Project Proposal - KME 2014-2018

Applying organisation

Chalmers University of Technology, Department of Materials and Manufacturing Technology

Organisation number (Organisationsnummer)

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GKN Aerospace Sweden AB

Project

Continuation of KME 506

Title

Weldability of nickel-base superalloys for energy applications

Svetsbarhet hos nickelbaserade superlegeringar för energitillämpningar

Summary

Increased operating temperatures as well as intermittent cycling of land-based gas and steam turbines motivate studies on high performance alloys such as Ni-based superalloys. However, these high performance alloys are known to be “hard-to-weld”. Therefore, the scope of the currently suggested continuation project within KME is to disclose how to investigate and clarify the fundamental cause of formation of weld cracking, or more specifically strain age cracking. As basis for this overall aim, the goal is also to establish a test procedure for the assessment of the susceptibility towards strain age cracking of precipitation hardening Ni-based alloys.

Sammanfattning

Ökad användningstemperatur och cyklisk drift av landbaserade gas- och ångturbiner motiverar studier av högprestandamaterial som exempelvis Ni-baserade superlegeringar. Dessvärre så är dessa material kända att vara mycket svårsvetsade. Det är därför som det nu förslagna fortsättningsprojektet inom KME skall utreda och förtydliga vilka grundläggande mekanismer som orsakar svetssprickor generellt eller specifikt töjningsåldringssprickor. Målet är också att utveckla ett förfarande för att utvärdera känslighet mot de så kallade töjnings-åldringssprickorna i utskiljningshärdade Ni-baserade superlegeringar.

Motivation

Ni-based alloys are already today present in gas and steam turbines and will most probable be present to a larger extent in the future if **engine efficiency** is to be increased which is normally accomplished by **increasing the operating temperature**. Another twist to reduce the environmental impact may be to use **alternative fuels** which for various reasons contribute to an overall less environmental impact. As compared to normal fossil fuels, however, the alternative fuels impose increased chemical wear in some cases, especially if the turbine should be able to run on different sorts of fuels. The Ni-based alloys are therefore also valid from this perspective in the most critical components since they have a higher resistance to chemical degradation in comparison with other metallic counterparts. On the other hand, the Ni-based alloys such as Alloy 718 are more prone to welding problems such as weld cracking and reheat cracking which is a concern in manufacturing of components containing these types of materials. Welding is despite the associated problems a process which is frequently used to produce components for different gas and steam turbines. It is both used in new production as well as for repair of i.e. worn out parts [1]. The former KME-406 and KME-506 projects did look into to the fundamental aspects related on weldability of Ni-based alloys [2, 3]. The findings and outcome from these two projects did by far exceed the expectations in terms of amount of publications (**19 publications in total**), international collaboration and established network, building of new and unique testing equipment [4], Dr. Joel Andersson has based on previous research in i.e. the KME-projects been appointed session chair in two international and highly recognized conferences on weld cracking [5] and superalloys [6] and many other things. The former projects did primarily look into how to assess or interpret weldability from a hot cracking (cracking that occurs during welding) point of view and resulted in a procedure on how to approach and determine the overall weldability of metallic alloys in general to avoid costly mistakes. It also disclosed important mechanisms related to susceptibility towards hot cracking, such as, segregation induced liquation, constitutional liquation of secondary phases, importance of weldability testing parameters and so on [1].

In the presently proposed project the aim is therefore to direct the research to another cracking phenomenon known as strain age cracking (SAC) or reheat cracking [7]. This type of cracking is primarily believed to take place during the post weld heat treatment (PWHT) or at repair welding which involves multi layer pass welding [7]. The AC is as well as hot cracking a cause for a lot of problems in welding and treating components made of Ni-based alloys and therefore an area wherein a better life and significant cost reduction could be obtained if it is avoided. This cost reduction and component life improvement leads to an **improved competiveness** which is very important for the Swedish industry. An improved ability to cope with “hard-to-weld” material also means design freedom and it enables the possibility to use more sophisticated materials that potentially may increase the ability for gas and steam turbines to operate at higher temperatures, also in connection with use of alternative fuels, which is in line with the **industrial and energy relevance**.

The former KME-projects did also aid in succeeding to get other funds in various project applications, both national (KK foundation) as well as EU funded projects (Clean Sky). Here, collaboration has been established between GKN, Chalmers, University West, Malmö University College and Luleå University of Technology. The KME-projects and the related spin-off projects have led to an increased interest and ability to build an infrastructure related to welding and weldability of metallic alloys at the Production Technology Center (PTC) in Trollhättan. This research center enables several companies of different size to (i.e. GKN Aerospace and Siemens) gain from the research in an efficient way since they have direct access to PTC. This makes **implementation** of new technology easier since the industry is close to where the research is performed and may advice early on and on a regular pace in the project on what they find important. The focus on fundamental aspects of weld cracking and primarily on SAC will bring **new results** in terms of how to **evaluate the susceptibility** towards this type of cracking. This was slightly touched upon in the previous project, KME 506, and will now be focused on in more depth to take the current understanding to a more comprehensive level. The results gained from this project may not only find itself useful in relation to gas and steam turbines but also in other disciplines where welding and metallic alloys are incorporated.

The project will contribute to the overall program objective through the following areas:

- Enabling a more **tailored operation window (cyclic operation)** for the turbine due to increased understanding of materials processing and welding of more fatigue resistant alloys which is needed to support i.e. alternative energy sources.
- Enabling an **increased operating temperature** of the gas or steam turbine through manufacturing of more high temperature capable alloy.
- In the long term, enabling the **usage of alternative fuels** due to the increased understanding on how to manufacture components using more resistant material in terms of corrosion.

GKN Aerospace is as an industrial partner very interested in the project and will make sure that the results will be implemented as soon as possible. Implementation of results is to some extent secured by the fact that one of the project members, Dr. Joel Andersson, although having his major position at GKN is also engaged as guest at Chalmers University of Technology, which will ease the **mobility of staff** between industry and academia. A reference group with people from both GKN Aerospace and Siemens will together apart from this jointly shared role for Joel Andersson make sure that the **industrial relevance** is kept on track and that the industry will be able to **utilize results** and know-how developed.

Background

The proposed project is a continuation of previous project abbreviated KME 506, in which fundamental aspects on weldability in general and especially hot cracking during welding of Ni-base superallosy were in focus. Within the KME 506 project, the problems associated with strain age cracking (SAC) were slightly touched upon. The SAC is related to precipitation of hardening phases, primarily γ’ phase, occurring at heating up to the PWHT temperature. The PWHT is performed to relief the residual stresses invoked in the material due to inhomogeneous heating and cooling during e.g. welding and also to prepare the material for the following ageing [8-11]. In general, an important cause for SAC is that the lattice parameter of the hardening phase, i.e. γ’ phase, is smaller than that for the austenitic matrix phase. This causes a negative mismatch as can be seen in Figure 1. During homogeneous nucleation of the hardening phase, tensile stresses at the grain boundaries are hence created during the precipitation [12].

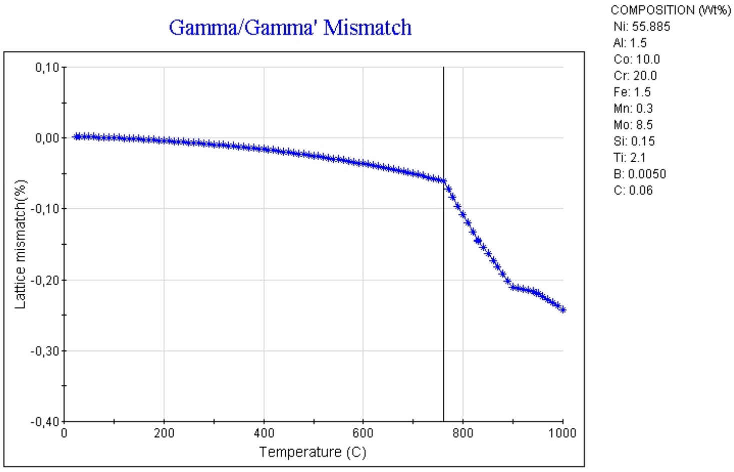

Figure 1. Modelling using JMatPro, showing the mismatch ratio in between γ' and γ phases as a function of temperature in the Ni-base alloy Haynes 282 [2].

It is believed that if the tensile stresses invoked on the grain boundaries during precipitation exceed a criticial level connected to the fracture toughness of the material, then cracking will appear [12]. However, there are different theories describing what actually governs the susceptibility or resistance to SAC which also goes hand in hand with the various approaches to evaluate SAC for different alloys [7]. In addition, hardening of the alloy generally leads to a reduced overall ductility [8]. Loss of ductility may on its own lead to something known as ductility dip cracking (DDC), another type of cracking more commonly encountered in solid solution hardening alloys, where it is thus not related to precipitation hardening. The ductility drop is presumably associated with severe strain concentrations at grain boundary triple associated with grain boundary sliding. Research has indicated the beneficial effects of carbide precipitation (e.g. $M_{23}C_6$ and MC) in resisting grain boundary sliding and decohesion at elevated temperatures. It is believed that precipitation of MC carbides beneficially restrict grain boundary migration, and hence creates tortuous grain boundaries by pinning [9]. However, other factors than those mentioned above may increase the susceptibility to cracking. A relation between content of Al and Ti was proposed by Prager and Shirra, who suggested that a strong influence on the precipitation characteristics of the γ' phase exists [10]. Basically, the higher the content of these hardening elements the more susceptible the alloy will be to cracking, since a higher volume fraction of the y' phase is present [12]. It has also been reported that carbide films at the grain boundaries together with partially liquated grain boundaries increase the susceptibility to cracking [11]. These material specific factors together with the stresses developed during the welding operation add to the severity of the cracking. There have been different attempts to evaluate the susceptibility towards SAC such as multipass repair welding which was carried out in KME 506 as well as Gleeble based methods. The Gleeble based methods usually involve some kind of thermal cycle to accommodate for temperature and stresses relevant to the PWHT. However, there is no test present today which successfully may explain or predict susceptibility towards SAC. One of the major tasks in the continuation project is therefore to develop a testing rationale that accurately predicts susceptibility towards SAC.

Goal

The **continuation project** aims to investigate and clarify the fundamental cause of formation of weld cracking, or more specifically strain age cracking. As basis for this overall aim, the goal is also to establish a test procedure for the assessment of the susceptibility towards strain age cracking of precipitation hardening Ni-based alloys.

Project plan

Approach to research

It is believed that at least two material constituents are of prime concern in relation to SAC in precipitation hardening Ni-based alloys; **the hardening phases**, especially the γ' phase, and the **carbides** (both primary and secondary carbides). In addition to these two groups of phase constituents, the boundary conditions posed on the material during e.g. welding and/or heat treatment is crucially important wherein specifically the **restraint** condition, **heating rate** and **residual stresses** are believed to be important.

Material – hardening and carbide phases

The hardening phases (i.e. γ' phase) do primarily precipitate intragranularly whereas the carbide phases primarily precipitate intergranular [12]. However, both types of precipitates are governed by equilibrium and non-equilibrium precipitation mechanisms and may therefore be influenced by the solution heat treatment in terms of volume fraction, size and morphology. The solution heat treatment is normally performed both prior as well as after welding. There are also other effects apart from the hardening and carbide phases that can be involved during this type of treatment depending on the time and temperature. These effects do in general relate to:

- Role of grain size
- Secondary phase precipitation (i.e. δ phase)

The effect of these parameters as well as the hardening phases and carbides on SAC will be included in the planned research.

Boundary conditions – heat treatment and welding

As briefly explained above, outer boundary conditions, as governed by the specific processes, do as well as concomitant with the material specific properties presumably influence the sensitivity towards SAC. A general claim is for instance that the residual stresses pose an important role [13]. The idea here is that higher degree of residual stresses will weaken the material. The same goes for the restraint condition, that is, more restraint induce a higher probability towards SAC. However, it is sometimes necessary to highly restrain a component to avoid distortion during cooling from a soak temperature at e.g. a solution heat treatment. It would then be useful to know what level of restraint it is possible to utilize until it becomes a problem from a SAC point of view. The last major concern relates specifically to the welding process, i.e. the liquation of the grain boundaries. Even though SAC do not occur during welding, it is strongly believed that the liquation of grain boundaries that takes during welding highly influence the susceptibility to SAC during the PWHT since a liquated grain boundary presumable reduce the toughness at the grain boundary and consequently puts the material into a worse position. Higher degree of liquation would thus be expected worsen the situation; however, this is still to be verified together with the specific mechanisms through which a material may liquate. The general mechanisms through which superalloy material grain boundaries may liquate are supposed to be as follows:

- A hypothetical superalloy composition (Nb > Cm) with Laves phase reacting with the matrix (γ + Laves → Liquid) [1, 7].
- Melting of a hypothetical superalloy composition (CNb > Cm) with eutectic microstructure constituent (γ + (γ + Laves) → Liquid) [1].
- Constitutional liquation of secondary phases such as Ni2Nb (Laves) and NbC or NbC phases in cast and wrought Alloy 718, respectively.
- Melting of residual eutectic in cast material [1, 7].
- Segregation induced liquation by grain boundary sweeping mechanism leading to accumulation of solutes like B and S at the migrated grain boundaries [1, 13].

To what extent any of these mechanisms is of most importance remains to be settled. Hence, the investigation of them will be an integrated part of the project to depict the underlying mechanisms and causes for increased or decreased susceptibility towards SAC in NI-base alloys.

Experimental Techniques

Dedicated thermo-mechanical simulations will be performed to simulate and investigate the nature of strain age cracking. These simulations will later on be validated through dedicated welding and heat treatment operations as performed by professional welders at the industry. The methods used to fundamentally investigate the mechanisms for SAC will be as follows:

1. Differential scanning calorimetric analysis.
2. Multipass layer repair welding.
3. Gleeble thermo-mechanical simulation based techniques or similar.

Detailed microstructural analyses will be performed on the material tested in different experimental set-ups. The use of microscopy and spectroscopy techniques included s as follows:

1. Optical microscopy (OM)
2. Scanning electron microscopy (secondary and backscatter imaging modes) (SEM)
3. X-ray energy dispersive spectroscopy (EDS) (XEDS)
4. Transmission electron microscopy (TEM)
5. Auger nanoprobe analysis (Auger)

The techniques will complement one another. The OM will give overview characterization of microstructures, SEM/XEDS will provide specifc information about the distribution of phases, precipitaties and their composition. When needed more specific information about precipitates will be depecited from TEM characterization. Auger will be used primarily as nanoprobe technique to complement SEM/XEDS ands also to analyse surfaces fractured specimens (when cracking occurs it is then possible to analyse at around the cracks to find out more about local chemistry).

JMatPro (developed by Sente Sodtware, UK) material modelling will also be an integrated part of the toolbox to fully gain a fundamental understanding about SAC. (Chalmers has a full license for JMatPro, which enables basically complete modelling of transformation kinetics, physical properties and mechanical properties for most metallic material including any Ni-base superalloy).

Material

Ni-based superalloys such as Alloy 718, ATI 718Plus, and Haynes 282 will be included in the project. The material will be provided by GKN Aerospace Sweden AB.

Project Deliverables

The project time schedule and its deliverables (milestones and keystones) are specified in Table 1. The project duration is 42 months with start Q4 2014 and end Q1 2018. The milestones and keystones are summarized below.

1. Detailed project description lining out all the tests and microstructure analyses that are to be carried out. (M1: 3 months)
2. PhD student employed at Chalmers within the project (K1: <3 months)
    a. Licentiate engineering degree after ~2 years of study (M2: 24 months)
        i. The licentiate thesis report will be based on at least 3 articles as published in reviewed conference proceedings or journals
    b. Doctoral degree after ~4 years of study (M3: 48 months, 6 months after project end)
3. The doctoral thesis report will be based on at least 6 articles as published in reviewed conference proceedings or journals
4. A final report will be provided upon completion of this project (M4: 42 months), which will contain the following information:
    a. The various factors that influence susceptibility towards SAC
    b. How these factor can be influenced
    c. How SAC can be prevented
5. Economic statement on in-kind contribution from GKN will be delivered every year (M5: 12 months, M6: 24 months, M7: 36 months and M8: 42 months)

Time schedule

The time scheduling as well as the major project deliverables are specified in Table 1. Estimated project start is 1 Sep., 2014.

Table 1.Project time schedule and deliverables

Activity	Type of deliverable (Milestone/ Keystone)	2014				2015				2016				2017				2018			
Project start	K				■																
Hiring PhD student	K				■																
Detailed project description	M				■																
Literature review, SAC	K				■	■	■														
PhD courses					■	■	■	■	■	■	■	■	■	■	■	■	■	■			
Licentiate thesis report	M											■									
PhD thesis report	M																			■	■
Final report to KME	M																	■			
In-kind economic statement from GKN	M							■				■				■		■			
Project finished																		■			

Staff

The staff funded by the project together with the staff related to industry are specified in the table below.

Table 2. Staff that are funded by KME-funds or GKN in-kind contribution in relation to the project.

Name	Affiliation	Allocation (%)	Role in project	Funding
To be decided	Chalmers University of Technology	90	PhD student	KME
Joel Andersson	Chalmers University of Technology/GKN Aerospace Sweden AB	12,5 (25)	Main supervisor	KME, (GKN In-kind)
Lars Nyborg	Chalmers University of Technology	5	Project leader and assistant supervisor	KME
Bengt Pettersson	GKN Aerospace Sweden AB	25	Materials expert	GKN In-kind
Johan Ockborn	GKN Aerospace Sweden AB	25	Welding Expert	GKN In-kind
Erik Zackrisson	SIEMENS	-	Reference group member	Not applicable

Industrial reference and financing

GKN Aerospace Sweden AB confirms that 60 % will be financed as in-kind contribution. In total, the in-kind contribution will be 7 500 000 SEK/4 years.

Costs

The costs associated to the SEA-support are specified in Table 3.

Table 3. Project costs for SEA-support at Chalmers (kSEK)

Costs	**2014**	**2015**	**2016**	**2017**	**2018**	**Total sum**
Salary costs	167	670	680	695	175	2387
External services	5	10	10	10	5	40
Equipment	60	200	200	200	100	760*
Material	5	25	25	25	10	90
Laboratory costs	10	40	40	40	20	150
Travel	20	50	50	50	20	190
Other costs	0	0	0	0	0	0
Indirect cost	97	388	394	403	101	1383
Total sum applied funding	364	1383	1399	1423	431	5000

*Investments in PTC, Gleeble, etc, owned by Chalmers. Running costs and rent covered by University West and GKN (Project will NOT pay running costs for this dedicated equipment), incl. computer (10kSEK) for 2014.

Table 4: Project costs for in-kind costs at GKN Aerospace Sweden (kSEK)

Costs	2014	2015	2016	2017	2018	Total sum
Salary costs	510	2065	2065	2065	530	7235
Material	5	25	25	25	5	85
Travel	25	50	50	50	5	170
Total in-kind	540	2140	2140	2140	540	7500

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