

Proposal for new KME-project 2014-2017:

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Applying Organisation

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Organisation number

202100-3096

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Project

The project is partly a continuation of the project KME-502. However, new activities concerning LCF and TMF crack propagation testing and modelling is planned.

Title

LCF and TMF crack growth in cast nickel-based superalloys

Summary

English

The aim of the proposed project is to validate materials for future industrial gas turbines with strong demands for high fuel flexibility, availability and efficiency, as well as cyclic operation. This will require materials with high corrosion resistance and good resistance to thermomechanical fatigue (TMF). The key objectives of the project is therefore to: (1) Validate a TMF crack growth test method that can be used to generate high quality data for cast nickel-based superalloys, including single crystals. (2) Generation of high quality test data for TMF crack growth in the corrosion resistant single crystal superalloy STAL15. (3) Improve the knowledge regarding the mechanisms that controls the crack growth rate in single crystal superalloys. (4) Develop TMF crack growth models and life prediction methodologies that will reduce the need for high safety margins. (5) Validate the models for component near conditions.

Swedish

Syftet för det föreslagna projektet är att validera material för framtidens industriella gasturbiner med höga krav på bränsleflexibilitet, tillgänglighet och effektivitet samt förmåga att klara cyklisk drift. Detta kommer att kräva material med hög korrosionsbeständighet samt högt motstånd mot termomekanisk utmattning (TMF). De viktigaste målen för projektet är därför att: (1) Validera en testmetod för spricktillväxt provning under TMF förhållanden som ger tillförlitliga data för gjutna nickelbaslegeringar, inkl. enkristaller. (2) Generera TMF-spricktillväxtdata för den korrosionsbeständiga enkristallegeringen STAL15. (3) Ge förbättrade kunskaper om de mekanismer som styr spricktillväxthastigheten i enkristallina superlegeringar. (4) Utveckla modeller för att prediktera spricktillväxt under TMF-förhållanden för att på så sätt möjliggör en kraftig minskning i osäkerhet vid livslängdsberäkningar. (5) Validera modellen under komponentnära förhållanden.

Motivation

Structural components in gas turbines as well as steam turbines are subjected to rather complex stress and temperature cycles due to the temperature gradients that occur during engine start-up and shut-down or within components during steady-state operation. The accumulated effect of such stress and temperature cycles leads to the possibility of failure by thermomechanical fatigue (TMF), which must be avoided by appropriate design of the components and choice of operating conditions. However, the service life of many hot components is not fully restricted by the number of cycles to crack initiation since, especially close to stress concentrations; one has also to rely on

stable and predictable crack propagation, which means that a certain amount of crack propagation is allowed before the component has to be replaced in service. Such damage tolerant approaches demand accurate predictions of the crack growth (CG) under the influence of simultaneous cycling of temperature and mechanical loads. Although methods have been developed to predict CG rates under isothermal conditions over a wide range of temperatures, frequencies and load ratios, as well as under sustained load/dwell times, only very few published studies on crack propagation under TMF conditions are available. Furthermore, since the translation of isothermally obtained fatigue crack propagation data into a true TMF context is questionable, the need for more experimental studies in this field is obvious. Unfortunately, mechanical testing under dynamic temperature conditions is more complex than other more traditional isothermal testing techniques.

Crack propagation in single crystal materials add an extra dimension of complexity since the failure modes are complicated due to the material anisotropy, the effect of crystal orientation and the very high temperatures that are typically of interest for single crystal components. In addition, previous studies within KME-403, KME-410 and KME-502 have shown that the deformation in single crystal materials is often very localized to a number of crystallographic deformation bands and that cracks follow these bands very easily. Thus, the cracks cannot be expected to follow the K_I -dependency (i.e. crack growth perpendicular to the applied load) commonly observed in conventional materials.

Contribution to the goals of the KME-programme

The proposed project mainly address the following two goals of the KME-programme:

“To test and validate new materials and surface coatings for future industrial gas turbines in order to permit high fuel flexibility, availability and efficiency, as well as cyclic operation.”

“To evaluate the mechanical properties and service life of various materials in relation to new material requirements for more efficient electricity production”

Two different materials will be investigated in the project; (1) Conventionally cast IN792 which is commonly used in turbine blades for industrial gas turbines, (2) the newly developed single crystal material STAL15 for which preliminary results indicate better fatigue and corrosion properties than conventional single crystal superalloys. This will support fuel flexibility as well as improve the capacity for cyclic operation of the next generation of advanced gas turbines for energy production.

Energy relevance

The energy market has appreciably changed over the past decade, and there is especially a need for energy sources that can be dispatched at the request of power grid operators; that is, power generating plants that can be turned on or off, or can adjust their power output on demand. With the introduction of large amounts of non-dispatchable wind and solar power it is nowadays necessary to have gas turbines that can operate under more cyclic conditions. However, most land-based gas turbines were designed for base load operation and might undergo significant damage due to change in operation conditions.

Industrial relevance

The common way today to deal with uncertainties in the crack propagation behaviour is to apply a conservative approach with large safety factors and/or regular inspections of critical components. This is for several reasons costly. With better tools in terms of models, design criteria, material data and test methods, the design of critical components can be optimised, costs can be reduced and safety can be improved. However, another important factor is that today many design solutions often rely on many years of service experience, and optimisation has been achieved in many small steps on a trial and error basis. Thus, novel and innovative design solutions are often hindered by the difficulty in verifying the solutions. Improved methods and tools are also necessary in order to speed up the time needed for introduction of new and unproven design concepts, e.g. new and innovative cooling systems in turbine blades and vanes can be utilised when introducing new manufacturing concepts that enable new possibilities in terms of shape and geometry and the introduction of new alloys will be easier if validation can be performed on a laboratory scale rather than by service experience. Increasing the knowledge regarding TMF crack growth is thus vital in order to preserve the competitiveness of the Swedish gas turbine industry.

General applicability

Even if the project will generate material data for a limited number of materials typically used only for gas turbines (IN792 and STAL15SX), the tools and methods for handling TMF crack propagation (testing and modelling aspects) are new and can be applied to other materials as well as to other applications such as steam turbines and boilers operating under cyclic conditions.

News value with the project

Crack propagation under TMF conditions is a very rarely studied phenomenon, which is probably due to the complexity of performing such tests under fully controlled laboratory conditions. As a consequence, all existing models have been developed more or less without any relevant experimental background. The need for such models is however high since the service life of most hot components, especially close to stress concentrations, relies on a “stable” and “controllable” crack propagation. The strength of the proposed project is that it aims to combine material modelling, material characterization and advanced testing techniques in a multi disciplinary manner. There will also be a focus on the newly developed alloy STAL15, which is a highly interesting alloy to study from an academic as well as an industrial perspective.

Background

This project is partly a continuation of the work performed in the two last programme periods of KME (KME-502, KME-403 and KME-410). In the previous projects most of the focus has been on characterization of the constitutive behaviour of single crystal superalloys and to study the deformation and damage behaviour during thermomechanical fatigue of smooth specimens and also to develop models for describing these phenomena. The results from previous projects are briefly summarized below.

Previous work

KME-403: Damage mechanisms during TMF of gas turbine blading materials

In this work it was revealed that the deformation and damage mechanisms in single crystal superalloy during TMF were rather different from those traditionally reported for creep or isothermal fatigue. In all alloys investigated the deformation was localized to a few number of deformation bands. In alloys like CMSX-4 these bands were comprised by twins while in other alloys like SCA425 the bands are better described as slip bands. In either case recrystallization followed by rapid crack growth along the deformation bands led to the failure of the specimens. All tests were performed on smooth specimens and gave valuable information regarding the constitutive behaviour of the materials and the mechanisms for crack initiation. However, no or limited information of the crack propagation mechanisms were gained from these tests. In this project only single crystal materials loaded along the $\langle 001 \rangle$ direction were investigated. For more details see references [1,2]

KME-410: TMF of notched components made of single-crystal nickel-base superalloys

This project was conducted in parallel with KME-403 with focus on constitutive modelling and lifetime predictions for single crystals materials. In this work a single crystal plasticity model was derived that takes anisotropy as well as tension/compression asymmetry into account. The model was used to evaluate fatigue crack initiation of smooth specimens subjected to LCF-loading at 500°C and by using a combination of a critical distance and a critical plane theory, the fatigue life of notched specimens could be predicted with good accuracy. In this project the effect of degradation and rafting and its effect on the low temperature yield stress was also investigated and modelled. For more details see references [3–6].

KME-502: Fatigue in nickel-based superalloys under LCF and TMF conditions

In this project, succeeding the two projects described above, the aim has been to focus more on the high temperature behaviour such as creep of single crystal materials and the influence of crystallographic orientation on the TMF behaviour. Testing and modelling has been performed on single crystals in order to describe the creep relaxation behaviour in both tension and compression for several different crystallographic orientations. The IP and OP TMF behaviour have also been compared for several different crystallographic orientations. In addition also conventionally cast polycrystalline superalloys have been investigated. Together with the previous projects this project has given a profound knowledge regarding TMF, creep and the elasto-plastic behaviour of single crystal materials. The models can be used for component near situations and can handle loading in any crystallographic orientation. The main limitation up till now is that only crack initiation life has been investigated and still no quantitative data for crack propagation is available. For more details see references [7–25].

Problem area – state of the art

The fatigue process in single crystal nickel base alloys are, despite the absence of grain boundaries, remarkably complex. Both crystallographic and non-crystallographic fracture modes are observed where their occurrence is depending upon temperature and stress-state. Crystallographic fracture is usually along multiple $\{111\}$ planes but can, under certain conditions, appear as cleavage along cubic (001) planes. The later behaviour can often be associated with environmental effects, such as hydrogen

embrittlement or sulphidation [26,27]. Studies have also shown that TMF cracks of single crystal nickel base alloys have different appearances depending on whether a compressive hold time at maximum temperature was introduced or not [28]. The introduction of a hold time in compression promotes the formation of twins and according to the findings in the previous KME-projects, crack propagation occurs rapidly along these twin planes [1,2,15]. This indicates that the deformation introduced in the material prior to the crack initiation is an important factor for the crack propagation behaviour.

Kersey et al. [29] have studied out-of-phase (OP) TMF crack growth from laser drilled holes in the single crystal alloy PWA1484. In this study it was found that major crack propagation took place at the low temperature portion of the cycle but there were also noticeable damage accumulation during the high temperature compressive load portion of the cycle. As a consequence it was found that crack propagation under TMF loading conditions is faster than corresponding isothermal LCF crack growth at similar temperature and loading conditions as for the tensile part of the TMF cycle. Furthermore, in this study it was found that the cracks started at the holes and initially propagated crystallographically and later changed to a non-crystallographic mixed mode growth.

Okazaki et al. [30] performed fatigue crack growth experiments at room temperature on the single crystal alloy CMSX-4 with different primary and secondary orientations of the single crystal relative to the specimen configuration and applied load. On the basis of apparent Mode I stress intensity factor range, the [001] specimens revealed the highest rates and the [111] specimens the lowest. However, the fatigue fracture was driven on the crystallographic {111} slip planes in all specimens. However, the dependency of crystallographic orientation almost disappeared when the rates instead were correlated to the stress intensity for shear mode fracture.

Bouvard et al. [31] have proposed a crack growth model for single crystal superalloys at high temperatures that follows the framework of classical linear elastic fracture mechanics (LEFM) that can capture time dependent mechanisms such as creep-fatigue and oxidation-fatigue interactions. The model was also verified against TMF tests but the effect of different crystallographic orientations were not taken into consideration. Others like Zhao et al. [32] have considered elastic-plastic fracture mechanics (EPFM) parameters such as the J integral and COD in the context of anisotropy and notch orientation of single-crystal superalloys.

Single crystal superalloys often display significant rafting, i.e. directional coarsening of the strengthening particle γ' [4]. Compressive loading at high temperature, as typically seen for OP TMF, leads to rafting parallel to the loading axis. Neuner et al. [33] have shown that this will enhance the TMF life since rafts along the loading direction will hinder crack propagation.

As shown by the examples above crack propagation in single crystal superalloys is a complex phenomenon and so far no unified model that takes all kind of microstructural and environmental effects into account is available. Thus, the need for more work in this field is motivated.

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Goals

The aim of the project is to validate materials for future industrial gas turbines where there is a strong need for high fuel flexibility, availability and efficiency, as well as cyclic operation. This will require materials with high corrosion resistance and good resistance to TMF. As a reference material commonly used in the industrial gasturbine industry the conventionally cast Super alloy IN792 will be investigated. However, focus will also be on the newly developed single crystal material STAL15 for which preliminary results indicate better fatigue and corrosion properties than currently used single crystal superalloys. Focus will be on TMF crack growth testing and modelling. This is a topic where significant technology improvements are expected to be possible.

The key objectives of the project is therefore to:

1. Validate a TMF crack growth test method that can be used to generate high quality data for cast nickel-based superalloys, including single crystals.
2. Generate high quality test data for TMF crack growth in conventionally cast IN792 and the single crystal superalloy STAL15.
3. Improve the knowledge regarding the mechanisms that controls the crack growth rate for conventionally cast superalloys as well as for single crystal superalloys (e.g. influence of crystal orientation, phase shift and temperature-strain history).
4. Develop TMF crack growth models and life prediction methodologies that will reduce the need high safety margins. Today the safety of single crystal crack growth is in the order of three decades. The idea is to bring this order of magnitude down by one decade.
5. Validate the models for component near conditions.

Project plan

The project will consist of two main activities closely linked together. One part mainly involves modelling and simulations (M), while the other part is focused on the experimental (E) work (mechanical testing and microstructure investigations). The work is divided into a number of work packages (WP) as described below:

Work packages (WP)

Experimental WPs

E-WP1: Thermomechanical fatigue crack growth testing

Crack growth testing under dynamic temperature conditions is a complex task that has not been studied in a wide extent in the academia or in the industry.

- A new test rig at LiU dedicated to TMF crack growth testing will be set-up.
- Validate a test method that can generate high quality data. (Goal 1)
- Generate TMF crack growth data for IN792 and STAL15. (Goal 2)

E-WP2: Mechanisms for crack propagation in single crystal superalloys

Crack propagation in single crystal superalloys can, under some conditions, occur in a highly crystallographic manner. In addition plastic deformation is highly localized to deformation bands in the microstructure that are susceptible to cracking.

- Investigation of favoured crack growth planes in single crystal superalloys under different strain and temperature ranges, dwell times and phase shifts. Find a criterion for when the crack propagation switch from Modus 1 to deformation band cracking. (Goal 3).
- Identify how the crack closure level depends on dwell times and phase shift. (Goal 3 and 4).

E-WP3: Investigation of the ageing effects in single-crystal superalloys

Rafting and other degradation mechanisms are expected to influence the crack growth mechanisms.

- Find a convenient method to artificially simulate a service-exposed microstructure, e.g. by pre-deformation and furnace exposure.
- Pre-deformation in notched or smooth configuration.
- Perform TMF crack growth tests on degraded material in order to see if or how the crack growth rate has changed (Goal 3).
- Rafting phenomenon is quantified and analysed.

Modelling WPs

M-WP1: Crack propagation modelling for LCF conditions

The crack propagation of cast nickel-based superalloys is investigated and modelled. LCF testing data, such as number of cycles to failure and crack propagation rates da/dN , has been generated at SIT and is available to the project.

- Crack propagation model for notched single-crystal superalloys specimens under LCF conditions at 500°C.
- “Paris law” like model is to be implemented in a state of the art fatigue crack propagation program. (Goal 4)
- Incorporate criterion for crystallographic crack growth. (To be delivered from E-WP2).
- Accounting of elastic and plastic anisotropy, as well as tension/compression asymmetry.
- The applicability of LEFM is to be investigated.

M-WP2: TMF crack propagation modelling

The TMF crack propagation behaviour for a notched geometry at temperature cycles 100-750°C, 100-850°C and 100-950°C is to be investigated. (To be delivered from E-WP1).

- Is the crack propagation model for LCF conditions sufficient, or do we need to incorporate other mechanisms. (Goal 4)
- Hold-time effects are expected to influence the propagation behaviour, an issue to take into consideration.
- Creep during the hold-time is expected to yield an impact on the crack propagation behaviour.
- No ageing, such as rafting, will be taken into account here.

M-WP3: TMF crack propagation modelling for aged conditions

The ageing of the microstructure due to high temperatures as well as its effect on the material behaviour is studied. Plastically deformed specimens are exposed to high temperature for a long time.

- Ageing effects on the material properties and TMF crack propagation. (From E-WP3)
- Same as in M-WP2 but with the aged conditions, no evolution of ageing is considered. (Goal 4)

M-WP4: Component near demonstration

Validate the defined models for a more component like geometry or if not available, another test specimen geometry and different loading conditions. (Goal 5)

- Blade – disc interaction is to be performed and evaluated.
- Fatigue data from testing to be analysed.
- Coupling effects between the different materials, as well as LCF and TMF.

Implementation of the results

The knowledge and methodology derived in this project will be used directly in the design of future gas turbine components. The development of a damage tolerance design tool that can account for the high temperature conditions in the hot gas turbine components will reduce the uncertainties by several orders of magnitude and thus also reduce the number of inspection intervals needed to account for the uncertainties. The design tool will be integrated directly into existing state of the art codes used for crack growth calculations. This will result in a user-friendly tool for every day usage by the design engineers. However, to make such a tool useful it must be fed with material models that can only be derived based on the knowledge gained from load condition relevant tests and subsequent material characterization. The data and material knowledge generated will be essential in creating reliable material data sheets and guidelines and also to enhance the overall understanding of the limitations of fatigue damage tolerant design. In total the implementation of the generated results will provide the industry with tools that will be utilized to develop gas turbines that will fill an important role in the future sustainable energy system.

Time schedule

Start the project: 1:st of October 2014

Finish the project: 15:th of April 2018

Progress reports: 2 times a year (September & March)

	2014	2015	2016	2017	2018
E-WP1		EM1			
E-WP2			EM2	EM3	
E-WP3					EM4
M-WP1		MM1			
M-WP2			MM2		
M-WP3				MM3	
M-WP4					MM4

EMx and MMx refer to the main milestones for the Experimental and Modelling part of the project. Each milestone will be a journal article covering the content as described for each WP.

Staff

The project will be conducted at the Division of Engineering Materials and the Division of Solid Mechanics at Linköping University. This constellation has been fruitful in previous works, *i.e.* KME-502, where the experimental and modelling perspective have generated a large knowledge bank regarding high temperature phenomenon. It is the project staff's belief that when combining these perspectives a greater understanding is achieved compared to what is possible in standalone projects.

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*Mikael Segersäll is a PhD-student from the previous project KME-502. He will continue in the new project (80%) until he graduates. His dissertation is planed for December 2014.

Industrial reference and financing

Industrial partner of the proposed project will be Siemens Industrial Turbomachinery AB (SIT). The project cost at LiU to be applied for from the Swedish Energy Agency is 5.735.480 SEK in total as specified in the table below. The sum to be allocated at SIT as in kind is 8.700.000 SEK. The in kind contribution from SIT has been confirmed.

Due to the cut down in budget of approximately 1.700.000 SEK, suggested by the "Energimyndighetens Programråd för Materialteknik", the cost for the two PhD projects are not fully covered by proposed project. The remaining cost will be covered by other sources.

Costs

In the table below the project costs at LiU are specified.

Kostnader	2014	2015	2016	2017	2018	Summa
Lönekostnader	188940	1002678	1025723	1075277	348690	3641308
Köpta tjänster						
Utrustning	20000	35000	35000	35000	15000	140000
Material						
Laboratoriekostnad	21667	75000	75000	75000	19167	265834
Resor		10000	40000	10000	40000	100000
Övriga kostnader						
Indirekta kostnader	93082	438095	447606	452494	157061	1588338
Summa sökta medel	323689	1560773	1623329	1647771	579918	5735480