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KME-506/518

Weldability limits for superalloys

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Preface

The project has been performed within the framework the fifth stage of the material technology research programme KME.

KME, Consortium Materials technology for demonstration and development of thermal Energy processes, was established 1997 on the initiative of the Swedish Energy Agency. In the consortium, the Swedish Energy Agency, seven industrial companies and 18 energy companies participate. The programme stage has been financed with 60.2 % by participating industrial companies and with 39.8 % by Swedish Energy Agency. The consortium is managed by Elforsk.

The programme shall contribute to increasing knowledge to forward the development of thermal energy processes for various energy applications through improved expertise, refined methods and new tools. The programme shall through material technology and process technology developments contribute to making electricity production using thermal processes with renewable fuel more effective. This is achieved by

- Forward the industrial development of thermal processes through strengthen collaboration between industry, academy and institutes.
- Build new knowledge and strengthen existing knowledge base at academy and institutes
- Coordinate ongoing activities within academy, institutes and industry

KME's activities are characterised by long term industry relevant research and constitutes an important part of the effort to promote the development of new energy technology with the aim to create an economic, environmentally friendly and sustainable energy system.

Abstract

The aim has been to the establish knowledge platform for assessment of weldability of Ni-based superalloys. This aim has been limited to a number of selected the objectives, namely: to develop a testing rationale that can be used to assess the overall weldability in a reliable way; to develop a reliable testing method (the Varestraint method) to assess susceptibility towards hot cracking; the develop a testing rationale to assess the susceptibility towards strain age cracking.

In short, the results show that different types of cracking and associated mechanisms may be active and interact at the same time and that the weldability concept needs to be evaluated in relation to specific welding processes concept since the cracking mechanisms may alter between these processes. Hence, a systematic integrated procedure is suggested to assess weldability in a consistent and cost effective way.

When considering different alloys it is then found that hot cracking susceptibility of Haynes[®] 282[®] is less than that of ATI 718Plus[®] and that ATI 718Plus[®] liquates through constitutional liquation involving carbide phase. Hence, a hypothesis regarding liquation eutectic transformation of similar kind n Haynes[®] 282[®] is possible. Insight regarding transformation characteristics of strengthening phases and the functions of different elements has also been obtained using JMatPro and DTA/DSC.

Sammanfattning

Målet har varit att etablera en kunskapsplattform när det gäller utvärdering av svetsbarhet hos superlegeringar på nickelbas. Detta mål har begränsats till insatser kopplat till följande utmaningar: etablering av ett testprotokoll/tesprocedur som kan användas för robust utvärdering av svetsbarhet; framtagning av en testmetod (Varestraintmetoden) som kan användas för att bedöma känsligheten för varmsprickning vid svetsning, etablering av metodik för bedömning av känsligheten för sprickbildning på grund av deformationsåldring.

Projekten (KME506 och KME518) har genomförts i samarbete mellan Chalmers tekniska högskola och GKN Aerospace Sweden AB, men också inneburit omfattande internationell samverkan med speciellt Universitet i Manitoba, Kanada. Majoriteten av arbetet har gjorts inom KME506. Det senare avsevärt mindre projektet (KME18) har speciellt adresserat delar av internationaliseringen. Referensgruppen har innefattat representanter från projektpartnern och en extern representant från Siemens Industrial Turbomachinery, Finland. Den nämnda Varestraintmetoden har möjliggjorts genom utrustning som har designat och byggts inom projektet KME 506. Genom Gleebleprovning (vid universitet i Manitoba), termisk analys (DSC/DTA), termodynamisk modellering och kinetikmodellering (JMatPro) samt elektronmikroskopi, har svetsbarheten för olika superlegeringar kartlagts och jämförts. Resultaten att olika typer av sprickbildning och mekanismer bakom sprickbildningen är aktiva parallellt och interagerar med varandra. Vidare gäller att svetsbarhetskoncept måste utvärderas kopplat till aktuella svetsoperationer eftersom mekanismerna för sprickbildningen kan ändras beroende på process. En systematisk och integrerad tesprocedur är därför nödvändig för att konsistent och kostnadseffektivt kunna utvärdera svetsbarheten hos olika superlegeringar.

Vid jämförelse av svetsbarheten hos olika legeringar visar studierna att känsligheten för varmsprickning är större hos Haynes 282 jämfört med den hos 718Plus samt att smältsprickor för 718Plus uppträder via så kallad konstitutionell smältfasbildning med karbidfas. En hypotes för Haynes 282 är då att liknande mekanism kan vara möjlig med annan karbidfas. Kunskap kring fastransformationer och kinetiken när det gäller utskiljningsförlopp med inverkan av olika legeringselement har utvecklats genom JMaPro-beräkningar och termisk analys (DTA/DSC).

Måluppfyllelsen bedöms som mycket god när det gäller det övergripande målet att påvisa specifika kombinationer av superlegeringar, svetsmetoder och värmebehandling som ökar potentialen för optimerade fabricerade strukturer till gasturbiner. Här ingår ett antal konkreta mätbara resultat som uppnåtts enligt följande: design och konstruktion av ny testanläggning (Varestraintmetoden), svetsbarhetsutvärdering för ett antal viktiga superlegeringar, genomförande av över 20 examensarbeten kopplat till projektet, produktion/publicering av 19 vetenskapliga artiklar, etablering av internationellt nätverk med ledande forskare i Kanada och Finland samt realisering av projekt in Clean Sky.

Nyckelord: svetsning, superlegeringar, testmetoder, svetsbarhet, sprickkriterier

Summary

The aim has been to establish a knowledge platform for assessment of weldability of Ni-based superalloys. This aim has been limited to a number of selected objectives, namely: to develop a testing rationale that can be used to assess the overall weldability in a reliable way; to develop a reliable testing method (the Varestraint method) to assess susceptibility towards hot cracking; to develop a testing rationale to assess the susceptibility towards strain age cracking.

The projects (KME 506 and KME 518) have been based on cooperation between Chalmers University of Technology and GKN Aerospace Sweden AB, but also led to extensive international co-operation with in particular University of Manitoba, Canada. Major work has been done within KME506. The latter much smaller project (KME518) has in particular been connected to internationalisation activities. The reference group has included local participants and an external member at Siemens. The so-called Varestraint testing method has been facilitated and equipment for this has been built and developed. By also using Gleeble testing (Univ. Manitoba), thermodynamics and kinetics modelling (JMatPro), thermal analysis (DTA/DSC) and electron microscopic studies, an extensive assessment of the weldability of a number of important superalloys has then been realised.

In short, the results show that different types of cracking and associated mechanisms may be active and interact at the same time and that the weldability concept needs to be evaluated in relation to specific welding processes since the cracking mechanisms may alter between these processes. Hence, a systematic integrated procedure is suggested to assess weldability in a consistent and cost effective way.

When considering different alloys it is then found that hot cracking susceptibility of Haynes[®] 282[®] is less than that of ATI 718Plus[®] and that ATI 718Plus[®] liquates through constitutional liquation of NbC. Hence, a hypothesis regarding liquation of MoC through eutectic transformation of Ni-Mo or Ni-Mo-S in Haynes[®] 282[®] is possible. Here, insight regarding transformation characteristics of strengthening phases and the functions of different elements has been obtained using JMatPro and DTA/DSC.

The goal fulfilment is considered to be more than complete with respect to the overall goal of finding specific superalloy combinations, welding methods and appropriate heat treatment schedules to increase the potential for hot gas turbine structures applications, including measurable achievements as follows: The design and building of a Varestraint testing machine; the development of a new testing approach for strain age cracking; the weldability assessment of different superalloys; the completion of more than 20 diploma thesis studies, the submission/publication of 19 papers; the establishment of an international network with leading scientists in Canada and Finland. Also, in addition a sub-project within the Clean Sky programme has been granted and run as a result.

Keywords: welding, nickel-base superalloys, testing methods, hot cracking, strain age cracking

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1 Introduction

1.1 Background

Components subject to the highest temperatures in energy systems are key elements for achieving efficient thermal processes. With the increasing temperatures, high performance superalloys must be used. Due to their specific nature their use is from technical point very demanding. From a cost and performance optimization point view it is often of interest to be able to join different superalloys together or to create components and structures using mainly one kind of superalloy. For this reason mastering of weldability is a crucially important aspect. Also, welding, in terms of repair welding, is an important means for maintaining long lifetime of components. Understanding the limits of welding of superalloys contributes to the implementation of cost-effective and reliable solutions when using these alloys in various applications. The primary focus of the proposed project relates to structural parts in gas turbines. However, the expected results have a wider perspective since all efficient energy power plants today faces the limits posed by traditional high temperature 12% chromium steels and with superalloys already being utilized. Through the project increased knowledge regarding the microstructural stability and performance of superalloys is gained. This is expected to be of general importance for a broad range of high temperature applications. In particular it is envisaged that the project will thereby contribute to the specific goals of the KME programme as follows:

- The goal of enabling the use of new materials – new superalloys as well as the combination of superalloys by means of welding are issues directly linked to this goal.
- The goal of relating the materials research in the KME programme to the strive for increasing the efficiency of gas turbines – the results of the projects are expected to facilitate the long term implementation of improved engineering solutions.
- Knowledge regarding processing of superalloys with respect to welding that can facilitate the use of superalloys in power plants.
- Knowledge development regarding melt processing of superalloys also of importance for other processes as thermal spraying of coatings.
- The strengthening of industrial-academic network with strong international connections (Finland, USA, and Canada) involving shared post-doc and PhD student.

1.2 Description of the research field

The research field has mainly covered precipitation hardening Ni-based superalloys (Alloy 718, Waspaloy, ATI® 718Plus™ and Haynes® 282®) which

have been examined from a metallurgical standpoint. Also, a thorough investigation and development of weldability testing methods, primarily Varestraint and Gleeble testing, have been carried out. Part of the research is described in the PhD-thesis produced within this project [1] as well as in the different articles generated throughout the project [2-19].

1.3 Research task (KME 506/518)

In the KME's program description for the period of 2010-2013 it is stated that: "The overall goal is to find specific superalloy combinations, welding methods and appropriate heat treatment schedules to increase the potential for hot gas turbine structures applications". The purpose of this research is to improve the knowledge about metallurgy, weld cracking and weldability testing of primarily Ni-based superalloys. However, the knowledge generated regarding weldability testing is applicable to other alloy systems as well.

Gas turbine applications needs profound understanding of the weld processes involved including basic metallurgy and reliable test methods to support reliable modeling of the weld application. The first task was to investigate, evaluate and also improve the Varestraint testing method. The second stage was to carry out Varestraint welding trials on chosen alternatives and analyze the results from a metallurgical point of view with i.e. DSC/DTA.

1.4 Goal

The aim of this research is to increase the knowledge concerning welding of Ni-based superalloys. This aim has been limited to the following objectives:

1. Develop a testing rationale that can be used to assess the overall weldability in a reliable way.
Goal is largely fulfilled since testing rationale for assessing weldability is developed to be applied in further R&D work.
2. Develop a reliable Varestraint testing method to assess susceptibility towards hot cracking.
Goal is fulfilled. A new machine has been developed and verified. The further development and application in future R&D is foreseen.
3. Develop a testing rationale to assess the susceptibility towards strain age cracking.
Goal is largely fulfilled, but specific actions to further develop the application of e.g. Gleeble testing.

1.5 Project organisation

The projects (KME 506 and KME 518) are based on cooperation in between Chalmers University of Technology and GKN Aerospace Sweden AB. Professor Olarewanju Ojo at University of Manitoba, Canada, has been involved as advisor in both KME 506 as well as KME 518. Professor Ojo has scheduled a research visit to Sweden (as part of KME 518) in the middle of May where he will take part in different workshops. The duration of his visit will be one

week. The reference group has included local participants and an external member, Eric Zakrizon at Siemens.

The total budget contribution from KME to Chalmers is 3,769 kSEK (KME 506) and 58 kSEK (KME 518).

The latter project has been specially used for internationalisation activities and some special thermal analysis.

2 Allocated Resources

The industrial partner of the projects (KME 506 and KME 518) has been GKN Aerospace Sweden AB. The in-kind contribution from GKN is 5,690 KSEK (KME 506) and 95 KSEK (KME 518), respectively.

Table 1. KME 506 project budget (funding to Chalmers and in-kind contribution from GKN)

GKN Aerospace Sweden AB	2010	2011	2012	2013	2014	Total
Labour – Technical staff	477000	403000	275 500	165 000	0	1 320 500
Labour – Senior researcher	811000	818000	860500	990 000	0	3 479 500
Labour – Company project manager	344000	255000	204000	132000	0	935 000
Cash	40 000	40 000	40 000	40 000	0	160 000
Total	1 672 000	1 516 000	1 380 000	1 327 000	0	5 895 000
Chalmers University of Technology						
Salary costs, PhD student	197100	403800	325500	366600	71400	
Salary costs, post-doc 25%	0	74200	155900	128700	13100	
Salary costs, project leader (Lars Nyborg)	45000	45000	45000	90000	15000	
Salary costs (10% researcher/15% research engineer)	0	9200	105800	113000	224500	
Computer costs	0	14600	0	0	0	
Equipment running costs (SEM, Auger, DSC, etc)	20000	25000	40000	40000	20000	
Materials	4000	49900	11800	24900	0	
Travel	56000	31000	4400	24200	1600	
University overhead (35% according to rules)*	112700	228400	240900	275600	115200	
Total	434 800	881 100	929 300	1 063 000	460 800	3 769 000

Table 2. KME 518 project budget (funding to Chalmers and in-kind contribution from GKN)

GKN Aerospace Sweden AB	2013	2014	Total
Labour – Senior researcher	99 000	0	99 000
Labour – Company project manager	12 375	0	12 375
Total	111 375	0	111 375
Chalmers University of Technology			
Costs, invited researcher (Prof. Olanrewaju Ojo)		15000	15000
Salary costs, post-doc 25%	5000	5000	10000
Salary costs, project leader (Lars Nyborg)	0	0	0
Salary costs (10% researcher/15% research engineer)	5000	10000	20000
Equipment running costs	5000	5000	5000
Travel		20000	20000
University overhead (35% according to rules)*	5000	19000	24000
Total	20 000	74 000	94 000

3 Results and Analysis

The results and analysis of the work carried out within KME 506 as well as KME 518 are presented below.

3.1 A proposed testing route to understand the overall weldability of superalloys

Weldability is an arbitrary expression for many reasons but nevertheless frequently used to explain different aspects in welding of different alloys. It is important to define what is meant by this expression to avoid confusion. One definition commonly used is how susceptible a material is to cracking during welding. This definition usually incorporate cracks associated with different types of liquation during welding and they are called hot cracks. Warm cracking, on the other hand, more or less precludes liquation and takes place during post weld heat treatment (PWHT). A third type of cracking is cold cracking which generally is associated with embrittling species like H and S during the service of the component [20, 21]. Weld cracking theories originates back to research on hot tears during casting. The most well-known are the "Strain theory of hot tears" [22] and the "Shrinkage-Brittleness theory" [23] which later were combined into Borland's combined theory known as the "Generalized theory" [24]. There are other theories as well [25-27] were the following material factors are believed to affect the susceptibility to hot cracking [21]:

1. The solidification temperature range.
2. The amount and distribution of liquid at the final stage of solidification.
3. The primary solidification mode.
4. The surface tension of the grain boundary liquid.
5. The grain structure.

There are many "weldability" testing methods where the term "weldability" often refers to the "inherent" resistance to cracking in a material during welding [20]. It should be noted that there is no testing method which can be used to uniquely forecast to the cracking and/or service performance of welds. Each weldability testing method has its own specific character. The different techniques available can be divided into different categories; the representative tests, simulative tests and high temperature mechanical tests [28].

Another concern relates to the fact that none of these methods have been properly standardized and large variations in the actual setup of the testing

are evident although the name of the test is the same. The lack of standardization in actual testing and interpretation of results have lead to misleading results in some cases [29].

It is often difficult to separate what kinds of cracking – HAZ liquation cracking, solidification cracking or SAC – that have occurred in the manufacturing of aerospace components. All these cracking mechanisms may be active at one or several occasions during manufacturing. This can often lead to misunderstandings of the overall weldability of a specific alloy. In the manufacturing shop Waspaloy is e.g. is known by real welders (!) to be the worst alloy to weld in comparison with the other alloys of our concern. However, when performing e.g. Varestraint testing it has been reported that Waspaloy actually possess a better “weldability” in comparison with e.g. Alloy 718 [30]. The reason or logic becomes understandable in a metallurgical perspective when comparing the secondary phases and segregation involved in these alloys. Waspaloy has a narrow solidification interval and less segregation in comparison [1]. When representative type of tests are carried out involving reheating through multi pass repair welding or heat treatment, it will reflect the fast age hardening response in Waspaloy, and consequently induce SAC and make it less weldable in comparison with Alloy 718 [7] This is in agreement with the practical experience of welders who often carry out repair work.

The discrepancy between the actual welding environment in the manufacturing shop and the results from the different single weldability testing methods emphasizes the importance to incorporate several tests and analyze the results in concert to cover the full picture of weldability. If properly done, weld cracking during the manufacturing and repair of damaged components may be minimized.

A schematic view of this integrated process to assess weldability (cracking response) is presented in figure 1.

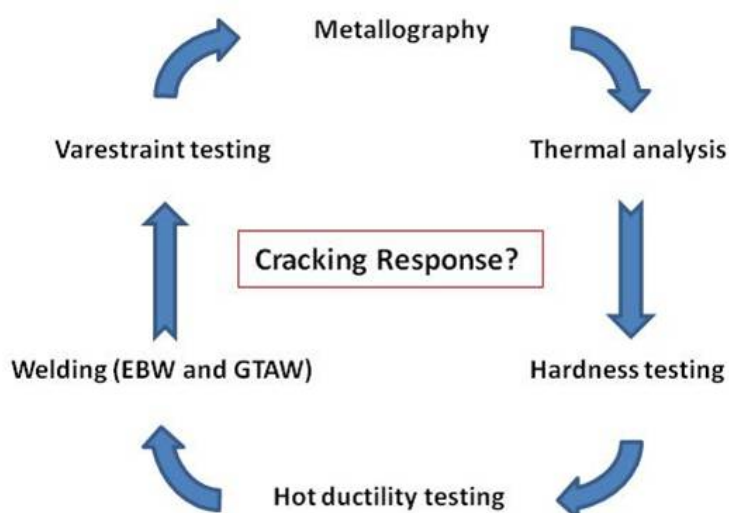


Figure 1. Proposed procedure to evaluate superalloy weldability [14].

The use of metallographic examinations of welds often provides simple and good information in terms of what phases constitute the actual material. This information can later be used for insight into the cracking mechanisms [31]. Thermal analysis aids in explaining possible phase reactions even though the heating and cooling rates are very slow compared to what is experienced during welding. Hardness testing along with heat treatment or repair welding is a quick and easy way to rank and determine if the alloy is susceptible to SAC [31]. The well known Gleeble testing is used to determine the hot ductility which is invaluable to gain information about how phase reactions (e.g. liquation) during fast heating and cooling influence the ductility [1, 32]. One concern with the Gleeble testing is that results may only be valid for the high heat input weld processes such as submerged arc welding [21]. The significance of the Gleeble test results depends on the present liquation mechanism of specific alloys as well as on the pre-weld condition; e.g. grain size and phase constituents. This is also why it is suggested to evaluate different welding processes, such as electron beam welding and gas tungsten arc welding which provides very different heat input, in terms of how these processes may trigger liquation mechanisms. It's finally suggested to use the Varestraint testing to evaluate different weld microstructures effect on the susceptibility to hot cracking. Testing methods like the Varestraint and Gleeble tests provide a way to develop different crack criteria which can be used to predict hot cracking not least in weld modeling processes.

3.2 Improved Varestraint testing

Bending tests, such as the Varestraint testing, are among the most frequently used tests for evaluating the ductility of a metal or welded joint by measuring its ability to resist cracking during bending. The Trans- and Varestraint tests, figure 2, are the two weldability testing methods that were developed by Savage and Lundin in the sixties [33] and are commonly employed when determining the weldability of a specific material. In the Trans-Varestraint testing method a weld is made transverse to the loading direction at the same time as a ram is pulling the plate downwards so that it is supposed to closely adhere to the mandrel located underneath the left-hand side of the plate. The die mandrel can be changed depending on what degree of strain one would like to achieve. Smaller radius gives higher strain. The crack length is then plotted as a function of strain. This testing method is primarily used for investigating the susceptibility towards solidification cracking.

The Varestraint testing which is primarily used for investigating heat affected zone (HAZ) cracking also addresses solidification cracking to some extent. The weld pass is performed in the longitudinal direction of the specimen as shown in figure 2.

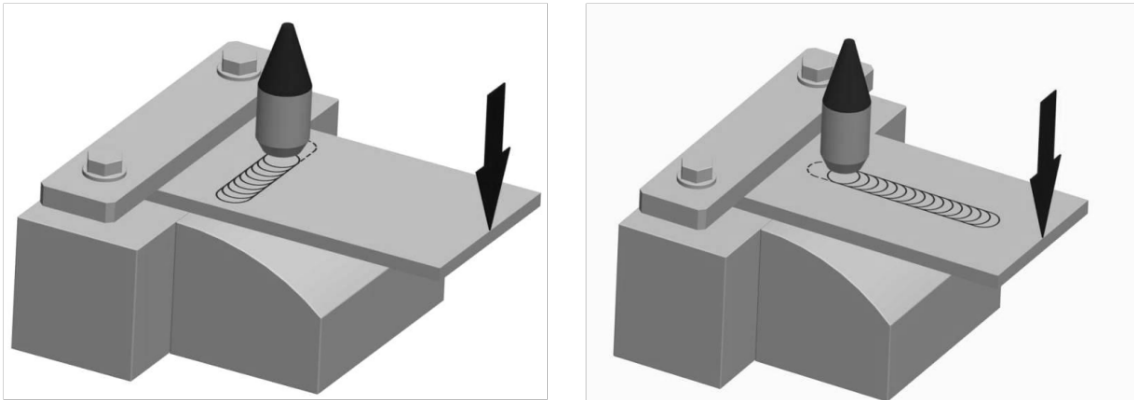


Figure 2. Trans- and Varestreint test, respectively.

3.2.1 Varestreint test specimen geometry

Due to the heating from the welding torch, e.g. by TIG, the material softens dramatically and a kink easily develops where the momentum is highest at the contact with the mandrel. The material does not fully adhere to the die located underneath the test material; as a consequence the material is not exposed to the intended ideal augmented strain, figure 3. When thin sheets are tested it is unfortunately not possible to avoid kinking as shown in the side view of Figure 3. The material at the kink does not experience the expected amount of strain which therefore makes the results more or less useless.

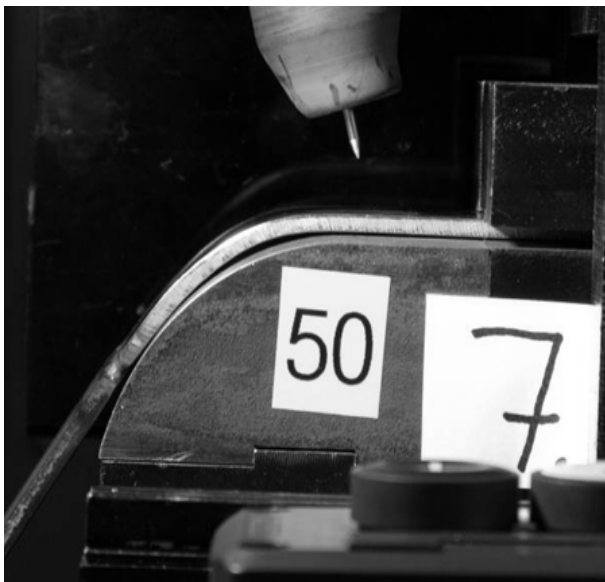


Figure 3. Sideviews revealing how the testing plate kinks in Varestreint testing.

To avoid kinking it is a common practice to use expendable support plates which force the test plate to ideally conform to the die mandrel since the effect of the soft spot due to the heating in the test material is reduced.

However, these support plates do not impose tensile stresses in the test plates as schematically shown in figure 4. As bending is the process by which a straight length is transformed into a curved length. The fibers of the metal on the outer (convex) surface of the bend are stretched, thus inducing tensile strains. Simultaneously, the fibers on the inner (concave) surface of the bend are exposed to compressive (negative) strains. Due to the physical nature of the bending tests both tensile (upper half of the plate) and compressive (lower half of the plate) stresses/strains are encountered during bending, figure 4.

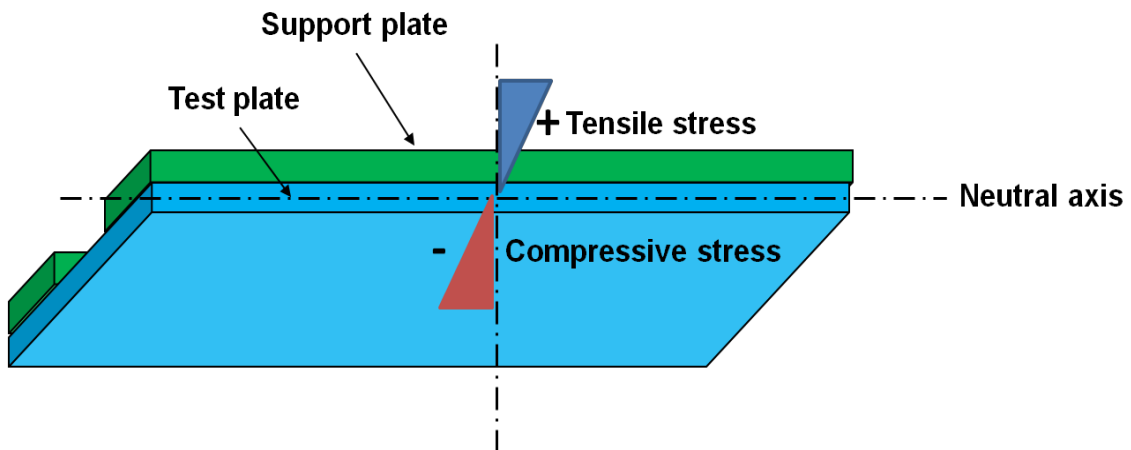


Figure 4. Schematic sketch of a test plate with two support plates on top to avoid kinking in Vareststraint testing.

This means that compressive stresses will develop within the weld in testing of sheet thicknesses below ~7 mm (assuming a weld depth of ~3 mm using TIG weld process). Thickness above ~7 mm is seldom used and the value of Vareststraint testing may be limited in this context and this limitation was addressed in the present study. The aim of the present study was to investigate how the state of stress/strain affects the cracking response in Vareststraint testing [11]. The total crack length response versus ideal augmented strain of ATI 718Plus® and Haynes® 282® in Vareststraint testing using both test configurations (that is with and without tack-welded support plates) is shown in figure 5 and 6, respectively. Surprisingly, no distinction between the different plate configurations could be made in Vareststraint testing of ATI 718Plus® and Haynes® 282® despite the presumably different strain situations within the materials. There is certainly a difference in state of strain in Vareststraint testing compared to pure bending where no weld fixturing interferes. The exact strain situation when welding influences to the bending process is complex and difficult to visualize. Another fact is that in the evaluation of the Vareststraint test materials, only cracks visible on the surface are considered and not the cracks underneath the surface. Since only surface cracks are measured and both test configurations are exposed to the same magnitude of strain at the top surface it seems that whatever state of strain under the surface it does not influence the cracking response at the surface. Thus, it does not matter if the lower half of the test plate is exposed to compressive strains and very thin plates can consequently be tested as long as support plates are used to avoid kinking.

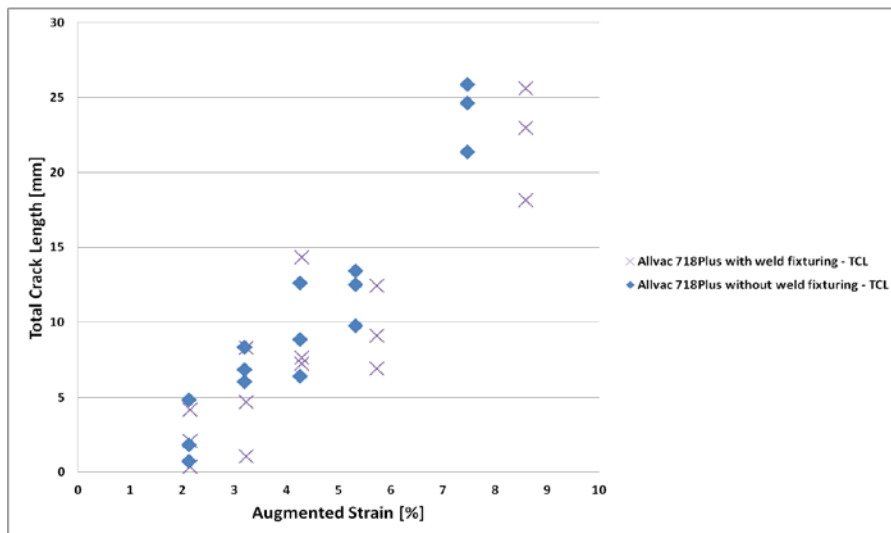


Figure 5. The crack response of ATI 718Plus[®] in Varestraint testing using both test configurations.

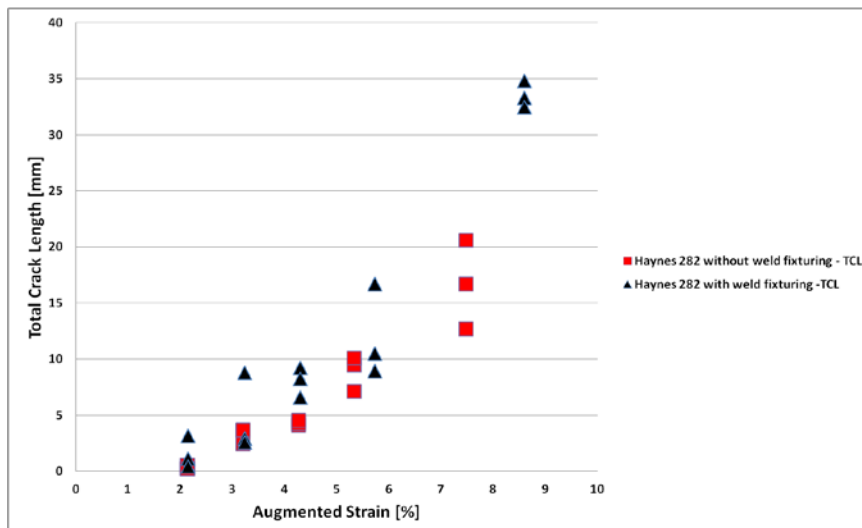


Figure 6. The crack response of Haynes[®] 282[®] in Varestraint testing using both test configurations.

3.2.2 Varestraint testing parameters

An extensive analysis [12] was carried out both in terms of the measurement analysis methods and also of how different welding parameters may affect the outcome of the cracking response. The outcome from evaluating the measurement system analysis (MSA) used in order to quantify the amount of cracking was that it is better if only one operator performs the measuring procedure, implied for both methods that were evaluated. Considering both measuring methods (stereo microscope and penetrant inspection), it is clear that the variation within the penetrant fluid procedure is smaller than the variation within the microscope testing procedure, even with outlier treated in

the microscope procedure. This can however be caused from the high accuracy in the microscope and the subjective judgment of the operator of what is and what is not a crack. However, with regard to the results, the penetrant fluid will be analysed further to see under what circumstances the variation due to the measurement system is as low as possible regarding different types of cracks. Regarding different surface material appearance in combination with large cracks, it doesn't significantly affect the measured variation, which means that the surface can be chosen upon other parameters from a measurement perspective. The variation due to reproducibility is 80.2 % which means that the measurement system isn't reliable enough according to certain standards when using two operators, which strengthens the recommendations previously mentioned that the tests should only be performed with one operator.

The parameters that can be used for comparing two materials are based on indications from a design of experiments [12]. Since these results constitutes of only three samples and a high internal variation, the settings shall be carefully considered. Parameter settings 5, 10, 12 and 14 can be used to compare different materials on a 95 % confidence interval as summarized in Table 3 below. Consider, the low mean values concerning number 5 and 14 and the measurement error.

Table 3. Summary of parameter settings at Varestraint testing.

Parameter setting	Welding speed [mm/s]	Current [A]	Radius [mm]	Speed of impact [mm/s]	Stdev	Stdev / mean	Mean TCL	-2 σ	+2 σ
5	1	70	60	10	144,9	3%	4525	4241	4809
10	3	70	40	250	437,2	6%	7866	7009	8723
12	3	90	40	250	206,0	2%	9028	8624	9432
14	3	70	60	250	939,9	20%	4608	2766	6450

3.3 A new testing approach to assess the susceptibility towards strain age cracking

Strain age cracking (SAC) is a type of cracking that occurs in the solid state due to hardening in the material when weld stresses are high at the same time and occurs in precipitation hardened superalloys and in γ' strengthened alloys in particular. In general, SAC takes place during the PWHT why it sometimes is referred to as "PWHT cracking" or "Reheat cracking" [20]. However, it may also occur during multipass welding, e.g. repair welds as was

evident as was reported in paper [7]. SAC is the biggest concern when welding γ' strengthened Ni-base superalloys.

The reasons for performing a solution heat treatment (PWHT) after welding are not only to restore the microstructure of the FZ and HAZ but also to relieve the stresses which build up during the welding operation. Unfortunately most of the stress relieve seem to occur concomitant with the precipitation hardening during the heating cycle of PWHT which impose high strain on the grain boundaries. Also the hardening of the alloy generally leads to a reduced overall ductility. Due to this loss of ductility, ductility dip cracking (DDC) may occur. DDC is another type of cracking more common in other alloy systems (e.g. solid solution strengthened alloys) where it is thus not related to precipitation hardening [20]. The ductility drop is presumably associated with severe strain concentration at grain boundary triple points due to grain boundary sliding. Research has shown the beneficial effects of carbide precipitation (e.g. $M_{23}C_6$ and MC) in resisting grain boundary sliding and de-cohesion at elevated temperatures [20]. According to Lippold et al. it is this beneficial effect by the precipitation of MC carbides which hinders grain boundary migration, hence, creates tortuous grain boundaries by pinning [34].

Regarding SAC several more factors than those mentioned above may increase the susceptibility. The relation between Al and Ti was proposed by Prager and Shirra who suggested a strong influence on the precipitation characteristics of the γ' and basically the higher the content of these hardening elements the more susceptible the alloy will be [35]. Carbide films at the grain boundaries together with grain boundaries partially liquated during the weld cycle are also reported to contribute negatively. These material specific factors together with the stresses developed by the welding operation add to the severity of the cracking susceptibility.

The new testing approach developed within the present KME-project utilizes the Gleeble based system according to figure 10.

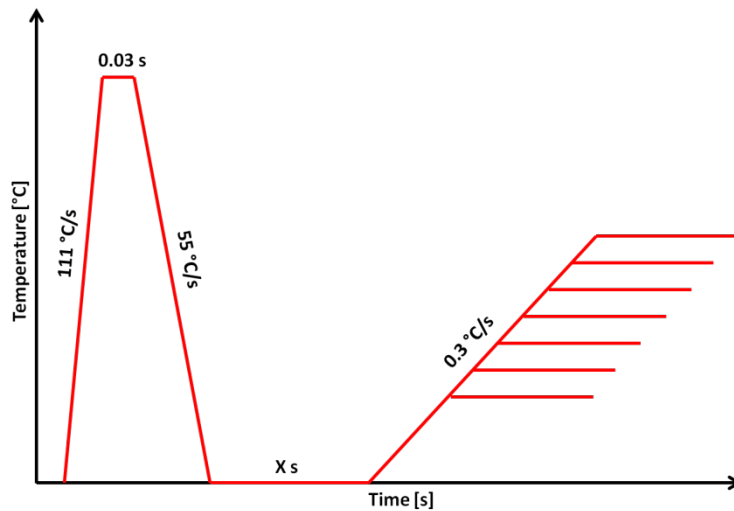


Figure 10. New testing approach to assess susceptibility towards strain age cracking.

First, a tensile specimen is exposed to a heat affected zone thermal cycle where after a slow heating to different ageing temperatures is initiated followed by slowly (1.6 mm/min) pulling the sample to fracture. Some preliminary results for Haynes 282 are shown in figure 11 below.

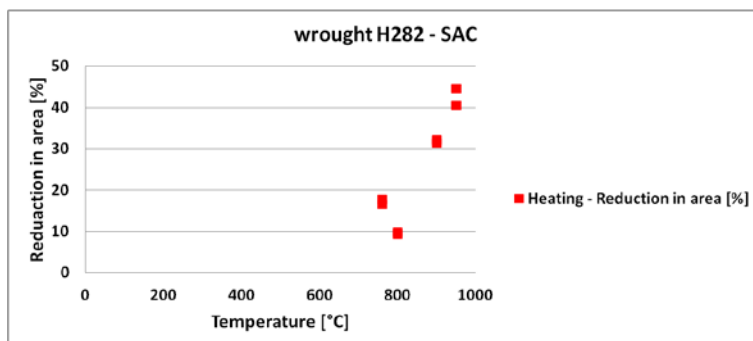


Figure 11. Slow heating rate test of wrought Haynes 282.

In Figure 11 it can be seen that a dip in ductility takes place at around ~800 °C. The reason for this behaviour is believed to be due to a shift in mismatch at around ~800 °C in between the γ and γ' phases causing tensile stresses on the grain boundaries. Further tests and analysis are needed to explain this more thoroughly.

3.4 Material modelling using JMatPro

The understanding of phase stability with respect to time and temperature is essential to tailor the microstructure of superalloys for high temperature applications. In this thesis study, the focus has been on the following aspects:

- The investigation of the primary alloying elements in the superalloys system, including their influence on the solution temperatures and behavior of strengthening phases during precipitation.
- The investigation of the kinetics of different strengthening phases in superalloys during the precipitation in order to understand their behaviors at different temperatures.

The goal is to obtain a better view on these elements regarding their impact on the phase equilibrium in the strengthening phases.

3.4.1 JMatPro

JMatPro stands for Java-Based Material Properties simulation software. Based on sound physical equations, it can be used to simulate and model the different properties of different types of alloys at different conditions, such as alloy compositions, heat treatment temperature and grain size. Version JMatPro 7.0 was used in the present KME-project. JMatPro is capable of calculating the properties of a wide range of material types, including Superalloys, Steels, Aluminum alloys, Titanium alloys, Zirconium alloys, Magnesium alloys and Cast iron; besides, it is also possible for users to create new material types or alter the compositions of the existing alloys freely and also to predict the corresponding properties [36].

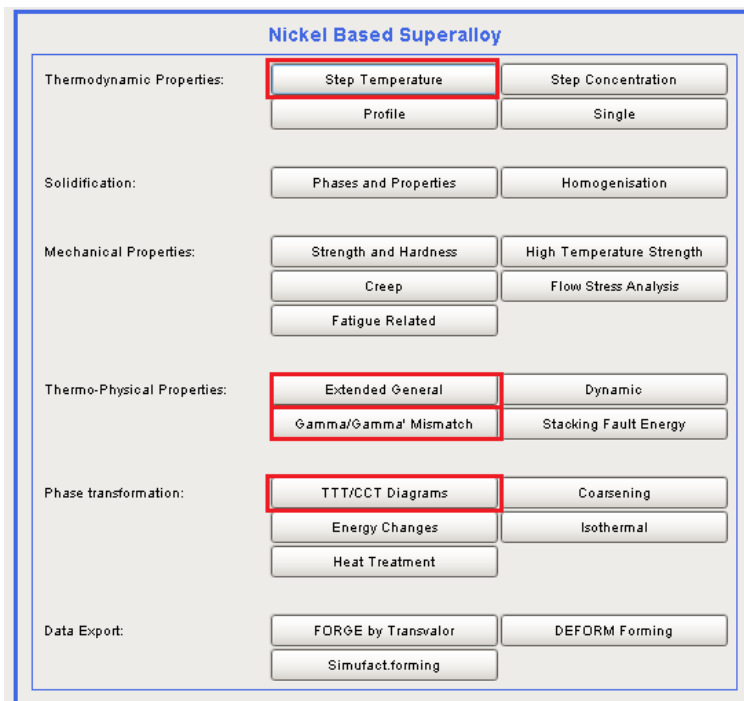


Figure 12. A screenshot from JMatPro v7.0 showing the operation window.

Figure 12 shows the calculations that can be carried out by JMaPro 7.0 for nickel-base superalloys. The features used in this study, shown in red, are 'Step Temperature' in Thermodynamic Properties, 'Extended General' and 'Gamma/Gamma' Mismatch' in Thermo-physical Properties and the 'TTT/CCT Diagrams' in Phase transformation. The first two are used to create diagrams of non-equilibrium thermal stability of phases. The third one is used to calculate mismatch and lattice parameter and the forth one is used to build TTT diagrams. Thermodynamics calculations in JMatPro are based on the CALPHAD method, short for CALculation of PHase Diagrams, which allows users to perform calculations on both stable and metastable phase equilibrium [37-38]. Figure 13 shows all available phases in the calculations regarding nickel-base superalloys in the version 7.0. They can be sorted in several classes; the most common phases including the matrix and strengthening phases, the deleterious phases, carbides and borides, and some other.

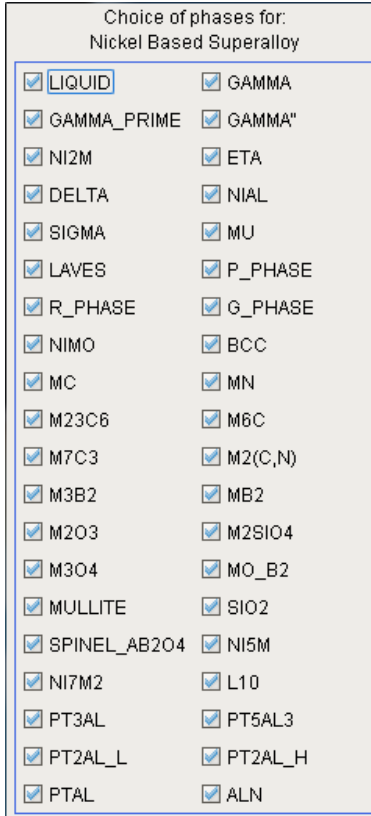


Figure 13. The available phases in JMatPro v7.0 for Ni-base superalloys calculations.

Phases such as gamma, gamma prime, gamma double prime, eta and delta are of primary concern. Others, like sigma phase, laves, carbides and borides are not all chosen in the calculations for each alloy, for both simplicity and accuracy reasons. For thermodynamic properties, JMatPro uses the Gibbs Energy Minimization routines to calculate. The equation is as follow:

$$\Delta G_m = \sum_i x_i \Delta G_i^0 + RT \sum_i x_i \log_e x_i + \sum_i \sum_{j>1} x_i x_j \sum_v \Omega_v (x_i - x_j)^v \quad (1)$$

This is a basic equation for Gibbs energy of a multi-component solution system. The first term on the right of the equal stands for the Gibbs energy of pure component. The second term stands for the ideal entropy and the third one means the interaction between two components. As for the physical properties of phases, JMatPro uses simple pair-wise mixture model to calculate, which can be written in the following form:

$$P = \sum_i x_i P_i^0 + \sum_i \sum_{j>i} x_i x_j \sum_v \Omega_{ij}^v (x_i - x_j)^v \quad (2)$$

where P is the property of the phase, P_i^0 is the property of the phase in pure element, Ω_{ij}^v is a binary interaction parameter and x_i stands for the mole fraction of the element in the phase [39-40]. TTT/CCT diagrams calculations are using a modified Johnson-Mehl-Avrami Kolmogorov model which can also be written as JMAK equation. The well-known form is written as [41]:

$$f = 1 - \exp\left(-\frac{\pi}{3} N v^3 t^4\right) \quad (3)$$

where N is the nucleation rate and v is the growth rate of the precipitating phase when it grows spherically and t is the time. In general, depending on the assumptions made regarding the nucleation and growth processes, a variety of similar equations can be obtained with the following form:

$$f = 1 - \exp(-kt^n) \quad (4)$$

where n is a numerical exponent held to have an integer value between 1 to 4, which is independent of temperature and reflects the nature of the transformation. On the other hand, k depends on the nucleation and growth rates and is therefore very sensitive to temperature. For example, in the case above, k contains N , v wherein both of them are very sensitive to temperature [41]. The mismatch calculation is based on the following equation.

$$\delta = \frac{2(a_{\gamma'} - a_{\gamma})}{a_{\gamma'} + a_{\gamma}} \quad (5)$$

In equation 5, δ is the mismatch percentage, $a_{\gamma'}$ is the lattice parameter of γ' phase and a_{γ} is that of gamma matrix [41].

3.4.2 Strengthening phases

Precipitation hardening superalloys are usually strengthened by two different mechanisms: solution hardening and precipitation hardening. The former one results from certain alloying elements in the system, such as Fe, Co, Cr and so on. The latter one is the primary strengthening method which contributes to most of the mechanical properties. Several important phases related to precipitation hardening are shortly described below.

3.4.2.1 Gamma Prime

Gamma prime phase (γ') provides precipitation strengthening effect to many superalloys. It has an FCC lattice structure ($L1_2$) and its stoichiometry can be

written as $\text{Ni}_3(\text{Al,Ti})$ [43]. In a unit cell of γ' , the 8 corners are occupied by Al atoms and 6 facet centers by Ni atoms. It is very coherent to the matrix lattice. The γ' phase has a higher solution temperature than the gamma double prime (γ'') phase and this makes it the primary choice if the producers or researchers want to increase the thermal stability of superalloys, i.e. in turn raise the maximum service temperature.

Gamma prime is the main strengthening phase for ATI 718Plus and Haynes 282. The strengthening effect is immediate. With increasing temperature, the morphology of γ' develops in the sequence: spheres, cubes, arrays of cubes and solid-state dendrites [43].

In reality, to achieve acceptable weldability and processability, the precipitation time for γ' during different processes should not be too short otherwise it will definitely cause some difficulties, such as strain age cracks [1]. The solution temperatures of γ' phase in the three superalloys studied in this thesis are shown in Table 4. Waspaloy is also shown for comparison. These calculations are done by means of JMatPro using the nominal composition [1] of each superalloy.

Table 4. The solution temperatures of γ' for four superalloys. Results are from JMatPro calculations.

Alloy	Solution Temperature/°C
Waspaloy	1012
Allvac 718Plus	969
Haynes 282	1005
Alloy 718	919

3.4.2.2 Gamma Double Prime

Gamma double prime phase (γ'') can also provide precipitation hardening effect for superalloys, for example Alloy 718. It has BCT lattice structure (DO_{22}) and the stoichiometry can be written as Ni_3Nb [43]. A γ'' unit cell can be considered as cuboid consisting of two cubes. 8 corners and the body center of the cuboid are occupied by Nb atoms. The center points of 4 long edges of the cuboid and 10 face centers of the cubes are occupied by Ni atoms. The γ'' has a lower coherence than γ' . This results in higher interfacial energy, higher driving force for particle coarsening and generates higher degree of mismatch with the matrix which can provide remarkable hardening effect. However, the solution temperature of this phase limits the service temperature and the potential for improvements. Also as compared to γ' , the hardening effect provided by γ'' is sluggish.

3.4.2.3 Elements

Superalloys are one of the most complicated alloy systems in the world. There are 10 elements in each system on average. The elements mostly used are Al, Ti, Nb, Cr, Fe, Co, Mo, W and Ta. Other nonmetallic elements are C, P and B. They have different kinds of influence on different phases in the alloying systems. Normally, the elements are described in three classes. The first class includes Ni, Co, Cr, Fe, Mo and W, whose atomic radii are not so different from that of the matrix element Ni and therefore these partition to the gamma matrix and stabilizes it. The second class includes Al, Ti, Nb, Ta,

whose atomic radii are larger than that of Ni, which will promote the formation of strengthening phases like γ' and γ'' . The third class includes C, B and Zr. They have very different atomic radii as compared to that of Ni and tend to segregate to the grain boundaries. Together with other elements, they will form borides and carbides [43].

3.4.3 Contribution of Elements to strengthening phases formation

The results are summarized in tables 5 through 7. '++' means the influence is strong. '+' means secondly strongest influence on that property. '0' means no apparent influence. Tables 5 and 6 show the influence of alloying elements on the behavior of γ' in Haynes 282 and ATI 718Plus, respectively. Table 7 gives the summary for γ'' in Alloy 718.

Table 5. Summary of element behavior on γ' phase in Haynes 282.

Property	Al	Ti	Mo
Precipitation Time	++	++	++
Solution Temperature	++	+	+
Weight fraction at 650°C	++	0	0
Weight fraction at RT	++	+	+

Table 6. Summary of element behavior on γ' phase in ATI 718Plus.

Property	Al	Ti	Nb
Precipitation Time	++	++	++
Solution Temperature	++	+	+
Weight fraction at 650°C	++	+	+
Weight fraction at RT	++	+	0

Table 7. Summary of element behavior on γ'' phase in Alloy 718.

Property	Al	Ti	Nb
Precipitation Time	++	++	++
Solution Temperature	+	+	++
Weight fraction at 650°C	+	0	++
Weight fraction at RT	+	+	++

The elements in different alloys have a clear positive, negative or positive threshold limit effect. As an example, the precipitation time cease to drop when the amount of element reaches a certain point. However, limited by the numbers of tested compositions and the assumption that the effects between every composition are linear, it is hard to say where this limit is exactly.

4 Conclusions

- A review of the weldability of precipitation hardening Ni-based superalloys has been made and an evaluation procedure to use in determining weldability is proposed.
 - Different type of cracking and associated mechanisms may be active at the same time and may interact.
 - The weldability concept needs to be evaluated in relation to specific welding processes concept since the cracking mechanisms may alter between these processes.
 - A systematic integrated procedure is suggested to assess weldability in a consistent and cost effective way.
- No influence of compressive strains on the cracking response in Varestraint testing was observed.
 - Thin test plates can be used as long as kinking can be eliminated when support plates are used.
 - Hot cracking susceptibility of Haynes[®] 282[®] is lower compared to that of ATI 718Plus[®] especially when grain size effects are considered.
 - ATI 718Plus[®] liquates through constitutional liquation of NbC.
 - A hypothesis regarding liquation of MoC through eutectic transformation of Ni-Mo or Ni-Mo-S in Haynes[®] 282[®] is possible.
- Varestraint testing and evaluation parameters have been investigated and optimum parameters have been determined
- The transformation characteristics of strengthening phases and the functions of different elements in Haynes[®] 282[®], ATI 718Plus[®] and Alloy 718 have been studied both using JMatPro and DTA/DSC.
- Through JMatPro modelling, equilibrium phase diagrams and TTT diagrams have been constructed.
 - o The results related to different elements have then been analyzed by means of statistical analysis using Minitab and TTT data were extracted to obtain the parameters of JMAK equations in order to quantitatively describe the phase transformation.
 - o Elements tested can reduce the precipitation time of γ' significantly, but a limit exists.
 - o Al and Ti both have strong influence on the solution temperature of γ' , but without sufficient Al, the influence of Ti will be diminished.
 - o Mo or Nb have smaller influence on the solution temperature of γ' than Al and Ti.
 - o As γ' forming elements, Al can augment the amount of γ' drastically; on the other hand, Ti, Nb and Mo have negligible influence.

- o Nb, as the primary γ'' forming element, has the strongest influence on γ'' in all aspects.
- o Ti has little contribution on raising the solution temperature and almost negligible effect on weight fraction, but can reduce the precipitation time.
- o Al has second strongest influence on γ'' , but the effect is opposite to that of Nb.

5 Goal fulfilment

The original motivation and project objectives were stated as follows:

1. The support to the competitive position to utilise superalloys
2. The evaluation of realistic superalloy combinations and the associated weldability limits
3. Improved understanding regarding the role of trace elements in the grain boundary cracking during welding.
4. Assessed heat treatment restrictions from a phase stability point of view

The overall goal was here to find specific superalloy combinations, welding methods and appropriate heat treatment schedules to increase the potential for hot gas turbine structures applications. This was supposed be achieved by improved understanding about the weld processes involved including basic metallurgy and reliable test methods to support reliable modeling of the weld applications.

This overall goal is fulfilled and the fulfillment is considered to be more than complete. In accordance and in addition to what was stated in the project plan for KME506:

- An extensive weldability assessment of different superalloys has been done (goals 1 and 4).
- A Vareststraint testing machine has been designed and built (goal 2).
- Testing parameters and specimen geometry have been evaluated (goals 2).
- Microstructure and phase stability have been investigated using DSC/DTA, JMatPro material modelling and various characterization techniques like optical and scanning electron microscopy (goal 3).
- A new testing approach for strain age cracking has been suggested and evaluated (goals 2 and 4).
- More than 20 thesis workers have been part of the project
- 19 papers have been submitted during the project.

For KME518 the additional goal fulfilled is:

- The establishment of an international network with leading scientists in Canada and Finland.
- Also, in addition a sub-project within the Clean Sky programme has been granted and run as a result of these KME-projects.

6 Suggestions for future research work

It is highly suggested to continue to investigate the fundamental aspects of weldability testing of various high temperature alloys which also can be used for other type of alloy systems as well. It is recommended that a future project would direct its research onto the aspects of strain age cracking or ductility dip cracking, something which was slightly touched upon in the present KME-project. It is also suggested to investigate some concerns in the regarding low ductility of the newly developed alloy Haynes® 282® which is of high interest in the energy sector (all around the world).

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8 Publications

2014

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