. Moverare, S. Johansson, K. Simonsson, M. Hörnqvist, T. Månsson, S. Sjöström (2011). *Influence of high temperature hold times on the fatigue crack propagation in Inconel 718*, International Journal of Fatigue, Volume 33, Number 11, pp. 1461-1469.
- IV. J.J. Moverare, D. Gustafsson (2011). *Hold-time effect on the thermo-mechanical fatigue crack growth behaviour of Inconel 718*, Materials Science and Engineering A, Volume 528, Number 29-30, pp. 8660-8670.
- V. D. Gustafsson, J.J. Moverare, K. Simonsson, S. Johansson, M. Hörnqvist, T. Månsson, S. Sjöström (2011). *Fatigue crack growth behaviour of Inconel 718 - the concept of a damaged zone caused by high temperature hold times*, Procedia Engineering, Volume 10, pp. 2821-2826.
- VI. D. Gustafsson, E. Lundström (2012). *High temperature fatigue crack growth behaviour of Inconel 718 under hold time and overload conditions*, International Journal of Fatigue, DOI: 10.1016/j.ijfatigue.2012.10.018.
- VII. D. Gustafsson, E. Lundström, K. Simonsson (2012). *Modelling of high temperature fatigue crack growth in Inconel 718 under hold time conditions*, Submitted for publication.

Own contribution

In the five first papers I have been the main contributor in the modelling, evaluation and writing, except in the fourth one where Johan Moverare did the main writing and evaluation work. In the sixth and seventh paper, the work has been shared with the co-authors even though the main part of the writing has been done by me. Experimental work has been carried out by Bo Skoog, Håkan Brodin, Johan Moverare and Sten Johansson. Microscopy work has been carried out by Sten Johansson.

Papers not included in this dissertation:

- VIII. M. Hörnqvist, T. Månsson, D. Gustafsson (2011). *High temperature fatigue crack growth in Alloy 718 - Effect of tensile hold times*, Procedia Engineering, Volume 10, pp. 147-152.
- IX. D. Leidermark, D. Aspenberg, D. Gustafsson, J.J. Moverare, K. Simonsson (2012). *The effect of random grain distributions on fatigue crack initiation in a notched coarse grained superalloy specimen*, Computational Materials Science, Volume 51, pp. 273-280.

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Part I

Background

Introduction

Due to environmental issues and economical factors, increasing demands on energy efficiency has driven the need for more efficient power generating turbines and aero engines. In such engines a higher operating temperature implies that a higher efficiency can be achieved. However, these high temperatures do not come without problems. Very few materials can withstand the operating conditions in the hottest parts of a gas turbine. For these components nickel-based superalloys are often employed as they possess unique properties under such severe conditions.

In gas turbines the high-temperature load carrying ability of significant components is one of the most important factors that set the limits of the design. Even though high temperature resistant superalloys are used, hot components are usually designed to run near their temperature and load limits. Uncertainties in models and methods used for fatigue life prediction under these circumstances therefore lead to problems. Usual ways to handle the situation are to:

- Reduce the temperatures or loads to attain a better safety margin, meaning a more conservative design and a lower thermal efficiency than would otherwise be possible.
- Prescribe shorter inspection and component exchange intervals, meaning cost increase and loss in engine availability.

Among the most important questions in gas turbine design is therefore how to predict the fatigue life of such components. The usual load case for these components is a start/stop thermo-mechanical load including a hold time at high temperature, where this hold time load is high enough to cause time dependent effects. Another complicating fact is that the mechanical properties degrade during long time exposure to high temperature and cyclic loads by e.g. microstructural changes, oxidation and grain boundary embrittlement, thus reducing the fatigue resistance of the material.

1.1 Design criteria

When designing for fatigue life, two types of criteria exists, namely fatigue crack initiation and fatigue crack propagation. When designing against fatigue crack initiation one determines the number of service hours from the first engine start until a crack of a certain length is likely to appear in the structure under consideration. Using this method it is important to be able to describe the mechanical behaviour under the specific loading conditions in order to predict the correct stress and strain distribution in the component. When designing with respect to fatigue crack propagation, one assumes that a crack of a certain length is already present in the material. The task is now to find the number of service hours until the assumed crack reaches a critical length. Using this methodology, a fatigue crack propagation model correctly accounting for the loading conditions in the studied component is of central importance.

1.2 The Ph.D project

This Ph.D project concerns the question of how thermomechanical cycling in combination with hold times at high temperatures governs the fatigue behavior, i.e. the initiation and propagation of fatigue cracks, of the gas turbine materials. By considering the effect of the cyclic loading and environmental effects (oxidation etc.), enhanced models for life time prediction are to be set up, which are not only capable of describing the observed fatigue behavior, but also simple enough to be used in real industrial applications. The knowledge gained in the project will be directly usable in the design of more efficient gas turbines. This work is restricted to the nickel-based superalloy Inconel 718 used e.g. in turbine disc components, but will involve both design criteria described above.

Concerning the fatigue crack initiation part, work has been done on modelling the constitutive behaviour under intermediate temperatures. More specifically, the issue of an adequate mean stress relaxation and initial loading softening description has been addressed. Concerning the fatigue crack propagation part, the fatigue crack growth behaviour under high temperature hold times has been investigated using material testing and microscopy studies. The results have been used in modelling of the observed behaviour.

As described previously, higher thermal efficiency calls for higher operating temperatures. To achieve this, one must carefully consider the fatigue design criteria described above. Without rigorous fatigue analysis such an increase in operating temperatures can lead to disastrous consequences.

1.3 The TURBO POWER programme

The research presented in this dissertation has been funded through the research programme TURBO POWER, which is run in collaboration between Energimyndigheten (The Swedish Energy Agency), Siemens Industrial Turbomachinery AB in Finspång, Sweden, GKN Aerospace Engine Systems in Trollhättan, Sweden and the Royal Institute of Technology in Stockholm, Sweden. The objectives of TURBO POWER are to

- Contribute to a sustainable and efficient energy system in Sweden in a medium and long term view
- Accomplish this by building technology and competence for industry and universities within the field of thermal turbomachines and processes. The programme is to strengthen relevant research groups at universities and to enhance the cooperation with industry
- Use and commercialise the obtained results

Siemens Industrial Turbomachinery AB develops and manufactures gas turbines for a wide range of applications. These are mainly land based turbines for generating power. GKN Aerospace Engine Systems develops and manufactures aero engine parts.

Gas turbines

Gas turbines are for example used for jet propulsion and electricity generation. The efficiency of a gas turbine is, as described above, highly temperature dependent.

The gas turbine has three major components; a compressor, a combustor and a turbine; see Fig. 1. Air is drawn from the inlet into the compressor where it is pressurized in several steps. The main part of the compressed air is led into the combustor where it is mixed with fuel and ignited, while a small amount of it is led into the turbine as cooling air. The hot gas is then led into the turbine where a major part of the energy is converted into rotational energy of the turbine. The turbine shaft drives the compressor and, in case of a stationary electricity-generating gas turbine, a generator and, in case of an aero engine, usually a propeller or a fan [1].

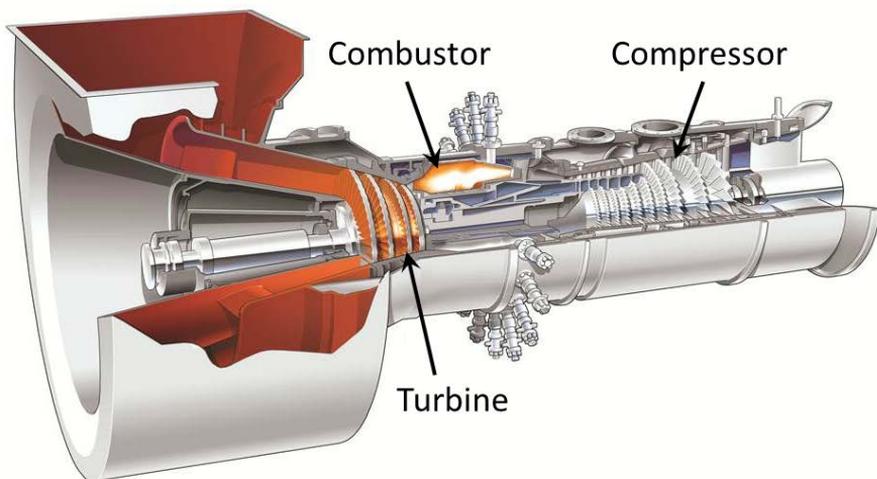


Figure 1: The interior of a stationary gas turbine, with permission from SIEMENS

2.1 Fatigue analysis in gas turbine applications

The importance of a proper understanding of the fatigue behaviour and the need for accurate simulations in a gas turbine context can be exemplified by examining an accident which occurred in Los Angeles, on June 2nd, 2006. The left engine of a Boeing 767-233 airplane exploded during a high powered ground run. In the investigation it was shown that the turbine stage 1 disk had failed from an intergranular fatigue crack. The investigation also revealed “one piece of disc, which initially bounced off the ground before penetrating the airplane, completely severed the airplane’s left-hand kneel beam and partially severed the right hand kneel beam before exiting the airplane and becoming lodged in No.2 engine’s exhaust duct” [2], as shown in Fig. 2. There is no doubt that if this accident had occurred at high altitude, the result would have been the loss of a substantial number of lives.

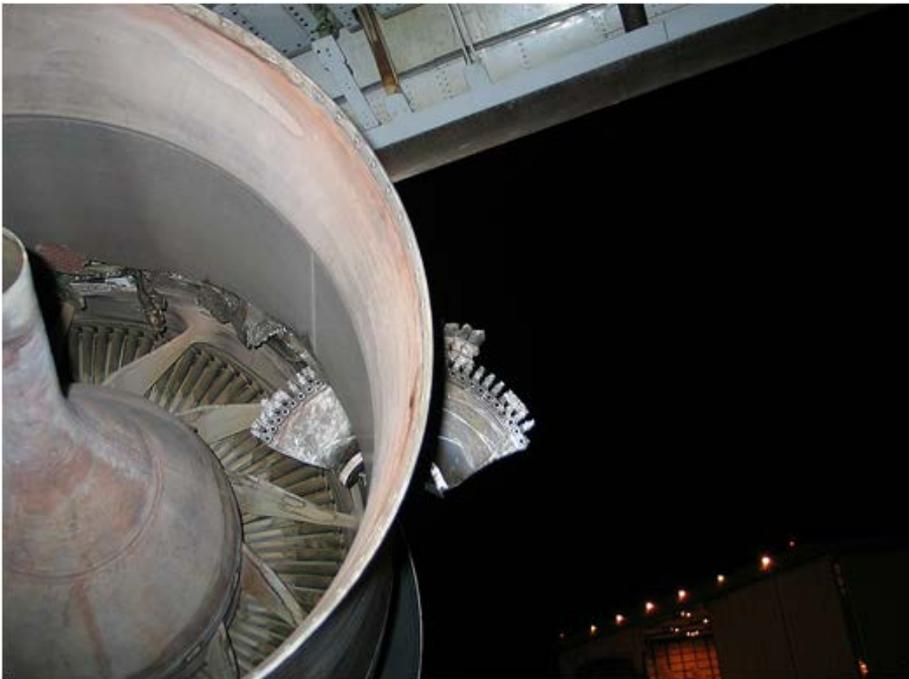


Figure 2: Los Angeles engine accident, June 2nd 2006. Failure of turbine disc, with permission from Pineau and Antolovich [2]

Nickel-based superalloys

Superalloys is a group of alloys that exhibit excellent mechanical properties at high temperatures [3]. They are often used in gas turbine applications [4], but are also found in various other applications where high temperature and otherwise severe operating conditions set the limit for the choice of material. The nickel-based superalloys were invented in the 1940's primarily for gas turbine applications because of their long-time strength and toughness at high temperatures. The early nickel-based superalloys typically contained 80%Ni and 20%Cr. Since then lots of alloying elements such as titanium, aluminium, tungsten, etc. have been added to enhance their mechanical properties.

The modern nickel-base superalloys have not only a complex alloy composition, but also an intricate phase chemistry and structure. A lot of different phases and precipitates can be found [5]. The most important are listed below.

- Gamma phase, γ , is the matrix phase of the nickel-based superalloys. The phase has a face-centered cubic (FCC) crystal structure and its composition is mainly Ni with solute elements such as Cr, Co, Fe and Mo.
- Gamma prime, γ' , is usually the main strengthening precipitate in the nickel-based superalloys and can make up more than 50% of the volume of the material. Like the γ phase it has an FCC crystal structure with a composition of Ni, Al and Ti.
- Gamma double prime, γ'' , is usually found in superalloys rich on iron. It is a strong coherent precipitate with a body-centered tetragonal structure. The γ'' is metastable and can under some circumstances transform into delta phase, described below.
- Delta phase, δ , is a non-hardening precipitate usually found at grain boundaries where it improves the creep-rupture and grain boundary sliding resistance. It is orthorhombic in its structure and is composed mainly of Ni, Nb and Ti.
- Various carbides and borides are often present as grain boundary strengtheners.

There are a few main reasons for the good temperature behaviour of nickel. The FCC structure of nickel makes it both ductile and tough. It is also stable in its

FCC structure when heated from room temperature up to its melting point. Nickel has a high activation energy for self-diffusion which makes it resistant to creep deformation. Other materials which display this crystal structure and behaviour are dense and/or very expensive, e.g. platinum [1].

3.1 Inconel 718

Inconel 718 is an alloy with many good mechanical properties such as high yield and ultimate tensile strengths, good creep and rupture strengths and high resistance to fatigue. It is the most commonly used nickel-based superalloy of all, due to both its excellent material properties and its relatively low cost. It contains a large amount of iron and is therefore often referred to as a nickel-iron superalloy. Inconel 718 is usually used in polycrystalline condition and with the normal composition (in weight %) presented in Table 1.

Table 1: Composition of Inconel 718 [1]

Element	Ni	Cr	Mo	Nb	Al	Ti	Fe	C
Weight%	balance	19.0	3.0	5.1	0.5	0.9	18.5	0.04

Like all modern superalloys it is precipitation hardened and like most superalloys with large amounts of Fe it contains both coherent γ' particles and γ'' particles, even though it has been shown that the main strengthening precipitate is the latter [1] which is in contrast to what was initially believed when the material was introduced on the market in the 50's. Despite the good strength attributed to the γ'' particles, it is also these particles that set the operating temperature limit of the material to about 650°C. Above this temperature the γ'' can transform to δ -phase, as described above, in which case the hardening effect of γ'' is lost.

Fatigue crack propagation

Once a crack is present in a material, it will tend to grow under the influence of e.g. cyclic loading. The crack may be initiated by fatigue, or may be pre-existing from manufacture e.g. in welds. If allowed to, the crack will propagate to a critical length when fracture will occur.

When calculations of fatigue crack propagation are carried out a load parameter representing the intensity of the crack tip stress is often used. The stress intensity factor K is indisputably the most common and well known of all loading parameters and is usually the standard parameter used in the industry. Generally the driving force for cyclic crack growth is taken to be the range of the stress intensity factor (ΔK). However, under special circumstances such as i.e. hold times at high temperatures the maximum of the stress intensity factor (K_{max}) can be the preferred loading parameter. For example, the stress intensity factor for Mode I loading is defined as

$$K_I = \sigma \sqrt{a\pi} f \quad (1)$$

where K_I is the stress intensity factor, σ is a reference stress, a is the crack length and f is a function of the component geometry and of the choice of reference stress.

4.1 General observations and hold time effects

Inconel 718 is a frequently used material for gas turbine applications at temperatures up to 650°C. For such components, the main load cycle is typically defined by the start-up and shut-down of the engine. In this main loading cycle, hold times at high temperature are generally present for critical components. During such high temperature hold times, the fatigue crack growth rate may become extremely high, which has been shown to be due to material damage in the crack tip vicinity causing the material to fail by intergranular fracture [6–8]. Between these hold times different types of cycles can occur e.g. overloads and sections/blocks of continuous cyclic loading. These can be caused by abnormal service conditions but can also occur on a more regular basis due to e.g. different weather conditions and engine vibrations.

4.2 Experimental programme

In order to investigate the effects of high temperature hold times, an experimental programme has been carried out during the project. Fatigue crack growth was studied at the temperatures 450°C, 500°C, 550°C and 650°C. However, towards the end of the project, focus was placed on 550°C.

Crack growth experiments were conducted on Kb-type specimens with rectangular cross sections of 4.3 x 10.2 mm, see Fig. 3. An initial starter notch of nominal depth 0.075 mm and total width of 0.15 mm was generated using electro discharge machining (EDM). Before the high temperature testing was carried out, the specimens were fatigue precracked at room temperature and $R = 0.05$, to obtain a sharp semicircular crack with a depth of about 0.2 mm. The fatigue crack growth testing was then carried out under load control using an MTS servo hydraulic machine, see Fig. 4.

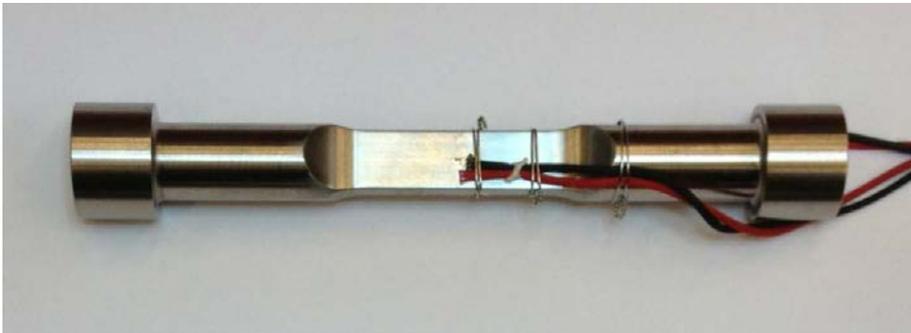


Figure 3: Instrumented Kb-type test specimen

All tests were interrupted at an approximate crack length of 2.5 mm. The crack propagation was monitored by the direct current Potential Drop (PD) technique according to ASTM E 647 [9]. This technique helps us to get an estimation of the crack length throughout the test by measuring the PD over the crack. In detail, a direct current of 10 A was run through the specimen and the PD signal was measured by probe wires spot-welded close to the notch at both sides of it. Additional reference probes were spot welded at the back face of the specimen, far from the notched cross-section. In order to reduce the problems associated with thermo-electrical effects, lack of stability in supplying current and changes in the instrumentation or changes of temperature, a normalized PD value was obtained by dividing the measured PD value with the reference value [9].

The measured PD ratio was translated to crack length (assuming a semi-circular crack front which was confirmed post-mortem) through an experimentally obtained calibration function based on initial and final crack lengths measured on the fracture surface as well as by measured induced beach marks, see Fig. 5. For a detailed record of the material and experimental conditions we refer to [6, 10–12].

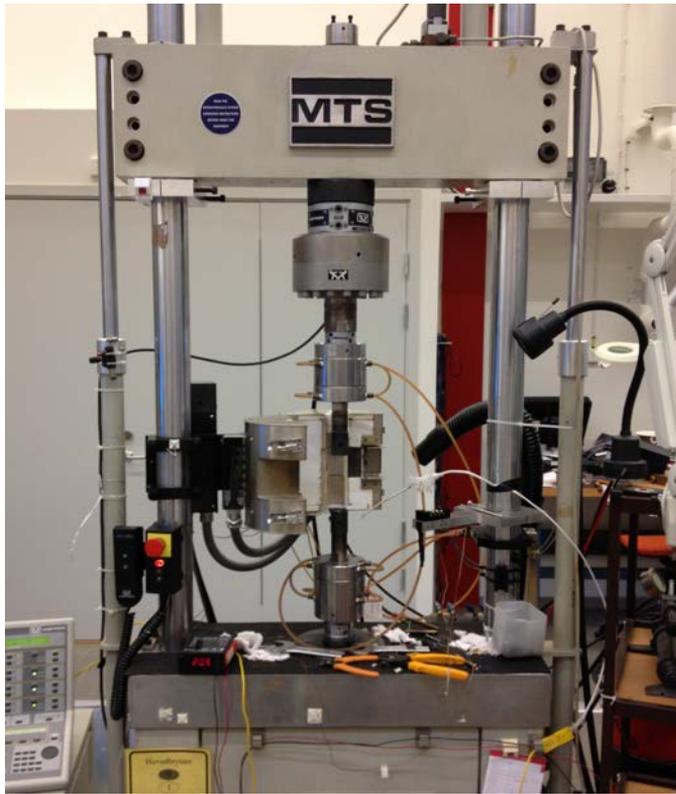


Figure 4: MTS servo hydraulic machine

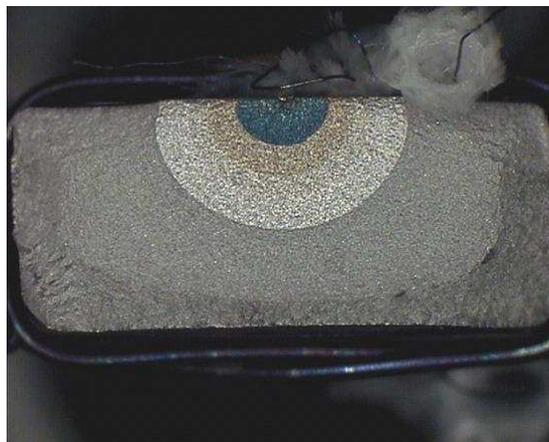


Figure 5: Fracture surface of the calibration specimen with visible beach marks

4.2.1 Results

To investigate the effect of hold times at high temperature simplified load curves have been used in the material testing, see Fig. 6. The crack propagation behaviour under high temperature hold times can be significantly different from the cyclic crack propagation behaviour without hold times. As can be seen in Fig. 7, the crack growth rate with respect to the number of cycles (da/dN) are significantly increased when a hold time is applied. Also, the crack growth rate increases with increasing temperature [6].

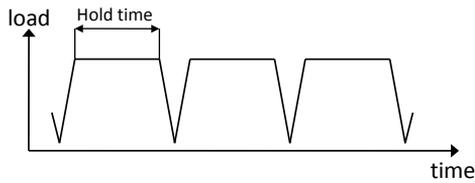


Figure 6: Load curve for hold time fatigue crack growth testing

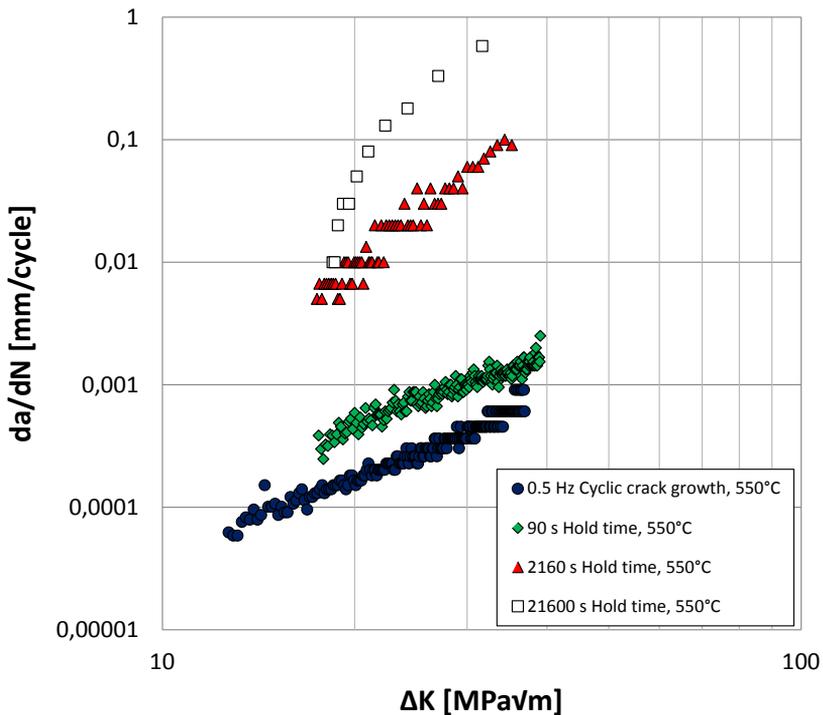


Figure 7: da/dN vs. ΔK for hold time tests at 550°C

4.2.2 Scatter in fatigue crack growth testing

Scatter is always present in the mechanical properties of structures and materials. Thus, this also applies to the fatigue properties of a material. The fatigue lives of similar test specimens under the same fatigue load can therefore be significantly different. Reasons of the scatter in experimental material data are the stochastic distribution of microstructural features, like grain size, microtexture, defects and chemical composition, as well as unavoidable inaccuracies in measuring, differences in specimen preparation and environmental conditions [13].

In laboratory investigations, different actions are taken in order to minimise the influence of such scatter. This generally implies that specimen production is done very carefully aiming for uniform and fine quality regarding both material properties, defects and surface finish. Furthermore, the tests are carried out under closely controlled conditions.

Since fatigue crack growth mainly depends on the bulk properties of the material the crack growth resistance can be fairly uniform in a single batch of material. Thus, scatter is usually low for fatigue crack growth. The low scatter of fatigue crack growth is advantageous for investigations on crack growth. As little as two specimens can be sufficient for a quantitative study if they show similar behaviour. In case of doubt, testing of a third specimen is advisable [14].

It should be pointed out that in our work we do not have access to a statistically relevant test population. Often, we have only one experiment for each loading case, which of course will make our observations only qualitative. Thus, if the research presented in this dissertation is to be used in an industrial application context, it is advised that complementary testing is performed, e.g. to determine exact material properties and behaviour from the current material batch etc.

4.3 Crack driving mechanisms

When considering fatigue crack propagation, most metals and alloys under normal situations experience transgranular fracture. By this is meant that the crack grows through the material grains in a fairly ordered way. The opposite of this is intergranular fracture, which typically occurs at high temperatures and/or in aggressive environments, where the crack grows mainly in the grain boundaries of the material [15]. For Inconel 718 it has been shown in e.g. [6–8], that for cyclic crack growth tests the active fracture mode is mainly transgranular cracking, while for hold time tests at high temperatures the active fracture mode is mainly intergranular cracking.

The high-temperature hold times give rise to an embrittlement that causes intergranular fracture. The mechanisms of the hold time effect affect a volume of material around the crack tip. This material volume, referred to as the damaged

zone, has a lowered resistance to fatigue crack propagation compared to the unaffected material, see e.g. [10] and [16].

A special type of loading cycle called block tests was designed to investigate the approximate size and mechanical effect of this damaged zone. In these tests cyclic and hold time loadings were alternated in separate blocks. They start with a cyclic loading (without hold time) up to a specific crack length, then hold time crack growth up to a specific crack length and then both of these steps again, thus ending with a hold time crack growth period, c.f. Fig. 8. An example of the results from this type of testing can be seen in Fig. 9. At the first transient of the test, the crack growth rate is progressively increased up to the stabilized level of hold time crack growth. This transient is interpreted as a progressive build up of the damaged zone. During the second one, found at the start of the second cyclic block, the crack growth rate is progressively reduced to the level of cyclic crack growth rate. This is interpreted as a progressive reduction of the damaged zone. It is believed that the length of the second transient can represent an approximate measure of the length of the damaged zone. Furthermore, it is evident that this damaged zone influences both cyclic and hold time crack growth.

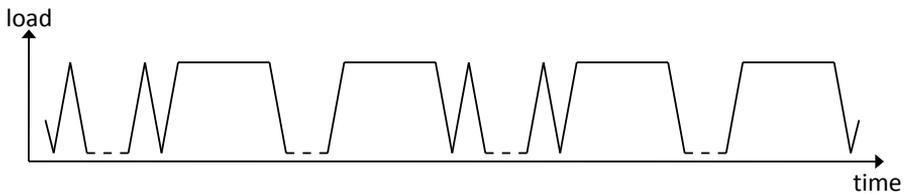


Figure 8: Load curve for block tests

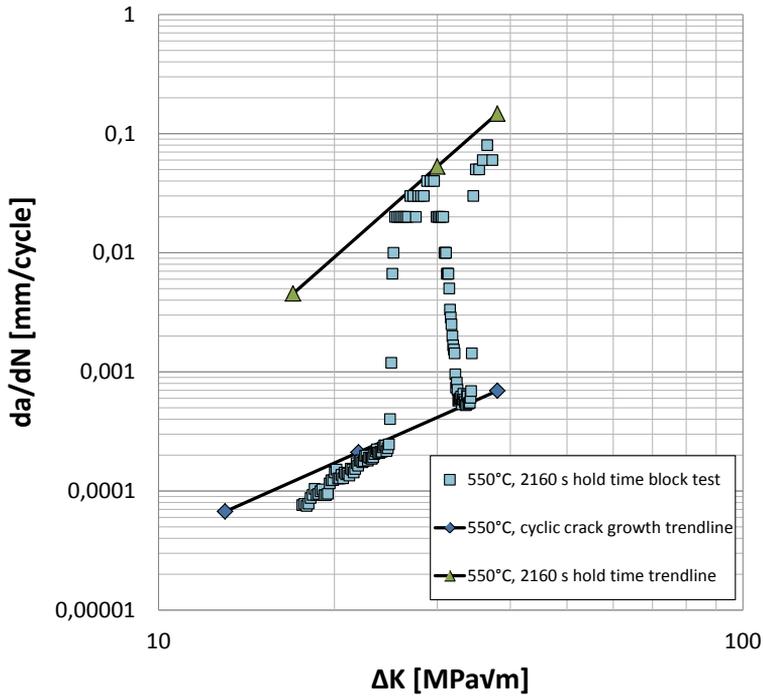


Figure 9: da/dN vs. ΔK for block tests at 550°C

The length of the measured damaged zone varies with respect to temperature and hold time but is usually, in a stabilized state, tenths of millimeters. For further discussion about measurement of the length of the damaged zone by changing load cycle type in the testing procedure see e.g. [10] and [17]. Finally, in [10] it was shown that, for sufficiently long hold times, the crack driving mechanism acting in front of the crack fully controls the crack growth rate. Whenever a load reversal is applied, the main crack will propagate into material with lowered crack growth resistance and, as long as the main crack does not propagate too far into the damaged zone, such a load reversal will not affect the overall crack growth rate per time increment (da/dt).

Hold times at high temperature do not always cause the material to fail fully by intergranular fracture, sometimes there can be a mix of intergranular and transgranular fracture. It has been shown that the ratio between transgranular and intergranular fracture depends on both temperature and hold time length [18]. Conceptually, three fracture type regions can be identified, representing i) fully cycle dependent transgranular fracture, ii) fully time dependent intergranular fracture and iii) mixed type transgranular and intergranular fracture, where the ranges of the latter become shorter for higher temperatures. Furthermore, it is to be noted

that even for long hold times and/or high temperatures, mixed mode cracking can be dominant in transient regions when a damaged zone is not yet fully developed.

The underlying mechanisms of the hold time effect is still not fully understood [19]. However, two dominating theories can be found: stress accelerated grain boundary oxidation and dynamic embrittlement [20]. The stress accelerated grain boundary oxidation process involves oxidation of grain boundaries ahead of the crack tip and subsequent cracking of the oxide, exposing new surfaces to the oxygen. The dynamic embrittlement theory, on the other hand, advocates embrittling of the grain boundary by oxygen diffusion, separation of the embrittled boundaries and subsequent oxidation of the fresh surfaces. Dynamic embrittlement requires oxygen diffusion only over very short distances, which has been shown to be consistent with the rapid halting of a crack growing under sustained load when the oxygen pressure is removed [21], see also [22].

Whatever mechanism is active, the damaged zone itself is probably a volume of embrittled and partially cracked material, see e.g. [21, 23, 24]. In these works it is shown that intergranular cracks grow in preferred grain boundaries which leads to an uneven crack front. Certain parts of the crack grow much faster and it is also shown that unbroken ligaments are left behind the crack front. Thus the material volume around the crack tip becomes partially cracked. For an example of this see Fig. 10 [12] and figures in reference [24].

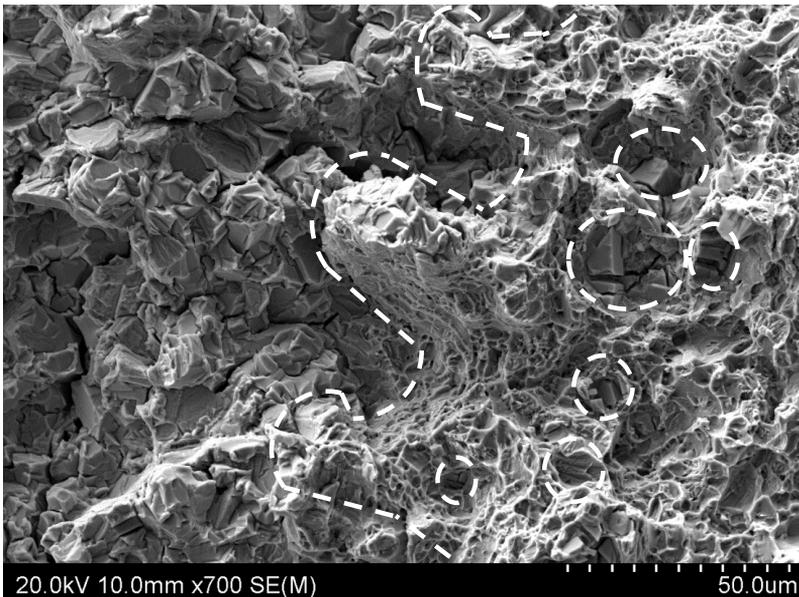


Figure 10: Fracture surface with an irregular crack front, ligaments left in the crack path and areas of intergranular fracture ahead of the crack front

4.4 Modelling of hold time crack growth

Fatigue crack growth in Inconel 718 with high temperature hold times has been extensively studied previously, c.f. [7, 8, 18, 22, 25–29]. The modelling of hold time effects is classically handled by additive models with a cyclic part, based on pure cyclic crack growth, and a time dependent part, based on pure time dependent crack growth, see e.g. [30–34]. However, this approach has been shown to be questionable from a physical point of view [10, 12]. In [10] and [11] it was concluded that not only the crack growth during the hold time was affected by the hold time period but also the crack growth during load reversals, see Section 4.3 above. It was found that a significant part of the cracking takes place during the unloading and reloading of the test specimen, see Fig. 11 showing the crack growth for five load cycles for a 2160 s hold time test at 550°C, see also [35]. These effects were also found in thermomechanical fatigue crack growth tests [36].

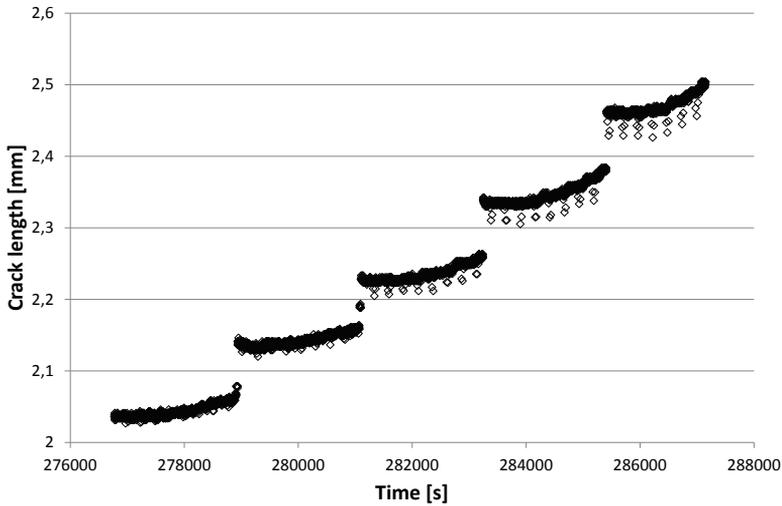


Figure 11: Five cycles crack length vs. time for a 2160 s hold time test at 550°C

When it comes to describing the time dependent behaviour, some authors use a simple phenomenological modelling approach, basically modifying the Paris law [37] by including parameters such as frequency and temperature to account for the time dependency of the high temperature crack growth process, see e.g. [18]. Others use a more physically based approach and their modelling is usually based on an observation of a specific crack growth or damage mechanism, such as oxide penetration see e.g. [38–42], and more recently [43] and [44].

4.4.1 Adopted modelling framework

As was discussed in Section 4.3, the damaged zone seems to be the controlling factor in hold time fatigue crack propagation in Inconel 718. Since the evolution of the damaged zone during hold times, as well as the resulting crack propagation behaviour, is affected by other load events, it becomes important to understand the interaction between hold times at high temperature and other load events, such as cyclic loadings, in order to be able to model the behavior during real component load cycles.

A modelling framework based on the damaged zone has been adopted [45]. In this model, the evolution of the damaged zone depends on two parts, the rate of damage and the rate of crack growth, respectively. By using the same description for the evolution of the damage as for the stabilized crack growth rate in a time dependent test, the combined rate produces a saturated length of the damaged zone for the stabilized parts of a simulated hold time and time dependent test. Furthermore, control of the crack growth rate is achieved by using an additive description where scale factors depending on the current length of the damaged zone are used for accelerating both the cyclic and hold time parts. The cyclic part predicts the rate of a pure cyclic crack growth when no damaged zone is present and is accelerated when a damaged zone is developed. The time dependent part is set to have no growth if no damaged zone is present. However, once a damaged zone is developed the time dependent part is allowed to accelerate and when the damaged zone is fully developed the time dependent part reaches the crack growth rate of a stabilized pure time dependent test. With the chosen evolution laws for the scaling factors, all crack growth rates will lie in between the pure cyclic fatigue crack growth rate and the pure time dependent crack growth rate.

Since our modelling framework is set up using the concept of a damaged zone as the foundation, its main domain of validity will be the time dependent region, see Section 4.3. Furthermore, only one temperature is considered. If the model was to be calibrated for higher temperatures, it would probably show a better agreement to shorter hold times since the time dependent region is growing with increasing temperature. Finally, in order to have an industrial relevance, the proposed model contains only a small set of material and fitting parameters which can be found from basic experiments.

4.4.2 Results

To illustrate the capabilities of the presented modelling framework some results are presented below. The modelling output is compared with experimental results reported in [6, 10–12].

Results for a pure time dependent crack growth test and a block test with 2160 s hold time can be seen in Figs. 12 and 13. These tests were used for parameter

calibration of the model. As can be seen, the proposed modelling description fits the test data reasonably well.

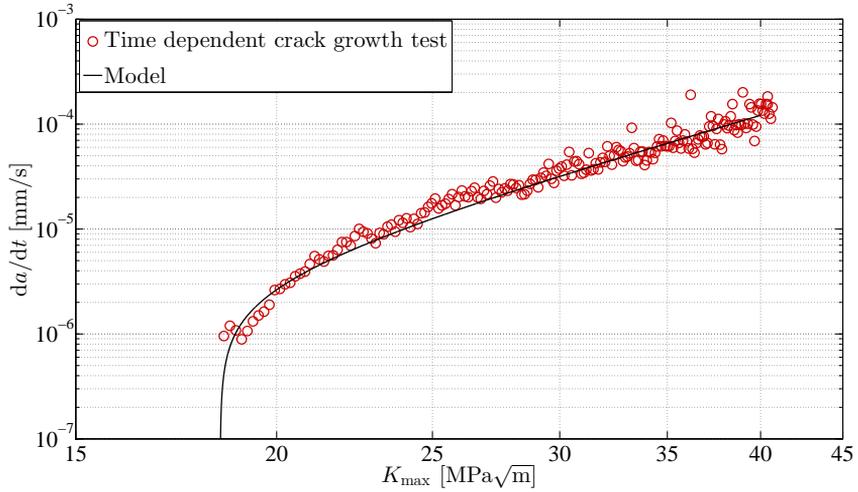


Figure 12: Model vs. time dependent test

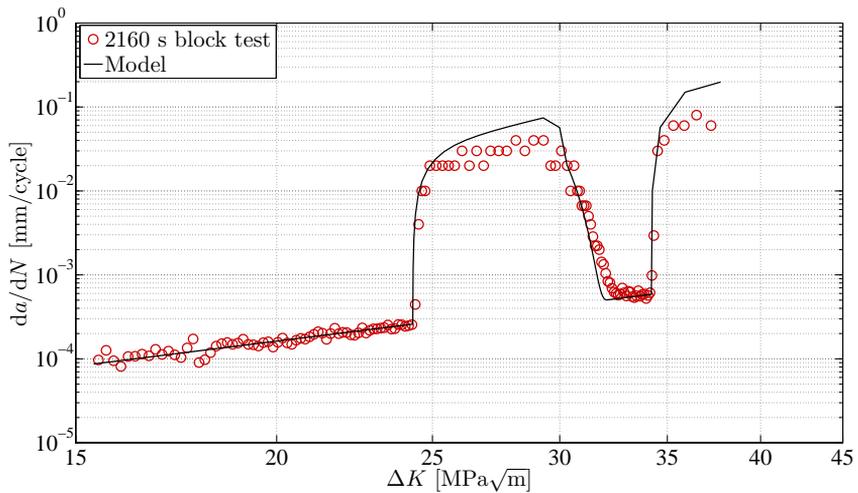


Figure 13: Model vs. block test with 2160 s hold time

Results for a hold time tests with 2160 s and 21600 s hold times, respectively are seen in Fig. 14. Also here, the model gives satisfying results for the tested conditions.

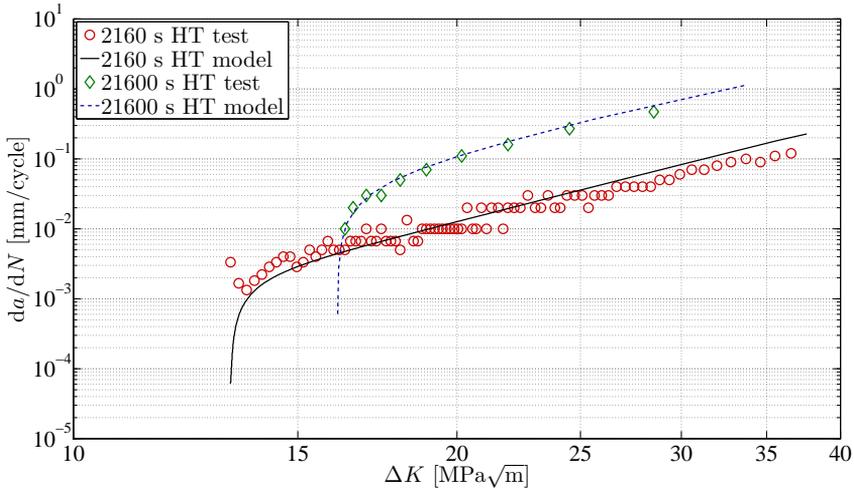


Figure 14: Model vs. hold time tests

However, as discussed in [45], the model does not fully produce results in agreement with experimental results for shorter hold times (too high frequency), does not fully capture the initial transient in a time dependent crack growth test with a longer pre-crack (too high damage growth) and does not predict a correct a vs. t diagram (due to lack of initial transient in experiments). More work needs to be done in order to understand and handle these shortcomings.

4.5 Overload effects

So far it has been shown that hold times at high temperature have a powerful accelerating effect on the crack growth rate of Inconel 718. In reality there is a possibility to find cracks in real structures subjected to K -levels and temperatures corresponding to the performed tests described in Section 4.2, above. Thus, the question arises why do not gas turbine components subjected to hold times at high temperature fail catastrophically as predicted by the material testing? There are several possible explanations for this. Probably one of the most important ones is that the hold time effect is strongly load cycle dependent.

Several authors have shown that initial overloads have a beneficial effect on the hold time crack growth behaviour [7, 46]. Tests were conducted in the context described in Section 4.2 using the load cycle found in Fig. 15. In Fig. 16 tests with a peak overload at the start of each cycle are presented [12]. As can be seen an overload of only 2.5% greatly reduces the crack growth rate in a test with 2160

s hold time. Furthermore, an overload level of 15% more or less completely cancels the hold time effect.

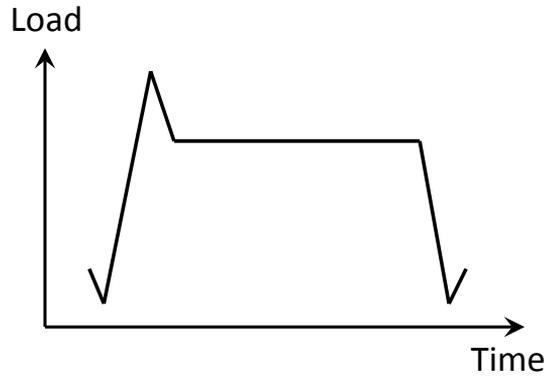


Figure 15: Overload load cycle

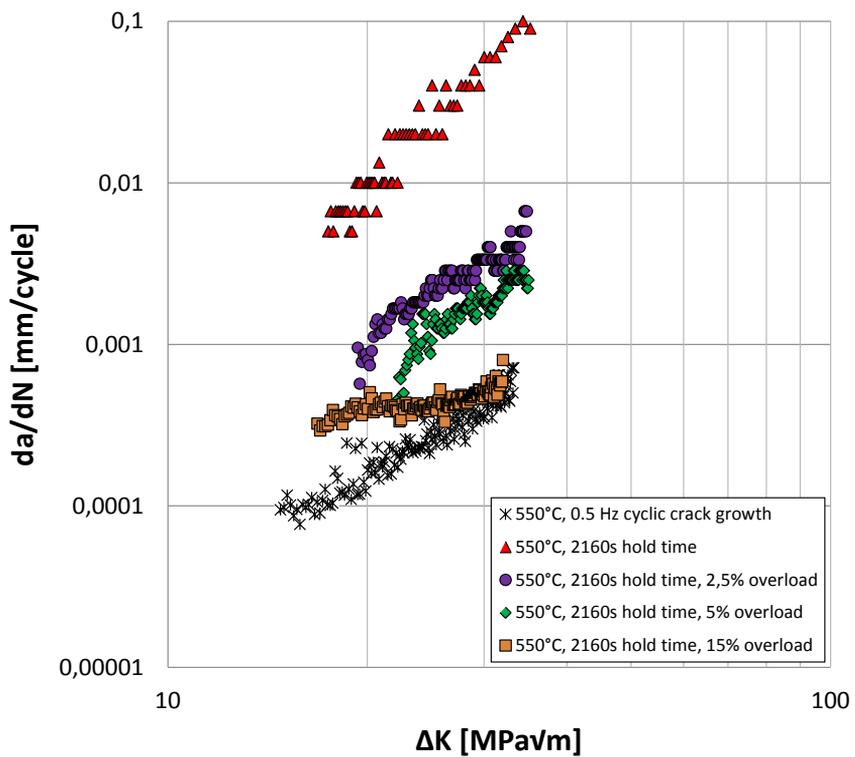


Figure 16: da/dN vs. ΔK for hold time tests at 550°C with initial overloads

It has been shown in e.g. [12, 46] that the overload level is probably closely related to the reduction of tensile stresses at the crack tip. When an overload is applied a partial unloading is made before the hold time. Such partial unloading strongly influences the stress field in front of the crack tip. It has been shown that this gives a massive reduction of the normal stresses perpendicular to the crack. Not only is the average normal stress state perpendicular to the crack tip greatly reduced, but close to the crack tip compressive stresses will even be found, see e.g. Fig. 17 showing results from an FE-simulation after a partial unloading of a plate with a central crack modelled in 2D [12].

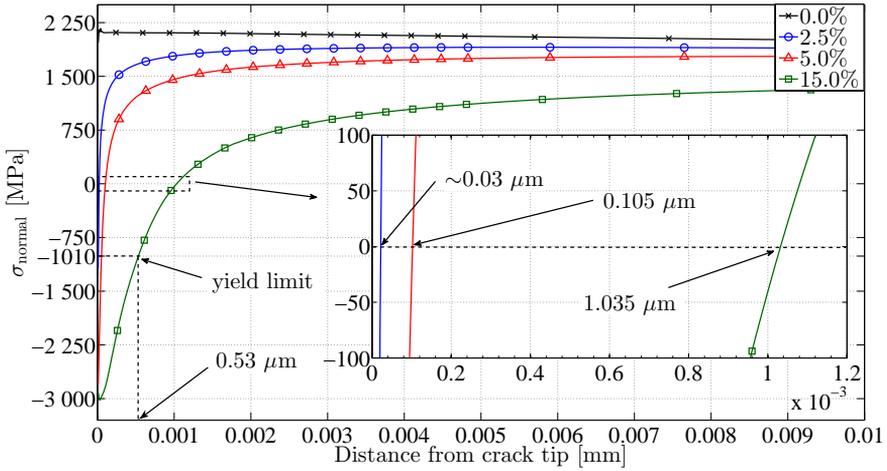


Figure 17: Stress normal to the crack plane for all the load cases

This compressive and reduced normal stress state is believed to be the reason of the less pronounced hold time effect after a partial unloading, since the crack driving mechanisms of the hold time effect likely are diffusion controlled and are thus likely to be promoted by high tensile stresses.

In order to perform a fatigue analysis of a component, it is necessary to know the stress and strain cycles that the component will be exposed to. A fatigue analysis therefore starts by a stress and strain analysis and, in order for this to be relevant, a representative constitutive model must be available in the adopted FE-software.

5.1 Constitutive behaviour of Inconel 718

The choice of constitutive description to be set up for the material must be based on the specific needs, i.e., in this case the fatigue crack initiation characteristics. Thus, it must be able to give a correct prediction of a stable hysteresis loop throughout its expected life. For the fatigue analysis, we need the typical stabilised stress/strain cycle. The analysis must therefore start by a rigorous analysis of the first few cycles, during which an important stress redistributions will always take place in an inelastic structure. This redistribution will be essential for the determination of the stabilised cycle that will dominate in the cyclic history to follow.

Difficulties arise with the description of ratchetting or mean stress relaxation effects. A material may cyclically harden or soften, and if subjected to a nonsymmetric cyclic loading, ratchetting or mean stress relaxation may occur depending on whether the stress or strain is prescribed, [47] and [48]. Ratchetting manifests itself by a progressive increase in strain at each loading cycle, while cyclic mean stress relaxation under strain-controlled loading represents its counterpart. Inconel 718 is known to exhibit the phenomena of ratchetting and mean stress relaxation [49], and since the mean stress of the material has an influence on the fatigue crack initiation life of the material [50], this must be considered.

Most nickel-based superalloys cyclically harden [2], but in contrast to this Inconel 718 cyclically softens. Cyclic deformation of Inconel 718 has been shown to be localized to planar slip bands, c.f. [51], where significant shearing of γ'' particles takes place [52]. This is believed to cause the cyclic softening of the material.

Another phenomenon found in cyclic tests is that at the initial loading of the material, a considerable softening takes place. This is in contrast to the cyclic softening which is a progressive phenomenon, see [53]. A substantial difference between the hardening modulus of the initial loading and the hardening modulus

of the following cycling can be identified. It is also to be noted that the visibly linear part (elastic region) in the initial loading is much larger than the visibly linear part of the following cycling. This initial softening is probably caused by the formation of planar slip bands during the initial loading of the material since this significantly lowers the resistance against subsequent plastic deformation.

5.1.1 Adopted mean stress relaxation model with corresponding initial softening model

The literature on the subject of ratchetting and mean stress relaxation modelling is vast and newer model advancements in this area tend to become very complex and therefore slightly lose relevance from an industrial point of view. However, we have adopted the extended Ohno and Wang model [54], which is similar to the decomposed nonlinear kinematic hardening model initially proposed by Chaboche [47]. Basically it is a superposition of several Armstrong and Frederick hardening rules [55], but includes a modification of the recovery terms to improve the ratchetting and mean stress relaxation prediction capability. This modification is in form of a slight nonlinearity for each rule at the transition from linear hardening to the stabilized critical state, see [53].

In order to describe the initial softening of the material an addition of a linear isotropic softening model was used. This model consists of several terms, where each one is associated to a specific backstress component in the Ohno and Wang model, see [53].

For a comprehensive discussion on models for mean stress relaxation, see [56].

Throughout the project our knowledge has increased substantially concerning the complex nature of fatigue crack growth in a high temperature hold time context. Much effort has been dedicated to material testing and evaluation in order to understand the material behaviour and to some degree also the complex physics behind the hold time effect. Later in the project we have been able to focus more on fatigue crack growth modelling. We have proposed a simple modelling framework for predicting hold time crack growth and the interaction between different load cycle types, which is critical for predicting the life of gas turbine components. However, it is still lacking the capability of predicting the influence of initial overloads. Since overloads have been shown to have such a substantial effect on the hold time crack growth rate of the material it is of outmost importance to be able to incorporate this effect. However, we are still lacking some basic knowledge of the material response concerning overloads which must be investigated in a more complete testing programme before continuing with the modelling work.

The aim of the modelling is to be able to describe real gas turbine load cases including high temperature hold times. Thus, also non-isothermal gas turbine component cycles must be addressed. This can possibly be solved by introducing temperature dependent model parameters, but may also need other actions. The effect of other complex load cycles e.g. underloads also needs to be addressed. Hopefully, this issue can be handled by using FE-simulations for predicting the effect on the stress field around the crack tip due to the complex load cycle thus obtaining info to feed the fatigue crack growth model. Using this approach, the model will hopefully be successful in the development of gas turbines in the future.

It can finally be noted that plasticity effects such as crack closure may have some role in the observed behaviour. In order to better understand if this is the case or not, more simulations and material testing need to be carried out.

Paper I

Fatigue crack growth behaviour of Inconel 718 with high temperature hold times

In the first paper, fatigue crack growth measurements have been made on center-cracked tension specimens of Inconel 718, where the focus has been to observe the effect of high temperature hold times on the fatigue crack growth behaviour of the material. The material testing has been done at three different temperatures, namely 450°C, 550°C and 650°C. All testing was done in an isothermal fatigue crack growth context with a standard test method for measuring the crack growth rates. Hold time tests were found to show intergranular fracture while cyclic tests showed transgranular fracture. It was found that significant embrittlement of the grain boundaries must have occurred.

Paper II

Modelling of the constitutive behaviour of Inconel 718 at intermediate temperatures

In the second paper the nonlinear kinematic hardening law by Ohno and Wang has been used in combination with an isotropic softening law for describing stress redistribution for strain controlled uniaxial tests of Inconel 718. Focus has been placed on finding a simple model with few material parameters, and on describing the initial softening and the comparatively small mean stress relaxation observed during the material testing. The simulation results obtained by using the model fit the experimental results well.

Paper III

Influence of high temperature hold times on the fatigue crack propagation in Inconel 718

In the third work high temperature fatigue crack growth in Inconel 718 has been studied at the temperatures 450°C, 500°C, 550°C and 650°C. The tests were conducted without hold times, with hold times of different lengths and, finally, with a mix of both, referred to as block tests. Focus has been placed on quantifying the effect the hold time has on the crack growth rate and on how much it damages the material. This damage is related to the concept of a damaged zone in front of the crack tip. The size of the damaged zone has been measured from the tests and a microscopy study to confirm the findings has also been carried out. Furthermore, it has been investigated how this damage influences the actual cracking behaviour, i.e. were in the loading cycle the damage contributes most to the crack growth. It is found that the concept of a damaged zone can be a successful explanatory model to quantify the damage mechanisms acting around the crack tip due to high temperature hold times.

Paper IV

Hold-time effect on the thermo-mechanical fatigue crack growth behaviour of Inconel 718

In the fourth work in-phase thermo-mechanical fatigue (TMF) crack growth testing with different lengths of the hold time at the maximum temperature of 550°C has been conducted on Inconel 718 specimens. Focus has been on establishing a method for TMF crack growth testing and investigating the effect of high temperature hold times on the TMF crack growth of the material. The tests are compared to isothermal crack propagation tests and show good correlation. It is concluded that the controlling effect of the crack growth is an embrittlement in the material. This embrittlement is related to the concept of a damaged zone active in front of the crack tip. The size of this damaged zone will control the crack propagation rate and therefore it does not matter if the load is cycled under isothermal or TMF conditions.

Paper V

Fatigue crack growth behaviour of Inconel 718 - the concept of a damaged zone caused by high temperature hold times

In the fifth work further isothermal fatigue crack growth testing of the block test type was carried out. Further work regarding how to measure the length of the damaged zone is presented. Finally, an expression for the saturated length of the damaged zone for different hold times is obtained. It has been found that the evolution of this damaged zone can be sufficiently well described using a power law function.

Paper VI

High temperature fatigue crack growth behaviour of Inconel 718 under hold time and overload conditions

In the sixth work the effect of overloads on the hold time fatigue crack growth behaviour and its subsequent description has been studied. More specifically, crack propagation in Inconel 718 has been studied at the temperatures 550°C and 650°C with and without an overload at the start of the cycle. The effect of initial overloads was found to be substantial. A simple model for describing the effect of these loading conditions has also been set up. The model developed takes its inspiration in the concept of a damaged zone, present around the crack tip. Irregular crack fronts and unbroken ligaments left on the fracture surfaces seen in complementary microscopy studies seem to support this approach. Furthermore, the stress state in front of a crack tip in a 2D model was predicted both with and without an initial overload. The results were related to the observed crack growth retardation behaviour found in the material testing.

Paper VII

Modelling of high temperature fatigue crack growth in Inconel 718 under hold time conditions

In the seventh work modelling of the hold time fatigue crack growth behaviour of Inconel 718 in the time dependent region and at the temperature 550°C has been carried out by using the concept of a damaged zone, where scale factors depending on its length are used for accelerating both the cyclic and hold time parts. Using an evolution model of the damaged zone and the scale factors, hold time tests,

time dependent crack growth tests and block tests can be handled satisfactorily. Furthermore, in addition of having a reasonably sound physical foundation, the model has few fitting parameters which can easily be obtained from fatigue crack growth testing.

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