KME

2015-03-02

Project proposal to KME

Title

Development of weldability assessment and understanding of hot cracking in boiler and gas turbine materials
Utveckling av svetsbarhetsmetodik och förståelse för varmsprickor i pann- och gasturbinmaterial

Applying organisation

Chalmers University of Technology
Department of Materials and Manufacturing Technology
Organisation number: 556479-5598

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Co-applicants

GKN Aerospace Sweden AB

Project

New project

Summary

Swedish

Det finns ett stort antal olika typer av svetsar i de svenska värmekraftverken och gas turbiner vilket medför en komplexitet i form av exempelvis svetsat material som spricker både vid nytillverkning och under drift vilket i sin tur medför ökade tillverknings- underhålls-kostnader. Det föreslagna projektet kommer att bidra till ökad förståelse för uppkomst gällande specifikt varmsprickor, dvs sprickbildning under svetsning, och utveckling av metodik för att kvantifiera dessa. Projektet kommer även att bidra till att generera svetsbarhetsdata för material som är aktuella i värmekraftveken och gasturbinerna samt ge rekommendationer till hur man kan eventuellt förbättra svetsbarheten för de aktuella materialen.

English

There are a large number of welds in the Swedish bolier plants and gas turbines which add complexity to the situation in terms of e.g. welded materials that may encounter cracking both during manufacturing and at service which as a consequence increases the manufacturing and maintenance costs. The proposed project will contribute to increased understanding of hot cracking in particular, that is cracking which occur during welding, and development of testing methods to quantify them. The project will also contribute with weldability test data for materials which are relevant to the bolier plants and gas turbines as well as to provide recommendations in how to improve the weldability for these materials.

Motivation

Problem area

There are numerous of welds in boiler systems and gas turbines. Also, as steam and gas temperatures are increased, it will affect the materials used in the boiler plants and turbines. Some materials will no longer be able to withstand the higher temperature which in turn introduces new type of materials with limited knowledge regarding its weldability or resistance towards cracking during welding. The procedure in which weldability is being determined is for many reasons not always an easy target. There are many parameters which come to play when assessing a material's resistance to cracking where material chemistry, condition (e.g. cast or wrought, grain size etc), and welding parameters are important just to mention a few. The proposed project is two-fold in its content and specifically aims to investigate the weldability of materials that are of interest both to the boiler (superheater and reheater tubes) and gas turbine (turbine casings) manufacturers, secondly to develop further understanding and capability to perform the actual weldability assessment. Examples of materials that are to be included in the investigation are austenitic steels and superalloys; HR3C, TP 347 HFG, Alloy 718 and Haynes 282 [1,2]. The material selections for this project have been discussed with Amec Foster Wheeler and GKN Aerospace (GKN) who both participate in the project reference group. The actual weldability assessment will be carried out using a specially designed and state-of-the-art Varestraint weldability testing machine as well as Gleeble testing machine. This specific project (designated as KME 719) is different compared to the currently ongoing KME 706 in the following aspects:

1. KME 719 focuses on hot cracking (cracking which occurs during welding), not strain age cracking (cracking which occurs during heat treatment and/or repair) as is the case of KME 706.
2. KME 719 has a wider selection of materials included which includes relevance for both the boiler industry as well as the gas turbine industry, compared to KME706 which only include gas turbine materials.
3. KME 719 is a generic project which includes development of methods needed to quantify susceptibility towards hot cracking as well as development of theories used for explaining their existence.

Energy relevance

The project will support the programme goals of 2, 4, and 9 [3] by providing weldability data and know-how in materials as well as weldability testing that:

- will be useful in material selection for existing and new boiler systems (high temperature boiler applications specifically relevant to tubes). Specific applications of focus in the boiler systems are superheater and reheater tubes.
- will be used to predict weldability, specifically hot cracking in boiler plant (superheater and reheater tubes) and gas turbine applications (turbine casings).
- will be used as guidelines in selecting welding parameters for manufacturing as well as for repair to improve the processability. The specific welding recommendations in boiler plants includes tube to tube butt welding, and tube to plate weld for tube attachment and support welds.

Industrial relevance

The project will provide valuable weldability data and know-how for weldability of steam boiler and gas turbine materials which will be readily available and shared within the boiler and gas turbine industry.

News value with the project

The generic and fundamental hot cracking weldability data on the previously mentioned austenitic steels used in the boiler industry is very limited which is one of the major outcomes expected in the project. Another outcome is increased understanding of the actual weldability assessment which in specific will deal with e.g. the influence on strain rate at Varestraint weldability testing and its influence on hot cracking. The influence on strain rate on susceptibility towards hot cracking is not fully understood and is believed to be of significant importance when quantifying the weldability. Existing hot cracking data on superalloys, generated in previous KME project 506, will be used to compare with a new modified testing approach to investigate the influence of e.g. strain rate. Gleeble testing will also be used in developing the new testing approach.

Implementation of results

The results which will be generated in the project will be discussed in depth and shared with the reference group. The aim is to develop results as generic, which is fundamental testing (no specific application), as possible which then will serve as many applications and situations as possible.

Implementation of project

A state-of-the-art Varestraint weldability testing machine was developed within an earlier KME project [2] and is now available in the project. An upgrade will be made on this machine which enables measurements of the stroke rate that can be used to calculate the strain rate at testing. The project will also support the acquisition of a Gleeble machine which will be used as a complement to the Varestraint machine in order to quantify the susceptibility towards hot cracking. There is also, apart from weldability testing capabilities and know-how, state-of-the-art equipment available for microstructure characterization. A decision on what analytical tool to use will be based on the project outcome.

Background

Problem area

The reasoning and review of theories on hot cracking that now follow is relevant for most austenitic steels and superalloys which are of interest to the project. Hot cracking relates to cracking phenomena that occurs during welding and is associated with the presence of liquid in the microstructure, more specifically liquid films present along the grain boundaries in the fusion zone (FZ) and in the partially melted zone (PMZ) in the heat affected zone (HAZ). These liquid films usually persist to a temperature much below the equilibrium solidus temperature, as such extending the solidification interval of the alloy. To what extent the solidification interval increases is highly dependent on the solute and impurity segregation [4]. There are primarily two types of cracks which belong to the group named hot cracks; solidification cracks and HAZ liquation cracks. There are several theories for hot cracking which have been developed throughout the years. Most of these theories emanates from the casting field and more specifically theories on hot tearing during casting. In general there are two original theories on solidification cracking.

First, in the early 1950s Pellini proposed the strain theory [5] relating to the formation of a continuous liquid film which separates the solidifying metal. The strength and ductility of these solid grains separated by a continuous liquid film is very low and was accepted as the “Film stage” [5-6]. As thermal contraction and shrinkage stresses increase appreciably near the solidus temperature, this film stage causes intergranular rupture. The time, temperature and the ability of the liquid phase to spread along the grain boundaries to form a semi or continuous liquid film affect the susceptibility to liquation cracking.

The shrinkage-brittleness theory on the other hand recognizes the inability of the newly formed dendrites to accommodate strain [6]. Pellini ("Film stage") on the contrary proposed that the stresses that are formed in the mushy zone are uniformly distributed and postulated that cracking cannot occur at this stage. However, in the shrinkage-brittleness theory it is suggested that the temperature range at which cracking occurs is between the solidus and the coherency temperature which is the temperature at which the dendrites meet for the first time. If a certain critical strain is exceeded within this temperature range, recognized as the brittle temperature range (BTR) and if no liquid phase is present to heal, a hot tear would appear [6]. The BTR is highly dependent on alloy composition which means that alloys possessing a wider solidification range are more prone to solidification cracking.

Later Borland proposed a new generalized theory based and modified on some of the previous theories [7]. He divided the solidification sequence at welding into four different stages:

- Primary dendrite formation, where movement of both solid and liquid phases is significant.
- Dendrite interlocking (coherency temperature), involves the development of continuous formation of both solid and liquid phases. However, it is only the liquid which is able to move freely between the interlocking dendrites.
- Grain boundary development (the critical temperature), where the semi-continuous network of dendrites restricts free movement of the liquid phase.
- Solidification, where the final liquid phase solidifies.

According to Borland a crack can possibly appear as temperature drops below the coherency temperature and is more specifically related to the so called "critical solidification range" (CSR) which belongs to "the critical temperature" where the interlocking mechanism of dendrites restrict liquid phase movements, hence, relative movement and healing is hindered. The susceptibility to liquation cracking is enhanced as the CSR is increased. Further, Borland emphasize the importance of the relationship between the ratio of the interphase (solid/liquid) boundary tension (γ_{SL}) and grain boundary tension (γ_{SS}) to the dihedral angle (distribution of liquid phase on grain corners, edges and faces). When the dihedral angle is 0° it ($\gamma_{SL}/\gamma_{SS} = 0.5$) means that the liquid phase completely penetrates the existing grain boundaries leading to complete de-cohesion between the adjacent grains. However, the stresses are very low which leads to low cracking susceptibility. As the dihedral angle is increased the liquid phase will progressively occupy less of the grain faces and at an angle of 60° it will only exist as continuous network along grain edges. At even higher angles the liquid phase will be more and more limited to grain corners. Dihedral angles slightly above 0° will lead to small bridges of the dendrites, hence, building up high stresses which lead to high susceptibility to cracking. At higher dihedral angles more bridging will take place and reduce the susceptibility to cracking [7].

There are many other hot tearing theories proposed in addition to the ones previously presented [8-12]. The metallurgical factors which have been known to affect the solidification cracking susceptibility can nevertheless be summarized in the following way [13]:

- The solidification temperature range.
- The amount and distribution of liquid at the final stage of solidification.
- The primary solidification mode.

- The surface tension of the grain boundary liquid.
- The grain structure.

Segregation is of prime concern and it is due to the inevitable partitioning of the many chemical elements involved in complex alloy systems. How extensive the segregation becomes is dependent on the so called partitioning coefficient k, defined as the ratio of the concentration of the solute in the solid to that of the liquid in equilibrium [9]. Solidification cracking of austenitic materials is strongly dependent on the solidification temperature range and in particular the solidification events at the grain boundaries and interdendritic regions which in turn is strongly influenced by the segregation [10-12].

HAZ liquation cracking on the other hand occurs intergranular along the grain boundaries in the PMZ in the HAZ. They normally form during the cooling sequence of the weld thermal cycle, above the effective solidus temperature and relates to liquation of the grain boundaries during the heating part of the weld thermal cycle. In general there are two proposed mechanisms for the onset of liquation; penetration mechanism and segregation mechanism. The penetration mechanism requires both a liquation phenomenon and a grain boundary motion. Segregation mechanism involves enrichment of some solute and/or impurity element along the grain boundaries which significantly may decrease the melting temperature relative to the surrounding material and as a consequence melt prior to the matrix phase. There are many theories which derive from these two main mechanisms previously mentioned [13-34].

State of the art

There are doubts regarding the currently existing theories which rely on the critical coherency temperature, originally developed by Borland, and also some of the mechanically induced mechanisms. The project will therefore aim to further develop some of the already existing theories which are based on e.g. Pellini et al or in fact develop new theories which aid in explaining the underlying mechanism of hot cracking which more solely rely on a coupled approach in between the “liquid film” approach and the technological strength theories relying on minimum ductility required for fracture. This approach is believed to be excellent when combining the capabilities of the Varestraint and Gleeble weldability tests. As such, a substantial part of the project will be focused on developing a suitable testing approach for hot cracking using the two aforementioned weldability tests. This development work will for instance be related to the affect of strain rate on hot cracking sensitivity, something which has briefly been touched upon before in other studies within KME 406/506 [35-36].

Description of problem

Since the boiler plants contain thousands of welds it goes without saying that weld cracking is a serious concern since it endangers component life and in turn cost large amounts of money if the weldability is not adequate enough. It is also so, that with increasing demand for more efficient boiler systems (e.g. higher steam temp. and pressure), more advanced materials will be needed which in fact increases the weldability concern. At alloy development it is always a “fight” in between weldability and strength; when one of these properties is increased it is done on the expense of the other one which goes hand in hand with the increasing demands and in turn material concerns in the Swedish boiler systems. Another aspect is worn out parts which have been under the scope in several studies funded by Värmeforsk [38-42]. However, what is lacking in these studies is fundamental and generic understanding of how to assess the weldability or specifically the repair weldability which the current project is expected to shed some light on.

Challenges and opportunities

Today, there is no hot cracking theory which fully explains the reason for its occurrence. Also, there is no weldability hot cracking test and testing rationale available with full confidence despite the numerous amounts of different weldability tests which are available. In former KME projects (KME 406 & 506/518) it was investigated how various process parameters affected the cracking response and reliability of the outcome of the Varestraint test [36, 43]. It was also investigated how the deformation zone during testing affect the cracking response [37]. These investigations led to important findings, both in terms of reliability aspects of the actual testing methods (Varestraint and Gleeble) as well as on the importance of test specimen geometry. These findings will now serve as input to the present project which will take some steps further in understanding of hot cracking mechanisms (solidification and HAZ liq. - cracking). The present project will be focusing more on the actual loading situation during Varestraint and Gleeble testing and attempt to couple it with a unified theory on hot cracking for suitable boiler materials. This will lead to increased capability and understanding of weldability testing (Varestraint and Gleeble) as well as underlying mechanisms of hot cracking.

Goal

The overall goal of the project is to increase the overall understanding of hot cracking mechanisms as well as to develop weldability testing capability towards hot cracking in a reliable way. At the end of project, we expect to have a testing methodology both from theoretical and practical point of view that can be used as generic means of assessing weldability of high temperature materials.

Academic goals

The academic goals are the following:

1. To accomplish a licentiate engineer
2. To develop a unified theory for hot cracking
3. To develop a testing rationale for hot cracking

Industrial goals

The industrial goals are the following:

1. To generate weldability test data on materials relevant to the boiler industry
2. To recommend materials and parameters for improved weldability
3. To establish a testing methodology that can be used for assessing weldability with respect to hot cracking susceptibility

Project plan

Description of project

The project aims to investigate and develop further understanding of hot cracking mechanisms as well as on how to assess the susceptibility towards these weld cracks in a reliable way. The project also aims to recommend and make guidance to boiler plant manufacturers and other relevant industries in terms on how to minimize the type of problems which are associated with hot cracking. These recommendations could aid in design and manufacturing of new plants as well as repair of worn out parts. The applications of interest are superheater, reheater tubes, and gas turbine casings and the materials that will be investigated in the project are: HR3C, TP 347 HFG, Alloy 718 and Haynes 282. HR3C and TP 347 HFG specimen will be excised from tubings to carry out Gleeble testing. The tubings will be provided by Amec Foster Wheeler. Equivalent type of stainless steel might be selected instead of HR3C and TP 347 HFG depending on the availability of sheet material. Hot cracking weldability data will be generated for different heat treatment conditions relevant to the industrial partners (GKN and Amec Foster Wheeler).

Achievements of goals and time plan

The time plan and associated plan for the project achievements can be visualized in table 2 below wherein the milestones are underlined. A PhD student will be hired as early as possible (within 3 months from project start) and will attempt to accomplish a licentiate engineering status by the end of the project. A request for quotation of a Gleeble machine will be made within the project in collaboration with University West which means that the project itself will only cover a rather small but still necessary fraction of the overall cost of such equipment. The installation and acceptance testing of the machine itself will be carried out during 2016. At the project start, an upgrade of the already existing Varestraint weldability testing machine will be performed. This upgrade is necessary to be able to calculate strain rate at testing which is believed to be of great importance and something which will be focused upon in the weldability testing trials. The actual upgrade will be carried out by outsourcing since that type of knowledge is not available in the project consortium. Reference group meetings will take place on a regular basis to meet the expected output from the project. The reference group members are shown in table 1. Dissemination will be carried out through the reference group meetings, KME conferences, international conferences per table 2, journal paper and licentiate report and seminar as well as KME final report. A design of experiment will be performed prior testing to account for later analyses on the impact of various parameters on the hot cracking response. The actual weldability testing and material analyses will be performed in iterative loops throughout the middle part of the project duration. The actual weldability testing will be performed with the purpose to investigate the nature of hot cracking (cracking that occur during welding) and will be carried out using the Varestraint and Gleeble machines for which the actual testing rational is to be determined and validated within the project. The material analyses will consist of simple light optical microscopy and by using scanning electron microscopy with associated X-ray detectors. The department of Materials and Manufacturing at CTH is well equipped, advanced Auger spectroscopy and differential scanning calorimetric thermal analysis equipments are also available depending on what turn the project will make.

Project organisation

The project organisation can be viewed in table 1. A PhD student will be allocated to 80% and will be supervised by Dr. Joel Andersson and Prof. Lars Nyborg. Mr. Johan Ockborn and Mr. Jan Häggander at GKN Aerospace both have extensive experience on welding and associated concerns of a wide range of materials including stainless steels, aluminium alloys and superalloys. Mr. Ockborn and Häggander will participate in the project organisation and reference group meetings to provide valuable input to the project. Amec Foster Wheeler, Sandvik Materials Technology, DONG Energy and Swerea KIMAB also participate in the reference group and will provide valuable input and guidance in relation to the boiler system materials and related processing challenges.

Table 1. Project organisation that includes CTH, GKN, Amec Foster Wheeler, Sandvik Materials Technology, DONG Energy and Swerea KIMAB reference group partners.

Name	Affiliation	Allocation (%)
PhD student	Chalmers University of Technology	80
Joel Andersson	Chalmers University of Technology/GKN Aerospace Sweden AB	10/20
Lars Nyborg	Chalmers University of Technology	5
Johan Ockborn	GKN Aerospace Sweden AB	40
Jan Häggander	GKN Aerospace Sweden AB	40
Edgardo Coda Zabetta	Amec Foster Wheeler	N/A
Jouni Mahanen	Amec Foster Wheeler	N/A
Dilip Chandrasekaran	Sandvik Materials Technology	N/A
Rikard Norling	Swerea KIMAB	N/A
Hans Poulsen	DONG Energy	N/A

Time schedule

The project intends to start by summer 2015 and end by spring 2018, table 2. The total project period is maximum 3 years. The project will be divided in two stages with first stage ending by end of 2016 and second stage run until project end. The major milestones are summarized below.

Table 2. Time plan for the project

Activity	2015		2016				2017				2018	
Project start	■											
Reference group meeting		■			■				■			■
Hiring a PhD student	■											
Detailed project description	■											
Request for quotation, Gleeble machine	■	■										
Installation Gleeble machine			■	■	■							
Upgrade of the Varestraint testing maching	■	■										
Literature review on hot cracking and weldability testing	■	■	■									
Formulation of hypothesis on hot cracking			■	■								
Design of experiments for weldability testing				■								
Selection and aquisition of material				■								
Weldability testing					■	■		■	■			
Material analyses						■	■		■	■		
Conferences					■				■			
Paper 1 (conference paper)					■							
Paper 2 (conference paper)									■			
Paper 3 (journal paper)										■		
PhD courses		■	■			■	■			■		
Licentiate thesis report											■	
Final report to KME												■
Project finished												■

Milestones and deliverables (reports refer to technical reports including scientific papers contents)
M1 (18m):Initial theoretical framework for hot cracking established (report)
M2 (18m):Initial combined testing approach for weldability settled (equipment and report)
M3 (18m):Initial post-testing materials characterisation for selected alloys (report)
M4 (36m):Final theoretical framework for hot cracking established (report)
M4 (36m):Final combined testing approach demonstrated for selected alloys (report/data)
M5 (36m):Final post-testing materials characterisation for selected alloys (report)
M6 (36m):Final theoretical framework for hot cracking established (report)

Industrial reference and financing

Funding to Chalmers from the SEA will be 3 500 000/4 years, table 3. GKN Aerospace Sweden AB confirms that 60 % will be financed as in-kind contribution. In total, the in-kind contribution will be 5 600 000 SEK/4 years, see table 4.

Costs

The project funding and associated costs are shown in table 3. The topic named “consultants” in table 3 includes the cost to upgrade the Varestraint weldability testing machine whereas the equipment cost includes part of the overall project cost (440 ksek) to acquire a Gleeble machine. This sum refers to less than 10% of the needed financing. The in-kind contribution from GKN can be seen in table 4. The overall project budget is shown in table 5.

Table 3. The project funding, in ksek, as distributed to the respective topic.

Chalmers	**2015**	**2016**	**2017**	**2018**	**Sum**
Salaries	289	551	562	287	1689
Consultants	120	0	0	0	120
Equipment	70	150	150	70	440
Material incl. IT	15	30	31	15	91
Laboratory costs	20	40	40	20	120
Travel	10	40	40	10	100
Other costs	0	0	0	0	0
Indirect costs (university OH)	161	307	313	159	940
Sum	**685**	**1118**	**1136**	**561**	**3500**

Table 4. In-kind contribution per year from GKN Aerospace Sweden AB.

Project total cost	**2015**	**2016**	**2017**	**2018**	**Sum**
Salaries	686	1372	1372	1372	4802
Equipment	130	190	190	130	640
Material	10	20	20	10	60
Laboratory costs	10	20	20	10	60
Travel	10	10	10	10	40
Other costs	0	0	0	0	0
Sum	**846**	**1612**	**1612**	**1532**	**5602**

Table 5. Project budget.

Project budget	**2015**	**2016**	**2017**	**2018**	**Sum**
Salaries	975	1923	1934	1659	6491
Consultants	120	0	0	0	120
Equipment	200	340	340	200	1080
Material	25	50	51	25	151
Laboratory costs	30	60	60	30	180
Travel	20	50	50	20	140
Other costs	0	0	0	0	0
Indirect costs (university OH)	161	307	313	159	940
Sum	**1531**	**2730**	**2748**	**2093**	**9102**

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