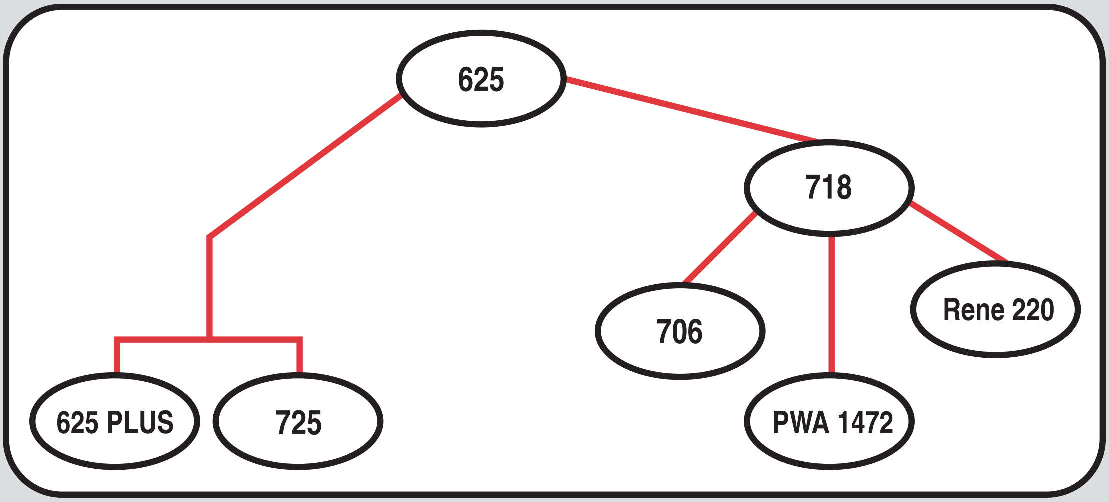
The Single Source on Progress and Problem-Solving in Superalloys



6th International Special Emphasis Symposium on

Superalloys 718, 625, 706, and Derivatives

October 2-5, 2005
Hyatt Regency Pittsburgh International Airport Hotel
Pittsburgh, Pennsylvania

FINAL PROGRAM

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Welcome to the 6th International Special Emphasis Symposium on
Superalloys 706, 625, 718 and Derivatives –
the Single Source on Progress and Problem-Solving in Superalloys!

CALENDAR OF EVENTS

Sunday, October 2	Time	Location
Registration	4 to 8 p.m.	Regency A Foyer
Welcoming Reception	6:30 to 7:45 p.m.	Regency BC
Sponsored by ATI Allvac		
Invited Overviews	7:45 to 9 p.m.	Regency A

Monday, October 3		
Registration	7:30 a.m. to 5 p.m.	Regency A Foyer
Authors' Coffee	7:30 to 8:30 a.m.	Lindbergh B
Melting and Solidification	8:30 a.m. to 12:30 p.m.	Regency A
Lunch	12:30 to 1:30 p.m.	Regency BC
Allvac 718Plus Development	1:30 to 5:30 p.m.	Regency A

Tuesday, October 4		
Registration	7:30 a.m. to 5:30 p.m.	Regency A Foyer
Authors' Coffee	7:30 to 8:30 a.m.	Lindbergh B
Processing Effects and Physical Metallurgy	8:30 a.m. to 12:10 p.m.	Regency A
Lunch	12:15 to 1:30 p.m.	Regency BC
Physical Metallurgy	1:30 to 5:50 p.m.	Regency A
Dinner Break	5:50 to 7:30 p.m.	At Attendee's Discretion
Registration	7:30 to 9:30 p.m.	Regency A Foyer
Design, Processing, Properties	7:30 to 9:45 p.m.	Regency A

Wednesday, October 5		
Registration	7:30 to 11 a.m.	Regency A Foyer
Authors' Coffee	7:30 to 8:30 a.m.	Lindbergh B
Processing Effects and Properties	8:30 a.m. to 12:10 p.m.	Regency A
Lunch	12:15 to 1:30 p.m.	Regency BC
Weldability and Applications	1:30 to 4:10 p.m.	Regency A

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6th International Special Emphasis Symposium on

Superalloys 718, 625, 706, and Derivatives

TECHNICAL PROGRAM

Sunday Evening, October 2, 2005

6:30 - 7:45 PM Welcoming Reception

Invited Overviews

Introduction by: *Robert E. Schafrik*, General Manager, EMPL, GE Aircraft Engines, Cincinnati, OH 45215 USA

8:00 PM

Allvac®718Plus™, Superalloy for the Next Forty Years: *Richard L. Kennedy*[1]; [1]ATI Allvac

Allvac®718Plus™ alloy is a new nickel base Superalloy with a highly desirable combination of excellent mechanical properties, increased temperature capability, good fabricability and moderate cost. This highly desirable combination of characteristics positions the alloy to very effectively fill the longstanding gap between the two most widely used wrought superalloys, 718 and Waspaloy. This paper will review the development of alloy 718Plus™, which has progressed over the last eight years, including the effects of chemistry, heat treatment, processing and structure on mechanical properties. The current production status and capability of the alloy will also be discussed along with ongoing applications development. Comparisons will be made to 718, Waspaloy and other superalloys illustrating that alloy 718Plus™ is the best available candidate to sustain the advances in engine development made possible over the forty-plus year life of alloy 718.

8:30 PM

Extending the Size of Alloy 718 Rotating Components: *Robin C. Schwant*[1]; J. Jay Jackson[1]; Ling Yang[1]; Martin Morra[2]; [1]GE Energy; [2]GE Global Research Center

GE introduced the use of Alloy 718 in its heavy-duty gas turbine rotors in the late 1990's. The size of these parts is an order of magnitude larger than those used in aircraft engines. The challenges associated with production of very large 718 ingots and forgings are discussed. The issues include segregation, grain growth, microstructure and production equipment size limitations. Property distributions and comparisons to another turbine wheel material, Alloy 706, are included.

Monday AM, October 3, 2005
Melting and Solidification

Session Chairs: Shailesh J. Patel, Special Metals Corporation; Laurence A. Jackman, ATI Allvac

8:30 AM

Alloy 718 Large Ingots Studies: *Carlo Malara*[1]; John F. Radavich[2]; [1]Foroni SpA; [2]Micro-Met Laboratories, Inc.

Alloy 718 VAR ingots of 34" diameter were successfully melted and processed to 20" diameter billets. A special melting route was followed resulting in a quadruple melted material: initial melting of raw materials into an electric arc furnace, liquid metal refining into an Argon-Oxygen Decarburization (AOD) converter, air pouring into round molds and solidification, vacuum melting of AOD ingots and pouring into electrodes using a Vacuum Induction Degassing and Pouring (VIDP) equipment and double VAR computer-controlled processing. Double VAR ingots were homogenized and hot forged on a 50 MN open-die, computer-controlled hydraulic press to 20" diameter, ultrasonic sound billets. Billets were macro examined showing no evidence of freckles, white spots, radial segregations or ring pattern. Billet microstructure showed an uniform grain size throughout the billet cross-section with no delta phase segregation, except light delta phase banding at center. Proper annealing and age hardening resulted in clean grain boundaries and mechanical properties matching requirements of both aerospace and oil patch specifications. Results of this study demonstrate the feasibility of large alloy 718 billets from 34" ingots of comparable quality to billets manufactured from standard 20" ingots and present an opportunity for forging large land base and aircraft engine disks of alloy 718.

8:50 AM

Metals Affordability Initiative: Application of Allvac Alloy 718Plus™ for Aircraft Engine Static Structural Components: *Eric Allen Ott*[1]; Howard W. Sizek[2]; [1]General Electric Company; [2]Air Force Research Laboratory

Mechanical property balance, malleability, and weldability of Alloy 718 have driven widespread utilization across the aerospace and non-aerospace industries over nearly 50 years; however, temperature limitations due to metastability are typically inadequate for applications above about 650°C. As a result, other more costly and difficult to process alloys, like Waspaloy, are used in such applications. These alloys, strengthened primarily by the gamma prime, are also more sensitive to weld-related cracking than Alloy 718. As part of the Metals Affordability Initiative CORE Program, several alternate alloys were identified and evaluated for aircraft engine static structural component applications for use temperatures of at least 705°C. The application-integrated project team consisting of engine manufacturers, GE, Honeywell, and Pratt & Whitney; forgers, Firth-Rixson and Ladish Company; primary metal producers, Allvac and Carpenter Technology; in combination with the Wright Patterson Air Force Base Materials Laboratory, selected the Allvac-developed 718Plus™ alloy chemistry for scale-up and validation. Subscale and full-scale experiments confirmed processability and weldability of this alloy were significantly improved relative to Waspaloy, and more similar to that of Alloy 718. Complex rolled rings varying in size from less than 50 to nearly 500 pounds have been processed validating the advantages of this alloy. Assessment suggests nearly equivalent strength levels and stability to Waspaloy to 705°C have also been achieved along with an acceptable balance of other properties. This presentation will summarize the successful processing, weldability, and mechanical property evaluation efforts performed under this project and the progress toward industrial implementation of this alloy.

9:10 AM

Advancing Alloy 718 Vacuum Arc Remelting Technology Through Model-Based Controls: *Rodney L. Williamson*[1]; Joseph J. Beaman[2]; Frank J. Zanner[3]; John J. deBarbadillo[4]; [1]Sandia National Laboratories; [2]University of Texas; [3]Zan Tek Enterprises; [4]Special Metals Corporation

The Specialty Metals Processing Consortium (SMPC) was established in 1990 with the goal of advancing the technology of melting and remelting nickel and titanium alloys. In recent years, with primary funding support from the U.S. Federal Aviation Administration, the SMPC technical program has focused on technology to improve control over the final ingot remelting and solidification processes to alleviate conditions that lead to the formation of inclusions and positive and negative segregation. A primary focus of the SMPC program is the development and application of advanced monitoring and control techniques to vacuum arc remelting (VAR), with special emphasis on VAR of Alloy 718. This has lead to the development of an accurate, low order electrode melting model for this alloy as well as an advanced process estimator that provides real-time estimates of important process variables such as electrode temperature distribution, instantaneous melt rate, process efficiency, total energy flux to the ingot pool surface, fill ratio, and voltage bias. This, in turn, has enabled the development and industrial application of advanced VAR process monitoring and control systems, and intelligent measurement filters. The technology is based on the simple idea that the set of variables describing the state of the process must be self-consistent as required by the dynamic process model. The output of the process estimator comprises the statistically optimal estimate of this self-consistent set. Process upsets such as those associated with glows and cracked electrodes are easily identified using estimator based methods.

9:30 AM

Alloy 718 Forging Development for Land-Based Gas Turbines: J. Jay Jackson[1]; *Jean-Francois Uginet*[2]; [1]GE Energy; [2]Aubert & Duval Holding

Alloy 718 forgings have been used extensively in gas turbines for aircraft engines for decades However their application to land-based power generation gas turbines has been limited to the size of the forgings which can be produced by available forging equipment. GE's recently developed heavy duty gas turbines now require forgings which must be produced from 915 mm diameter ingots which exceed 30,000 pounds. The initial hurdle was to melt these large ingots successfully without segregation defects. This was achieved and the results were discussed in a previous conference This paper describes the unique challenges to converting these ingots into the largest Alloy 718 forgings ever produced The development work associated with processing these ingots into a uniform fine grain microstructure with the required mechanical properties will be described. The importance of process modeling for developing a process to achieve the structure and property goals will also be discussed.

9:50 AM

Clean Metal Nucleated Casting of Superalloys: *William T. Carter*[1]; Joseph J. Jackson[1]; Robin M. Forbes Jones[2]; Ramesh S. Minisandram[2]; [1]General Electric Company; [2]ATI Allvac

The clean metal nucleated casting program is a cooperative research program between GE Energy and Allvac, sponsored by the National Institute of Standards and Technology under the Advanced Technology Program. The goal of the program is to develop a spray-casting technology for the production of extremely large, segregation-free superalloy ingots for use in turbine wheels in land-based gas turbines. The raw material for the process is a superalloy vacuum induction melted (VIM) electrode, which is melted in a bottom-pouring Electro-Slag Remelting (ESR) furnace that forms a stream of liquid superalloy for subsequent atomization and collection in a withdrawal mold. Gas atomization of the stream to form a spray occurs in a chamber where spray distance and gas-to-metal flow rates can be adjusted to cool the metal to a desired level before collection. The approach taken in the R&D program is to address key technical risks associated with the system through construction of a one-ton research plant. These include the design and operability of the ESR furnace, pouring system, and collection system. Computational models of all key components of the process are developed and validated against experiments performed on the research plant. The validated models will be used to extrapolate to commercial-sized ingots.

10:10 AM

Modification of Alloy 706 for High Temperature Steam Turbine Rotor Application: *Shinya Imano*[1]; Takashi Shibata[2]; Tsukasa Azuma[2]; Tatsuya Takahashi[2]; Hiroyuki Doi[1]; [1]Hitachi; [2]Japan Steel Works

To improve microstructure stability at temperature up to 700° and avoid segregation of Nb , we modified the chemical composition of Alloy706. It is known that Alloy706 is strengthened by GAMMA'(Ni3Al) phase and GAMMA"(Ni3Nb) phase. But these phases are unstable at high temperature after long-term exposure and transform into Nb rich DELTA or ETA phase. Modified alloy(FENIX-700) contains lower Nb and higher Al than Alloy706, so that it is strengthened by only GAMMA'(Ni3Al) phase. And we could not find DELTA or ETA phase in the FENIX-700 after creep and aging at 700°. Tensile strengths of the FENIX-700 at temperature from room temperature to 700° is almost same as that of IN706. Yield strength of FENIX-700 at room temperature is slightly lower than that of Alloy706, but equivalent to that of Alloy706 at high temperature. Tensile and yield strengths of FENIX-700 at temperature from room temperature to 700° are higher than that of Alloy706 after aging at 700°. In this paper, we discuss effects of Nb and Al on mechanical properties and microstructure, using mechanical testing, TEM observation and thermodynamics calculation result. And we show the mechanical properties and advantage of FENIX-700 for high temperature steam turbine applications.

10:30 AM Break

10:50 AM

Optimizing the Forging of Critical Aircraft Parts by the Use of Finite Element Coupled Microstructure Modelling: *Martin Stockinger*[1]; Johann Tockner[1]; [1]Bohler Schmiedetechnik GmbH & Company KG

The near-net-shape forging of high strength nickel base superalloys 718 and 720 for aircraft parts requires the usage of finite element simulations to ensure a proper thermo-mechanical treatment. Because of the strong mechanical requirements and narrow specifications of such parts not only a correct, defect free final geometry is necessary, but also a defined microstructure. The crucial point is therefore, to control all process parameters in a way to achieve the demanded properties. The typical forging processes like hydraulic, screw press and hammer forging imply a broad spectrum of strain rates. The influence of this different strain rates as well as forging temperature and strain on dynamic and post-dynamic recrystallization have been examined experimentally. Annealing tests at various temperatures and time periods have been performed, to investigate static recrystallization and grain growth behaviour as well as dissolution processes in this before mentioned materials during heating periods. The obtained data was used to build phenomenological models, which were implemented into a finite element code of a commercial special purpose finite element program. 2D and 3D Simulations of multiple step thermo-mechanical processes are compared with microstructure examinations of forged parts to show the usability and accuracy of such models as a tool to optimize complex forging processes of critical aircraft parts. In combination with systematic process data collection during production a stable processes and satisfactory mechanical product properties are guaranteed.

11:10 AM

Probabilistic Life of IN718 for Aircraft Engine Disks: *Stephane Deyber*[1]; Franck Alexandre[2]; André Pineau[2]; Julien Vaissaud[2]; [1]Snecma Moteurs; [2]Ecole des Mines de Paris

The current certified methods used to establish aircraft engine disks life are essentially phenomenological, and based on numerous fatigue tests. A statistical approach based on standard deviation is applied to fatigue test results to take into account dispersion and determine minimum life to initiation. Such methods are pragmatic and conservative, but cannot adapt easily to a change in materials or process, and can be over-conservative, especially in stress concentration areas. As a guide for materials and design engineers, an alternative approach is proposed. It is based on microscopic crack initiation and propagation mechanisms identified in IN718 through appropriate testing: micro-crack initiation on second phase particles (carbides or nitrides) and grains, and micro-crack propagation. Identified life models take into account microstructure and mechanical behaviour inherited from IN718 disk forging process. The combination of these microscopic models allows, at a macroscopic level, the description of the competition of all IN718 crack initiation sites. To determine disk life for a given probability of fracture, a probabilistic method has been developed, based on microscopic models identified at the previous stage. It is used as a post-processing of a structure finite element analysis. The probability of presence of a particle of given size and its probability of micro-fracture are calculated for all the elements of the structure; the integration of fracture probability over the whole structure leads to probabilistic structure life. In the end, the proposed probabilistic life method is validated by confrontation to notched fatigue experimental results obtained on Direct-Aged IN718.

11:30 AM

Processing of Rolling Technologies for IN718: *Michael Walter*[1]; Arnold Tatschl[1]; [1]Böhler-Edelstahl

The need of thermomechanical processing of IN718 for tighter properties is well known and published mainly for forged products. Less information are published for rolled products, while the today's requirements for increased productivity lead to the replacement from forging trough rolling steps, wherever it is possible. At Böhler-Edelstahl GmbH several rolling technologies for IN718 products were developed. Cogging of 20 inch ingots, two heat rolling from ingot to bar for AMS 5662/3 and

3 heat rolling to flat 2x0.5 inch for extended properties show the range of different rolling processes following the TMP demands of IN718. The aim was to establish the needed combination of temperature- and deformation windows in the relevant steps over the cross section of the real format. The evaluated aggregates varied from reverse roughing to continuous precision mills with flat and grooved rolls. The main challenge was the transmission of the thermomechanical demands to the technical possibilities of the aggregates. The method was a combination of simplified calculation model based on 2D FDM and systematic trials with an intense metallurgical evaluation. While the behavior of IN718 in single or several step deformation is predictable with FEM and attached micro structural models, in multi pass rolling a save prediction is not possible. The main reason is that the reaction movements of the rolls have to be predictable too. This would include a complete simulation of the hole rolling aggregate in reaction with a material, which is impossible for complete mills.

11:50 AM

Mechanical Properties of Counter-Gravity Cast IN718: *Sanjay Shendye*[1]; Blair King[1]; Paul McQuay[2]; [1]Metal Casting Technology, Inc.; [2]Hitchiner Manufacturing Company, Inc.

Three molds consisting of 36 test bar blanks each and test coupons were cast in IN718, using the Counter-gravity Low-pressure Inert-atmosphere (CLI) investment casting process. Test coupons were analyzed for chemical composition and the test bar blanks machined and tested for tensile and stress rupture properties. Larsen-Miller parameter was calculated from the stress rupture test data. Stress levels for the stress rupture test ranged from 75 to 130 ksi and the temperature ranged from 1000°F to 1300°F. Fracture surfaces and microstructure of the test bars were evaluated using optical and scanning electron microscopy techniques. Chemical composition of the alloy was found to be relatively stable and within the specification limits. A slightly higher oxygen and nitrogen content was observed as compared with the vacuum induction melted and gravity-cast IN718. This however, did not adversely affect the stress rupture properties. The experimentally determined Larsen-Miller parameter was found to be comparable to that published in the literature. Grain size ranging from 0.010" to 0.060" was observed. No notable defects were identified by non-destructive X-ray and fluorescent penetrant inspections (FPI), or by microstructure and fractographic evaluations. The CLI process was developed by Metal Casting Technology, Inc., and patented by Hitchiner Manufacturing Company, Inc. Several components are currently in production using the CLI process in other Ni-base superalloys.

12:10 PM

The Role of Niobium in Wrought Precipitation-Hardened Nickel-Base Alloys: *Gaylord D. Smith*[1]; Shailesh J. Patel[1]; [1]Special Metals Corporation

Niobium is recognized as an important alloying element in a number of key wrought precipitation-hardened nickel-base alloys. It is the purpose of this paper to examine the role that niobium plays in these alloys and describe the properties that are achieved as a result of its inclusion in these wrought superalloys. In addition to the general alloying characteristics of niobium as described in the technical literature, the specific contribution of niobium in the alloys X-750, 740, 706, 725 and 718 is examined. Niobium is examined for the microstructural role it plays and for the impact of the resulting microstructures on certain mechanical properties.

Monday PM, October 3, 2005
Allvac 718Plus Development

Session Chairs: Jon R. Groh, General Electric; Daniel F. Paulonis, Pratt & Whitney

1:30 PM

Structure and Property Comparison of Alloy 718Plus™ and Waspaloy Forgings: Ian Dempster[1]; Wei-Di Cao[2]; Richard L. Kennedy[2]; Betsy Bond[2]; Jose Aurrecoechea; Mark D. Lipschutz; [1]Solar Turbines Incorporated; [2]ATI Allvac

Alloy 718 has seen extensive use for many years due to its excellent mechanical properties, good processing characteristics, and relatively low cost. Numerous attempts have been made to develop a 718-type alloy with temperature capabilities higher than Alloy 718. One of the most promising alloys to emerge from these efforts is Allvac® Alloy 718Plus™. Interest in Alloy 718Plus™ has grown after initial testing showed a 55°C temperature capability improvement over Alloy 718, mechanical properties comparable to Waspaloy, and processing behavior similar to Alloy 718. A comparison between the structure and properties of Alloy 718Plus™ and Waspaloy was performed on pancake forgings produced using an open-die process. The forgings were subjected to grain flow evaluations and subsequently heat-treated. The tensile, creep, and stress rupture properties of the pancake forgings were determined and related to their respective structures.

1:50 PM

Solidification and Solid State Phase Transformation of Allvac® 718Plus™ Alloy: *Wei-Di Cao*[1]; [1]ATI Allvac

Allvac® 718Plus™ alloy is a new Ni-base superalloy developed at ATI Allvac with mechanical properties and thermal stability, equal to or better than those of Waspaloy, at temperatures up to 1300°F. The alloy also has castability, hot workability and weldability, approaching that of alloy 718. These desirable characteristics coupled with a relatively low cost make it an excellent candidate to replace Waspaloy type alloys in many applications. In parallel with several ongoing investigations of processing and properties, research has been conducted at Allvac to understand the physical metallurgy of this alloy, and relevant results are introduced in this presentation. Phase transformations of this alloy during solidification were studied by DTA and SEM/EDS techniques and compared with modeling calculations. As-cast microstructure and micro-segregation were interpreted from these solidification transformations. The chemistry, crystal structure and size distribution of precipitation phases responsible for age hardening were identified by TEM and X-ray analysis. Special attention was paid to grain boundary precipitates. The nature, morphology and formation kinetics of GB precipitates were studied. The effect of GB precipitation on mechanical properties, especially rupture ductility and hold-time fatigue crack growth were investigated. The transformation of this alloy during long-term thermal exposure was also studied and the implications to mechanical properties are addressed. The role of chemistry on phase transformation and resultant mechanical properties are also introduced.

2:10 PM

Structure Stability Study on a New Developed Modified 718 Alloy—Allvac® 718Plus™: *Xishan Xie*[1]; [1]University of Science and Technology Beijing

Recently a new modified 718 alloy to be used at 700° has been developed by ATI Allvac designated as Allvac® 718Plus™. The critical criterion for this alloy is long term structure stability at 700°. The chemical composition of alloy 718Plus™ for this study is 0.028%C, 17.42%Cr, 2.72%Mo, 1.04%W, 9.13%Co, 9.66%Fe, 5.48%Nb, 1.46%Al, 0.71%Ti and Ni in balance. Alloy 718Plus™ was thermal treated at 760° for 100, 350 and 500 hours after the heat treatment 954°/1h/AC + 788°/2h/FC/40°/h/ + 649°8h/AC. For comparison, the conventional alloy 718 was also thermal treated at 760° for 100, 350 and 500 hours after standard heat treatment. Phase prediction of 718Plus™ was calculated by Thermal-Calc software and the detail phase identification was conducted by SEM, TEM, SAD and XRD. Quantitative determination of different phases was conducted by electrolytical isolation and followed by micro-chemical analyses. The mechanical properties such as hardness, tensile properties, impact and especially stress rupture were tested after long-term aging at 760°.

2:30 PM

Press Forging of Alloy 718Plus™: *Joe Lemsky*[1]; Kevin E. Kloske[2]; Thomas D. Bayha[3]; Howard W. Sizek[4]; [1]Ladish Company, Inc.; [2]Pratt & Whitney; [3]ATI Allvac; [4]Air Force Research Laboratory

An emerging alloy that will fit the niche for low cost, high temperature applications is of great interest to the aerospace industry. One alloy, 718Plus™ has potential to replace high cost powder alloys in turbine engines and is the focus of on-going research. To investigate this potential alloy and application, an effort was undertaken to establish a manufacturing process route including hydraulic press forging and several heat treating methods. The paper will summarize the results obtained from press forgings given direct age and solution and age heat treatments. Issues relating to the alloy and TMP processing cycle will be assessed in regard to mechanical properties to determine the merits and/or limitations of this alloy.

2:50 PM

IsoCon Processing of Alloy 718Plus™: *Joe Lemsky*[1]; Kevin Kloske[2]; Thomas D. Bayha[3]; [1]Ladish Company, Inc.; [2]Pratt & Whitney; [3]ATI Allvac

Advanced thermo-mechanical processing techniques have allowed the forging industry to improve upon new and existing alloys and to provide enhanced microstructures and properties for components. Processes that develop and control uniform grain sizes in components have long been desired by the aerospace industry. Also, processes that retain metallurgical strain from deformation processes have also shown great value. Retained metallurgical strain can provide two benefits: 1) assistance in precipitation processes, such as with DA718, and 2) increase the amount of strain hardening in the alloy and resultant component, such as IsoCon Waspaloy. 718Plus™ is an alloy that has a relatively narrow processing window to produce uniform fine grain sizes. This new alloy has also shown gains in mechanical properties from direct age and retained metallurgical strain processing. An effort to apply IsoCon Alloy 718Plus™ has been undertaken. In this process a controlled isothermal forging step provides a highly refined preform geometry with uniform grain structure ("Iso" step in IsoCon). The preform is subsequently conventionally hammer forged ("Con" step) to develop the optimum metallurgical strain for enhanced mechanical properties. This paper will review the results from characterization work performed on IsoCon 718Plus™ Alloy forgings.

3:10 PM Break

3:30 PM

A T-T-T Diagram of a New Developed Modified 718 Alloy—Allvac® 718Plus™: *Xishan Xie*[1]; [1]University of Science and Technology Beijing

A new modified 718 alloy designated as Allvac® 718Plus™ has been developed by ATI Allvac to be used at 700°. For phase characterization, heat treatment selection and structure stability evaluation in high temperature range the determination of T-T-T diagram for 718Plus™ is not only a basic research but also a important matter for the alloy application at high temperatures. The chemical composition of alloy 718Plus™ for this study is 0.028%C, 17.42%Cr, 2.72%Mo, 1.04%W, 9.13%Co, 9.66%Fe, 5.48%Nb, 1.46%Al, 0.71%Ti and Ni in balance. The conventional alloy 718 has been also studied for comparison. Both alloys were solution treated at 1040° for full solution of precipitated phases except stable carbide MC. After solution treatment both alloy samples were thermal treated at 649°,732°,816°,850°,900°, and 954°, for the dwelling time from 3 minutes until 100 hours. Phase identification was mainly by means of SEM, XRD and partially TEM and SAD. Hardness test was also conducted on the samples as the indication of γ'' and γ' precipitation hardening. The experimental determined T-T-T diagrams were also compared with those calculated by Thermo Tech software. A detail discussion on the phase formation and alloy element affect on phase precipitation behavior has been described in this paper.

3:50 PM
Evaluation of Allvac® 718Plus™ in the Cold Worked and Heat Treated Condition: *Betsy J. Bond*[1]; [1]ATI Allvac

Cold worked and heat treated alloys such as 718 and Waspaloy have been successfully used for many years as high strength, high temperature fasteners. Newly developed alloy 718Plus™ has high strength, a significant temperature advantage over alloy 718 and a cost advantage over Waspaloy. The alloy also has excellent workability, similar to alloy 718, and has demonstrated a good response to direct age processing. These characteristics suggest it may be a desirable candidate for fastener applications. This paper examines the effects of a range of cold work on the mechanical properties of alloy 718Plus™. Cold working followed by direct aging results in a substantial increase in strength for alloy 718Plus™, with an associated loss in ductility, from room temperature through at least 1300°F. Properties are presented in comparison to traditional alloys. Both direct age and solution and age conditions are evaluated.

4:10 PM
Application of Direct Aging to Allvac® 718Plus™ Alloy for Improved Performance: *Wei-Di Cao*[1]; Richard L. Kennedy[1]; [1]ATI Allvac

Direct age processing results in significant improvement in mechanical properties of alloy 718. However, the effectiveness of direct aging in improving the performance of γ' strengthened alloys, such as Waspaloy, is not high, probably due to the rapid precipitation kinetics of γ' phase. Allvac® 718Plus™ alloy developed at ATI Allvac, shows excellent mechanical properties and high thermal stability up to 1300°F and processability approaching that of alloy 718. Since 718Plus™ alloy is gamma prime strengthened, it was uncertain if direct aging could improve its performance to the same degree as in alloy 718. However, the precipitation kinetics of γ' phase in this alloy are more sluggish than in normal γ' strengthening alloys. Thus it was of interest to determine if direct aging could be an effective strengthening method in this alloy, and if so, what would be the optimum process conditions. A test program was initiated involving a series of press forged pancakes. The variables evaluated included forging temperature, forging reduction and post-forging cooling rate. Testing included 1300°F tensile and 1300°F/80 ksi stress rupture along with creep and thermal stability tests on selected direct aged conditions. Microstructure after different direct aging treatments was examined. The results demonstrated that direct aging is feasible at a production scale for alloy 718Plus™ and significant improvement in performance can be achieved under well-controlled conditions. The mechanism responsible for such improvement is briefly discussed.

4:30 PM
Investment Casting of Allvac® 718Plus™ Alloy: *Kevin E. Kloske*[1]; Min Lu[2]; Thomas D. Bayha[3]; [1]Pratt & Whitney; [2]PCC Structurals, Inc.; [3]ATI Allvac

Many jet engine structural components are fabricated using investment castings, generally a lower-cost material alternative to built-up structures. Waspaloy is a nickel-base, age-hardenable superalloy with excellent high-temperature strength and good oxidation resistance, utilized in rotating aeroengine components up to 1300°F and higher temperatures for static components. Typical engine applications include casings, frames and rings. The producibility issues involving investment casting of Waspaloy range from too poor hot tear resistance to extensive welding and heat treatment requirements. Additionally, the raw materials for Waspaloy are very expensive. Allvac® 718Plus™ was developed as a cast-wrought material as a lower-cost alternative with elevated temperature mechanical properties roughly equivalent to those for alloys such as Waspaloy. Cast/wrought 718Plus™ also has formability and weldability characteristics that are very comparable to Alloy 718. Previous ATI Allvac evaluation of 718Plus™ cast-to-size test bars provided tensile yield strength of approximately 100 ksi at 1300°F. An evaluation of the producibility of investment cast components is necessary to determine suitability for Waspaloy replacement in high performance aeroengine components. The objective of this work is to evaluate and compare the castability of model components of 718Plus™ to Waspaloy. Generic molds to compare the fill, hot tearing and weldability of the two materials were investment cast and processed. Samples were excised from the castings and tested mechanically and compared to program goals.

4:50 PM
Effect of Thermal-Mechanical Treatment on the Fatigue Crack Propagation Behavior of Newly Developed Allvac® 718Plus™ Alloy: *Xingbo Liu*[1]; Jing Xu[1]; Nate Deem[1]; Keh-Minn Chang[1]; Ever J. Barbero[1]; Wei-Di Cao[2]; Richard L. Kennedy[2]; Tadeu Carneiro[3]; [1]West Virginia University; [2]ATI Allvac; [3]Companhia Brasileira de Metalurgia e Mineração

The newly developed Allvac® 718Plus™ alloy has shown superior tensile and stress rupture properties to alloy 718 and comparable properties to Waspaloy at the temperature up to 704°C. Regarding fatigue crack growth resistance, preliminary results show that for the FCG without holding time, there is no significant difference between the three alloys although, 718Plus™ has the best FCGR resistance and 718 the lowest. In hold time FCG, 718Plus™ shows comparable results to those of Waspaloy and both alloys show better FCG properties than Alloy 718. In addition to the normal solution plus aging heat treatment the effect of various thermal-mechanical treatments, including direct aging, pre-solution treatment, and long-term exposure, on the hold-time FCG behavior of 718Plus™ alloy were investigated and the results are summarized as follows: 1. The alloy shows elongated grain structure after DA. The hold-time FCGR of DA sample is slightly faster than that of the alloy without DA treatment. 2. Various pre-treatments were carried out to investigate the delta-phase effect and find the optimum delta-phase distribution. The results show that after pre-treatment at 857°C with up to 24 hours, the alloy's fatigue cracking resistance is improved because of delta-phase at grain boundaries. However, further increase of pre-treatment time to 48 hours reduces the alloys hold-time fatigue cracking resistance because of excessive delta-phase precipitation. 3. The long-term exposure tests show that the alloy's hold-time fatigue cracking resistance is improved after exposed at 760°C with 350 hours, which means that this alloy has good long-term structural stability.

5:10 PM

Properties and Microstructure of Allvac® 718Plus™ Rolled Sheet: Thomas D. Bayha[1]; *David Bergstrom*[2]; [1]ATI Allvac; [2]ATI Allegheny Ludlum

Design and construction of advanced aerospace systems capable of meeting demands of access-to-space, operations in and through space, and high speed/hypersonic flight are constrained by material challenges. Requirements for airplane-like operations of reusable systems fall most heavily on the needs for improved thermal protection systems and durable, lightweight structures. Robust and affordable industrial manufacturing procedures for these material systems frequently do not exist, even for materials such as nickel-based superalloys, which have attractive high-temperature performance, manufacturability, cost and durability. Applications of Alloy 718 are restricted to about 1200°F. Above this temperature the Ni_3Nb strengthening phase over-ages, and properties, particularly creep resistance, fall dramatically. There is a need for an alloy that maintains the excellent properties and processing characteristics of 718 to higher use temperatures. Allvac® 718Plus™ meets this need. The new alloy shows excellent hot-workability and weldability relative to Alloy 718, and better stress rupture and creep properties at 1300°F than Waspaloy. Only a small drop in mechanical properties is observed after long-term thermal exposure up to 1400°F. The Air Force Research Laboratory has funded ATI to evaluate the suitability of Allvac 718Plus™ rolled sheet product for elevated temperature applications. Hot- and cold-rolled sheet processes have been utilized to manufacture thin sheet of suitable for forming into structural components. Microstructure and mechanical property characterizations have been conducted to assess the sheet product capability in elevated temperature structural applications.

Tuesday AM, October 4, 2005 Processing Effects and Physical Metallurgy

Session Chairs: Alec Mitchell, University of British Columbia; John J. Schirra, Pratt & Whitney

8:30 AM

Characteristics of VIM/VAR Processed Alloy 718 Ingot and the Evolution of Microstructure during Cogging: *Nho-Kwang Park*[1]; J. -T. Yeom[1]; X. -X. Cui[1]; [1]Korea Institute of Machinery & Materials

Alloy 718 ingot with 300mm diameter was made by advanced vacuum melting process, i.e., VIM (vacuum induction melting) followed by VAR (vacuum arc re-melting). The ingot structure was characterized for the cogging process design essentially to achieve uniform structure and proper mechanical properties in the final billet. The remelting stock with inhomogeneous casting structures was homogenized and broken down by controlled cogging processes for uniform chemistry and microstructures, and sound mechanical properties. The VIM/VAR-processed ingot inherently contained three microstructure zones in radial direction, i.e. surface chill zone, intermediate columnar gain zone, and central equiaxed grain zone, because the overall solidification process varied depending on the location of the ingot. To understand the local deformation behavior and microstructure evolution of the ingot, compression tests were conducted on samples collected from different areas of the ingot in a wide temperature and strain rate ranges, i.e. 900~1150°C and 0.01~s^{-1}. The difference in microstructures within the ingot resulted in different compression behavior, which is attributed to the formation of preferred orientation in the columnar grain zone. The local deformation behavior of the ingot is highlighted in relation to the microstructural evolution. [1]R. M. F. Jones and L. A. Jackman, *JOM* 51(1) (1999), p. 27.

8:50 AM

Modeling Microstructure Evolution in 718 Ingot to Billet Conversion: *William Carden*[1]; [1]Vista Engineering, Inc.

Alloy 718 billet production is a complex process intended to convert the as-cast ingot microstructure to a fine grain, uniform and equiaxed grain structure. For billets used in the production of turbine disks, meeting microstructural requirements consistently and efficiently is critical to billet producers. To this end, studies were conducted to construct a profile of recrystallization during intermediate stages of the conversion process. Two 6,000 pound VIM-VAR ingots were processed normally through the first cogging pass and second upset operation. The partially transformed ingots were evaluated, modeled by finite element analysis, and sectioned for subsequent hot compression testing. A series of hot compression tests were used to replicate a range of thermo-mechanical conditions in the upsetting process. Quantitative microstructural information from the hot compression samples was used to create a collection of data for correlation of 718 microstructure evolution with the thermo-mechanical history of the material. Using this database, an empirical model was developed to predict microstructure evolution during 718 processing. A prototype software program is under development that would allow billet manufacturers to predict microstructures and optimize processing steps.

9:10 AM

Analysis of Microstructural Properties of IN718 After High Speed Forging: *Lars Renhof*[1]; Susanne Guder[1]; Ewald Werner[1]; Martin Stockinger[2]; [1]Technical University Munich; [2]Boehler Schmiedetechnik

The precipitation of the γ''-Phase is the key to the excellent mechanical properties of IN718. These can be improved by forging the material on a screw press (SP) instead of a hydraulic press (HP). The increase in hardness cannot be explained by grain size effects but is due to fine dispersed particles of about 5 to 10 nm in size for air cooled specimens and 3 to 5 nm for water quenched specimens. The time temperature transformation diagram of IN718 predicts the precipitation of the γ''-Phase during air cooling from the forging temperature but not for water quenching. Therefore it seems that the standard-TTT-diagram for IN718 is not applicable to SP-material as the precipitates develop much earlier than predicted. In this work investigations studying the effects of high strain rate forging on the precipitation behavior of IN718 are discussed. As main result a new TTT-diagram for SP-forged IN718 is introduced.

9:30 AM

Combined Effects of Large Reductions and Heating Temperatures-Times on Grain Size Control of Alloy-718 Rolled Rings: *Jorge A. Manriquez*[1]; Jorge Cardenas[2]; Hugo Guajardo[2]; Chris Harwood[2]; [1]Tecnologico de Monterrey; [2]Frisa-Wyman Gordon

This paper reports the results of an experimental study designed to evaluate the combined effects of critical process variables on grain recrystallization of VIM/VAR alloy 718 rings, rolled under production-size conditions. Forging temperatures and furnace dwell-times, as well as reduction percents during the final rolling pass, represented production conditions of critical impact on the integrity of the ring's mechanical properties. Final forging temperatures of 1900°F and 1825°F were used to achieve above and below delta-solvus conditions, respectively. Dwell-times at furnace of 30, 90 and 180 minutes were used to study the effects of residence time in the furnace prior to final rolling. Reduction percents of 10, 20 and 30% were applied during the final rolling pass, with total reductions in each case being, correspondingly, 20, 35 and 60%. Optical and electron microscopy (SEM-EDX) were used to characterize forged microstructures. It was found that the most notable effects on the size distribution of recrystallized grains along the part volume, came from temperature variation at long times regardless of the reduction percents. The combination of a 30% reduction, and 30 minute furnace time at 1825°F produced the finest microstructure (8.0 ASTM; ala 6.0) in the forged part. Pinning of grain boundaries by precipitating blocky delta particles was confirmed to be the mechanism for controlling grain recrystallization during final forging. Grain size maps were constructed to identify trends and to understand the grain recrystallization behavior of the forged microstructure. A correlation of observed recrystallization behavior with hardness was also analyzed.

9:50 AM

The Use and Performance of Wrought 625 Alloy in Primary Surface Recuperators for Gas Turbine Engines: *James M. Rakowski*[1]; Charles Stinner[1]; [1]Allegheny Ludlum

Recuperation increases the efficiency of a gas turbine engine by extracting heat from the exhaust gas stream and using it to pre–heat the compressor discharge air. High temperature oxidation and creep are major concerns, necessitating the use of heat–resistant alloys for the recuperator panels. Most current recuperator designs specify austenitic stainless steel foil as the material of construction. Water vapor, present in the exhaust gas as a by-product of combustion, has been shown to be detrimental to elevated temperature oxidation resistance, particularly for ferrous alloys. The protective chromium oxide scale breaks down rapidly in the presence of water vapor due to the formation of fast-growing iron oxide nodules. Increasing the amount of chromium and nickel appears to alleviate the risk of breakaway oxidation. Alloy 625, a common wrought nickel–base superalloy, is a candidate material for recuperator air cells. Long–term oxidation testing of 100 micron thick samples performed at 704–815°C (1300–1500°F) did not result in breakaway oxidation but indicated a tendency towards weight loss. The observed oxidation kinetics can be explained by a model combining the simultaneous growth and evaporation of an oxide layer. Evaporation of chromia appears to be accelerated in the presence of water vapor by the formation of volatile species such as chromium oxyhydroxide. Comparing these results to those of other nickel-base superalloys such as Alloy HX, and high-alloy content stainless steels, revealed that minor element chemistry can be modified to mitigate evaporation by the formation of an external spinel oxide layer.

10:10 AM

The Effect of Nb, Ti, Al on Precipitation and Strengthening Behavior on 718 Type Superalloys: *Xishan Xie*[1]; [1]University of Science and Technology Beijing

Inconel 718 characterizes with unique mechanical properties and has wild application in different high temperature industries. However, the ceiling temperature for Alloy 718 is 650° because of the stability of main strengthening phase γ''-Ni3(Nb,Ti,Al). At high temperatures the meta-stable γ'' changes for stable phase δ-Ni3Nb with large size and plate-like morphology. In result of that Alloy 718 looses structure stability and strengthening effect. Recently, many researchers have studied the stability of Alloy 718 and try to develop modified 718 Alloys to be used beyond 650°. The basic idea of this paper is to raise the stability of γ'' and γ' strengthening phases in the following ways: raising the solution temperature of γ'' and γ', retarding the γ'' phase change for δ-Ni3Nb and changing the precipitation behavior of Ni3M phase. The experimental heats were prepared for this study in variation of Nb, Ti, Al and the atomic ratio among them on the base chemical composition of Alloy 718. The precipitated phase γ'' and γ' behavior was studied in detail by means of SEM and TEM and the weight fraction of γ''+γ' phases was exactly determined by electrolytic isolation and followed by micro-chemical analyses. The mechanical properties including hardness, tensile properties and stress rupture for several heats were also tested. The structure of a new developed 718 modified Alloy-Allvac

718Plus™ has been also adopted for comparison. A detail discussion has been conducted for 718 type superalloys in structure stability and strengthening effect both.

10:30 AM Break

10:50 AM
Primary Carbide Precipitation in IN718: *Alec Mitchell*[1]; [1]University of British Columbia

Several studies are reported in the literature on primary carbide precipitation in alloy 718, including a proposed pseudo-phase diagram. However, the experimental work supporting the proposed models of precipitation is sparse in respect of composition variations. In this study we report the results of work to define the carbide precipitation schemes as a function of temperature freezing rate, Nb and C contents in alloys with a constant nitrogen content. The composition ranges chosen are all within the normal range of commercial specifications. The work consists of DSQ and DTA studies supplemented by metallography and micro-analysis. The carbide volume fraction and size distributions are also reported. We present a relationship defining the limits of carbide precipitation as a function of composition. The precipitates are shown to have a volume fraction and size distribution which is related to freezing rate as well as to composition.

11:10 AM
The Effect of Sheet Processing on the Elevated Temperature Strength and Creep Behavior of INCONEL Alloy 718: *Carl J. Boehlert*[1]; Nate Eisinger[2]; [1]Michigan State University; [2]Special Metals Corporation

The grain size, grain boundary character distribution (GBCD), creep, and tensile behavior of INCONEL alloy 718 were investigated to identify processing-microstructure-property relationships. The alloy was cold rolled (CR) to 0, 10, 20, 30, 40, 60, and 80% followed by annealing at temperatures between 954-1050°C then aging. The creep behavior was evaluated in the applied stress range of 172-700MPa and the temperature range of 638-700°C. Tensile creep experiments were used to measure the values of the steady-state creep rate and the consecutive load reduction method was used to determine the values of backstress. The lowest backstress values (300MPa<sigma<310MPa) were exhibited for the most severely CR microstructures, while the baseline 0%CR microstructure exhibited a significantly greater backstress value (540MPa). The greatest backstress values, 620 and 610MPa, were exhibited by the 20% and 30%CR conditions, respectively. The values for the effective stress exponent, 1<ne<2, and activation energy, Qa=304kJ/mol, suggested that the transition between the rate-controlling creep mechanisms was dependent on effective stresses. Overall, the 20%CR and 30%CR microstructures exhibited the most attractive combination of elevated temperature tensile and creep strength, while the most severely CR materials exhibited the poorest elevated-temperature properties. Electron backscattered diffraction was performed to identify the GBCD as a function of CR and annealing. The data indicated that annealing above 1010°C increased the grain size and resulted in a greater fraction of twin boundaries, which in turn increased the fraction of coincident site lattice boundaries. This result is discussed in light of the potential to grain boundary engineer this alloy.

11:30 AM
Predicting Microstructural Transitions via Computer Modeling and the Importance of Strain and Temperature in IN718 Forging Design: Andrew Haynes[1]; *Tim Howson*[2]; [1]Pratt & Whitney; [2]Wyman-Gordon Forgings

Press forged IN718 is widely used for high strength gas turbine engine disks. Meeting yield strength requirements with statistical process capability is important for these high strength applications and that capability depends on the microstructure of the material, with subtle microstructural differences having an effect on yield strength. The differences in microstructure within a forging can be related back to the strain and temperature history of any one area, which can now be readily simulated with computer software. Linking the capability of the computer simulation software, microstructure and tensile properties to design in process capability has been the goal of forgers, researchers and OEM users of IN718 for the last decade. While generic rules of thumb and historical experience is sufficient for forging design in most cases, emphasis on weight reduction and process capability from the very first part, has increased the need for greater precision in forging design requirements. Additionally the relationship between strain and temperature in the development of a forging microstructure can be manipulated in forging design, if material models are further developed. Analysis of 1200°F tensile strength from solution treated and aged IN718 forgings as well as microstructure and the results of forging simulations were combined to regress a simple formula that would predict transitions in the microstructure that were associated with tensile scatter. This model was then modified into a design criteria that was applied to forging simulations for both validation and modification of forging designs.

11:50 AM
Metallurgical Evaluation of Spray Deposited and Ring Rolled IN718: *Guoqing Zhang*[1]; [1]BIAM

IN718 has been developed in China for applications as aero-engine disks, seals and rings during the last twenty years. Although wrought products of IN718 could meet the requirements of aero-engine components, they exhibited chemical segregation and large grain structure and were difficult-to-process. To overcome the problems encountered with the wrought alloy, a research program aims to develop a unique spray forming process to make sound ring performs and ring rolled parts. Trials were conducted to optimize the process parameters for producing high quality rings. This paper summarizes the results of metallurgical and mechanical evaluation for IN718 in the forms of as-sprayed, spray formed plus ring rolled preforms. Compared to the ingot metallurgy process for wrought products, the unique spray forming process utilized in the program was capable of producing ring preforms with remarkably reduced segregation, finer and more homogeneous microstructure, significantly improved hot workability, and comparable and improved mechanical properties. It was indicated from the evaluation that spray forming could also be utilized to process more highly alloyed and more difficult-to-process than the conventional wrought IN718, and even previously non-forgeable alloys.

Tuesday PM, October 4, 2005
Physical Metallurgy

Session Chairs: Robin C. Schwant, General Electric Company; Gaylord D. Smith, Special Metals Corporation

1:30 PM
A Structural Comparison of Alloy 718Plus™ to Alloy 718: *John F. Radavich*[1]; Tadeu Carneiro[2]; [1]Micro-Met Laboratories, Inc.; [2]Reference Metals Company Inc

A study was carried out on alloy 718Plus™ to compare the structural preparation and phase behavior to that of alloy 718. It was found that a number of electrolytic preparations that are used for alloy 718 can be used for alloy 718Plus™ depending on the thermal condition of the alloy. Unlike the gamma double prime and gamma prime phases in alloy 718, the strengthening phase appears to be gamma prime in alloy 718Plus™ which is formed during the aging treatment at 7880°C (1450°F). Various preparation techniques as well as structures in alloy 718Plus™ and in alloy 718 will be presented.

1:50 PM
Carbides and Their Influence on Notched Low Cycle Fatigue Behavior of Fine-Grained IN718 Gas Turbine Disk Material: *Prabir R. Bhowal*[1]; Agnieszka Wusatowska-Sarnek[1]; [1]Pratt & Whitney

Notched low cycle fatigue properties were evaluated in forged Inconel 718 superalloy heat treated with conventional solution and aging cycles. The microstructure of the material was fine-grained with average grain size of 11 microns and with occasional grains as large as 30-40 microns. Tests were conducted at room, intermediate (290 and 450°C) and higher (540 and 610°C) temperatures at several levels of notch root 'concentrated' stresses (1400-1650 MPa). The cycles to failure were analyzed in terms of stress, temperature and fatigue initiation sites. In all tests, fatigue originated from either grain facets or carbides, and the relative occurrence of each depended on temperature and stress of the test. At lower temperatures and high stress amplitudes, carbide initiation was dominant, but with increase in test temperature and reduced stress, grain facet initiation was observed. The fatigue life reduction due to carbide initiation (relative to the grain facet initiation) was significant at lower temperature/high stress conditions. In such situation, improvement of fatigue properties from fine-grained microstructure could not be attained. These results are discussed in terms of cracking of carbides that was promoted by carbide brittleness at lower temperatures, a high 'concentrated' notch-root stress and larger carbide size.

2:10 PM
Characterization of the Effect of Discrete Laves Particles on Low Cycle Fatigue Lives in Premium Grade Forged and Heat-Treated Inconel 718: *Robert A. Grelotti*[1]; Paul D. Genereux[1]; John J. Schirra[1]; [1]Pratt & Whitney

Increasing usage requirements in gas turbine engines requires strict quality control of secondary phases in premium grade wrought Inconel 718. In addition, process control has reached a level of maturity where the occurrence of intrinsic melt defects has been minimized. Previous evaluations have used modified process parameters to produce and evaluate the effect of Laves phase on Inconel 718 behavior. In this paper the effect of Laves formed in conjunction with freckles during industrial processing on low cycle fatigue behavior at 288°C (550°F) under R = .05 and 1034 MPa (150 KSI) test conditions was evaluated. The material tested was a forged and heat-treated Inconel 718 disk which was observed to have laves laden equiaxed and elongated freckles. Freckles were captured in the gage of the LCF specimen, tested in a servo hydraulic load frame in load control to rupture. The results indicated an approximate 3X reduction of life. Scanning Electron Microscopy (SEM / EDS) and Electron Micro Probe (EMP / WDS) verified that the globular particles in the freckle region were Laves phase (consistent with the presence of segregation in a freckle). Despite an elevated amount of matrix MC carbides the Laves particles were the predominant fatigue origins. Interrupted test inspections and post-test analysis of the fracture surface indicated that the freckled specimens exhibited a fatigue crack initiation incubation life reduction relative to baseline specimens, however, a significant fatigue incubation time was still observed indicating the availability of a usable LCF life.

2:30 PM
Effect of Delta-Phase on the Hot Ductility of Wrought Alloy 718: *Göran P. Sjöberg*[1]; Tomas Antonsson[2]; Hans Fredriksson[2]; Saied Azadian[3]; Richard Warren[4]; [1]Volvo Aero Corporation; [2]Royal Institute of Technology; [3]Luleå University of Technology; [4]Malmö Högskola

In weld repair cycles of wrought alloy 718 the solution temperature is usually selected low enough to avoid grain growth in order to preserve the fatigue properties. At such temperatures, however, delta-phase also precipitates and the amount increases with each repair cycle. It is well understood that the overall ductility is reduced by the presence of the delta-phase in alloy 718 and, as such, may reduce the repair weldability. But it is also reported that the delta-phase may cause incipient melting at heat affected zone, HAZ, grain boundaries through a niobium rich melt fed by the local abundance of this element from attached delta-phase platelets. The purpose of the present work was to shed light on this issue through experiments in a special hot tensile test equipment. In this equipment the hot ductility of re-melted material was also possible to examine. Materials with two levels of delta phase and with two grain sizes were included. To reveal possible niobium segregation at grain boundaries secondary ion mass spectroscopy (SIMS) was used. The hot ductility test results, measured as the high temperature ductility recovery temperature and range, indicated that there is no deterioration by the presence of delta-phase. Neither did the SIMS examination suggest any local grain boundary enrichment of niobium. Anomalous results, much lower ductility recovery temperatures, were found in samples with large grain size and a small amount of delta-phase. For re-melted samples several hundred degrees lower recovery temperatures were measured.

2:50 PM

High Temperature Hold Time Effects on Fine Grain Processed 718 Fatigue Properties: *Dan Greving*[1]; Harry Kington[1]; Derek Rice[1]; Brian Hann[1]; [1]Honeywell Engines, Systems & Services

Fine Grain Alloy 718 is a relatively cost effective turbine and compressor disk alloy with superior yield strength and low cycle fatigue properties. An understanding of Alloy 718's response to environmental and temperature conditions under sustained peak or dwell conditions is a requirement for assessing actual in-service capability. This is especially critical when the disk operating conditions exceed historical engine experience with Alloy 718. This paper presents a detailed review of experimental dwell low cycle fatigue and cyclic crack growth results for fine grain alloy 718. The experimental fatigue results combined with the observed physical initiation and propagation mechanisms were used to develop a comprehensive life prediction system for fine grain Alloy 718 turbine disk.

3:10 PM Break

3:30 PM

Influence of Thermal Exposure on the Microstructure of Delta Processed Billet and Bar for Alloy 718: *Jeffrey Russell*[1]; [1]ATI Allvac

Delta processing of alloy 718 billet and bar provides a means to achieve very fine grain structures in rotating turbine engine components. However, thermal stability of the forging stock must be well characterized to establish practices for forging parts; temperatures arid times for these practices must avoid excessive grain coarsening without adversely affecting properties such as creep. This study investigated thermal stability for forging stock 2.5, 5.5, and 8 inches in diameter representing various distributions of delta phase. Hot working sequences for producing this material included a delta precipitation heat treatment. Thermal stability was evaluated by exposing the billet and bar to a wide range of temperatures and times. Analysis included measuring volume fractions and characterizing morphologies of delta phase.

3:50 PM

Dynamic and Metadynamic Recrystallisation of IN718: *Robert P. Guest*[1]; Sammy Tin[2]; [1]Firth Rixson Ltd; [2]Cambridge University

The recrystallisation kinetics of IN718 were investigated by the compression of cylindrical samples (12mm length, 8mm diameter) in a Gleeble 1500. Tests were conducted at temperatures of 980°C and 1040°C to strains up to 0.82, at strain rates between 0.01 and 1.1s-1, followed by a hold period of between 0 and 60 seconds before water quenching. This enabled microstructures representative of the hot-worked condition to be retained, and the separate dynamic and metadynamic processes to be identified. The critical strain for the onset of recrystallisation (ec) was identified to occur at e˜0.15, irrespective of the strain rate. Microstructurally, specimens deformed to strains of ~0.3 are identical. As dynamic recrystallisation progresses during deformation at strains above ec, the newly recrystallised grains begin to grow. The degree to which these grains can grow, however, is dictated by the strain rate. For high strain rates (>0.1s-1), recrystallised grains will only grow into the deformed matrix a small amount before the dislocation density either side of the moving interface becomes equal. For low strain rates (<0.1s-1), however, the grains can grow for a longer period of time before the driving force for the boundary migration ceases to exist. Once the new grains have reached their maximum size, the new grain boundary area can act as nucleation sites for more recrystallisation. Thus, microstructures deformed at high strain rates contain a higher density of recrystallisation nuclei. Metadynamic recrystallisation kinetics were seen to be extremely rapid, with complete recrystallisation occurring within 30s at 980°C.

4:10 PM

Modelling Microstructural Transformations of Nickel Base Superalloy IN718 during Hot Deformation: *Robert P. Guest*[1]; Sammy Tin[2]; [1]Firth Rixson Ltd; [2]Cambridge University

A predictive constitutive model has been developed to simulate microstructural changes of IN718 during hot deformation. The numerical model, written in Matlab, can be coupled to existing commercial finite element analysis software packages. Utilising the basic input parameters, the model accurately predicts changes in volume fraction recrystallised and provides grain size distributions. The model is sensitive to the initial microstructure (initial grain size and precipitate volume fraction), and to temperature, strain, and strain rate. Unlike other models, the microstructure is simulated stepwise during the processing, so changes in temperature and strain rate occurring during deformation can be modelled. The model has the capability to simulate microstructural evolution not only during deformation, but also pre and post deformation, resulting in a single tool capable of tracking the microstructure through an entire forging process. Predicted microstructures produced by the model have been experimentally validated against a large series of Gleeble 1500 hot compression tests, and large-scale industrial forgings. The model accurately predicts both the volume fraction recrystallised and produces a grain size distribution comparable to that found experimentally. This new model, therefore, advances the currently available models where the output is simply a volume fraction recrystallised and a single value for recrystallised grain size.

4:30 PM

Influence of P on Creep Performance of DA IN718: *Joe Heaney*[1]; Jeff Russell[2]; Pawel Mrowczynski[3]; [1]GE/MPED; [2]ATI Allvac; [3]Wyman Gordon Forgings

Achieving a balance between LCF and creep in IN718 critical rotating hardware has become challenging as the application conditions of IN718 become more aggressive and geometries more challenging. Optimization of both forge practices and of minor chemistry variations are required to meet this property balance. A review of potential factors influencing creep variation in direct age IN718 forgings identified phosphorus level as a statistically significant factor over the range of 50 ppm to 120 ppm. Verification of the findings was accomplished using a combination of subscale IN718 heats and a series of full scale heats with phosphorus levels targeted to an 80 ppm minimum. Data from the 13 VIM heats included 98 creep tests spread across multiple forgings exhibited an average creep life of 114 hours with Q1 and Q3 distributions of 77 hours and 140 hours, respectively, when tested at 1100F/120 KSI and 0.2% strain. This is a 52% increase in mean life from historical levels. The results of the evaluation show phosphorus levels above 80ppm but below 150 ppm will improve creep performance of DA IN718, provided a stable and robust forge process is used.

4:50 PM

Influence of Phosphorus on the Deformation Mechanism and Mechanical Properties of IN718 Alloy: *Wenru Sun*[1]; L. F. Huang[1]; S. L. Yang[1]; S. R. Guo[1]; Z. Q. Hu[1]; [1]Chinese Academy of Sciences

The phosphorus level in the IN718 alloy of the test is as follows (mass %): 0.0008, 0.016, 0.040. After homogenizing, forging and rolling, the alloys with different phosphorus additions were given a standard heat treatment of IN718 alloy. The alloy deformed by the dislocation glide during the rolling at 1100°C, the tension and the impact at room temperature. While deformed by the dislocation glide as well as the twin formation during the tension at 650°C. A large quantity of thin twin bands was easily observed and the dislocations were difficult to be found in the microstructure of the crept specimens under 650°C and 690MPa. By comparison and analysis of the deformation forms under different conditions, it was concluded that the twin formation in the IN718 alloys under the low level of stress such as creep is a thermal activated process. For the alloy with 0.016% phosphorus addition, twins were found to be formed in three directions intersected with each other. While for alloy with 0.0008% and 0.040% phosphors addition, twins could only be formed in not more than two directions. Phosphorus hardly influenced the tensile properties of IN718 alloy at room temperature and 650°C, while it at 0.40% addition reduced the impact energy of the alloy. When phosphorus level was increased from 0.0008% to 0.016%, it greatly decreased steady creep rate and prolonged steady creep stage and hence the rupture life of IN718 alloy. The effect of phosphorus on the deformation and mechanical properties of the IN718 alloy was analyzed.

5:10 PM

Alloy 625 and 725 Trends in Properties and Applications: *Lewis Edward Shoemaker*[1]; [1]Special Metals Corporation

INCONEL® alloy 625 (UNS N06625) has been widely used for over 50 years in the marine and petroleum industries for applications requiring high strength, fracture toughness, fabricability and resistance to corrosion. By increasing the titanium content of the alloy in the presence of its content of niobium, an alloy that can be significantly strengthened by heat treatment is created. By the precipitation of various secondary phases in an austentitic matrix, INCONEL alloy 725 offers the high strength of alloy 718 along with the corrosion resistance of alloy 625. The metallurgy of alloy 725 is discussed along with information about its properties, fabrication, and applications. INCONEL is a registered trademark of the Special Metals family of companies.

5:30 PM

Heat Affected Zone Microfissuring in Electron Beam Welded Allvac 718 Plus™ Alloys: Krutika R. Vishwakarma[1]; Norman L. Richards[1]; *Mahesh C. Chaturvedi*[1]; [1]University of Manitoba

Allvac 718Plus™ alloy is a variation of Inconel 718 superalloy whose chemical composition was optimized to improve its high temperature properties over those of Waspaloy and Inconel 718. The chemistry of a superalloy is known to influence its welding characteristics, therefore this project was initiated to study the effect of concentrations of Band P and pre-weld heat treatments on weldability this alloy. Two versions of the alloy, HC 20 (0.003 wt% Boron, 0.006 wt% Phosphorus) and HC 49 (0.005 wt% B, 0.014 wt% P), along with Inconel 718 were used in this study. The samples were solutionized at 950°C and 1050°C followed by WQ, and then electron beam welded using bead-on-plate method. Microstructural evaluation was done by optical and analytical electron microscopy, and cracking susceptibility was determined by crack lengths measurements. Allvac 718Plus™ alloys exhibited a greater cracking susceptibility than Inconel 718. Of the two Allvac 718Plus™ alloys, the one with higher boron and phosphorus concentration was found to be more susceptible to HAZ cracking. The cracking also increased with the increase in the solutionizing temperature for all the alloys, which may be attributed to the increase in grain size. The HAZ cracks were often associated with liquated grain boundaries with re-solidified products on them, which were analyzed in detail by energy dispersive x-ray micro-analysis technique. The details of the microstructural and microfissuring analysis of the welds, and inter-relationship between them will be presented.

Tuesday Evening, October 4, 2005
Design, Processing, Properties

Session Chairs: John F. Radavich, Micro-Met Laboratories Inc; Edward A. Loria, Consultant

7:30 PM

Design Optimization of Alloying Elements and Their Concentrations for Specified Strength, Temperature, Time-to-Rupture, Cost and Weight: *George S. Dulikravich*[1]; Igor N. Egorov[2]; [1]Florida International University; [2]IOSO Technology Center

A brute-force optimization of an alloy with N alloying elements would involve creating an N-dimensional matrix of experimentally obtained data points and then interpolating and searching for the extreme points in such a matrix. If concentration of each alloying element is to be varied within a specified range, this variation could be approximated by, say, six parameters. This means that such an "optimization" of an N-component alloy would require creating and experimentally testing 6**N alloy samples for just one objective. In order to reduce time and cost, there have been efforts to develop and use several complex mathematical models based on thermodynamics of solids. However, the exclusive use of this approach has been shown to possess dubious reliability and versatility. This paper is based on the use of experimental data and a new evolutionary truly multi-objective optimization algorithm for simultaneously optimizing several properties of steel alloys while minimizing the number of experimental evaluations of the candidate alloys. This approach has been shown to have the potential of identifying new chemical compositions with as few as 80 new alloy samples that otherwise could not be identified with classical techniques without requiring thousands of new alloys. Furthermore, this approach has been demonstrated to have the potential for determining concentrations of alloying elements for a specified set of alloy's properties for specific applications, thereby maximizing their utilization. Cost and weight are two of the objectives in addition to the more standard simultaneous objectives like maximized operating temperature, tensile stress and time to rupture.

7:45 PM

Spray Forming and Post Processing of Superalloy Rings: *Michael Walter*[1]; Johann Tockner[2]; Martin Stockinger[2]; Nils Ellendt[3]; Volker Uhlenwinkel[3]; [1]Bohler Edelstahl GmbH; [2]Bohler Schmiedetechnik GmbH & Co KG; [3]University Bremen

Spray forming as a technology to produce near net shape components or preforms for additional forming operations with defined microstructural properties is well known for several alloys and applications. The production of spray formed superalloy rings made of IN718 and U720 for aero-engine components in order to reduce production cost is the goal of the current EU-research project. Several spray runs were carried out at University of Bremen to optimize the process parameters regarding a low porosity, low segregation and a high yield. Macro and micro-etchings were prepared to analyse the influence of the parameter variations on before mentioned structural properties. Several optimized rings were used to examine the influence of thermomechanical processing on porosity and microstructure of spray formed superalloy rings. Hot isostatic pressing and forging processes were performed separately as well as in combination in order to obtain the ideal post processing route, which was determined via microstructure analysis. As a result of this project, it became clear that HIPping is an integral part of the post-processing of as-sprayed material, due to the fact that it was not possible to produce as-sprayed material without porosity. The development of micro- and macrostructural properties through all these processes and their variations will be shown. Another paper presented here will focus on the final properties and applications of this material.

8:00 PM

A Unified Computer Model of the Spray Forming Process of Inconel 718 Billets and Rings: Iñaki Garmendia[1]; Aitor Landaberea[1]; Udo Fristching[2]; Omar Belkessam[2]; Patrick S. Grant[3]; *Jiawei Mi*[3]; [1]INASMET; [2]University Bremen; [3]University of Oxford

A complete computer model of the process of spray forming Inconel 718 billets and rings has been developed. The target of the model is to optimize the process input parameters to achieve a good shape, correct microstructure and small porosity final billet or ring. The model is divided in three main parts that correspond to the atomization phase of the material, the flight behaviour of the particles and the solidification and growth of the billet or ring. Different modelling techniques have been used for each part of the model. For the atomization step, stability analysis for the primary atomization and Samenfink model for secondary atomization were used. Computational fluid dynamics calculations for the thermal and mechanical behaviour of the droplets in their travel were also used for the in flight behaviour step. Shape and growth models, as well as thermal models, based on finite element calculations were also used to predict the final shape and temperature history of the final component. Various computer programs have been written to link results between different submodels and to transform the format of intermediate computer files. Sensitivity analysis on the influence of the different input parameters of the process has been done. Predictions of microstructure state, porosity and temperature/time history of different parts of the final components for different input parameters from the model are compared with real experiments, and some good correlations are found.

8:15 PM

Sprayforming Optimization of Superalloy Aeroengine Components: *Oscar Caballero*[1]; Dominique Fournier; Wilfried Smarsly[2]; [1]ITP; [2]MTU Aero Engines

The use of the sprayforming technologies has extended in several applications, with a range of components manufactured from different alloys. A research is presented here on the application of this process to the manufacture of Aeroengine Components in IN718 and U720 alloys. These components are mainly Low Pressure Turbine casings (and likely others of similar geometries), where the much shorter proposed manufacturing route would mean a significant cost reduction. The process key parameters ruling final results have been investigated and optimized, with the aid of modeling, to finally obtain a product with the appropriate quality to be used in the intended aerospace application. A different previous paper focuses on the spraying process parameters and post-processing routes optimization. Herein. the products coming from these different routes have been assessed through metallurgical evaluation and mechanical tests, and the results will be presented. All considered facts of technical suitability and economy of the proposed manufacturing route indicate the interest of availability of the process for Aeroengine Builders.

8:30 PM

Thermophysical Properties of IN738LC, MM247LC and CMSX-4 in the Liquid and High Temperature Solid Phase: *Rainer K. Wunderlich*[1]; H. J. Fecht[1]; L. Battezzati[2]; R. Brooks[3]; P. N. Quested[3]; I. Egry[4]; J. Etay[5]; J. P. Garandet[6]; B. Vinet[6]; K. C. Mills[7]; A. Passerone[8]; E. Ricci[8]; S. Seetharaman[9]; R. Aune[9]; [1]University of Ulm; [2]Universita di Torino; [3]National Physical Laboratory; [4]DLR-Köln; [5]CNRS EMP; [6]Commissariat à l'Energie Atomique/CEREM; [7]Imperial College; [8]IENI-CNR; [9]Royal Institute of Technology

The numerical simulation of casting and solidification has found widespread application in industry for process and product optimization. The predictive quality of numerical simulations is, however, limited by the accuracy and availability of thermophysical property values of liquid metallic alloys. The deficiency in these input values is caused by the difficulty of handling liquid metals for thermophysical property measurements at elevated temperatures. The ThermoLab project makes a dedicated effort for the measurement of thermophysical properties of industrial alloys in the liquid phase. Conventional techniques such as standard calorimetry and the laser flash method for calorimetric and transport properties, the sessile and pendant drop method for the surface tension and, the oscillating cup method for the viscosity are combined with containerless processing techniques such as electromagnetic levitation to arrive at best agreed upon values between the participating laboratories. In addition, measurements with an electromagnetic levitation device are performed under reduced gravitiy conditions such as available on parabolic and sounding rocket flights for the containerless measurement of the surface tension and the viscosity by the oscillating drop method, the heat of fusion, electrical resistivity and the ratio of the specific heat capacity to the total hemispherical emissivity. The alloys to be investigated are suggested by an industrial project user group. We report about specific results for the surface tension and the viscosity of IN738LC, CMSX-4 and MM247LC and, the thermal diffusivity and density of CMSX-4 in the liquid phase.

8:45 PM

Microstructural Investigations of Electron Beam Welded Alloy 718: *Sundararaman Mahadevan*[1]; Padmakar Potdar[1]; [1]Bhabha Atomic Research Centre

Electron beam welding is used to join components where welding distortions have to be minimized and good weld integrity is a must. This paper reports the results of microstructural investigations carried out on Alloy 718 welded in the aged condition. A region of width 200µm at a distance of 500µm from the fusion zone interface in the heat affected zone (HAZ) showed extensive deformation bands. Micro-hardness measurements showed softening in the HAZ region close to the fusion zone interface and hardness values the same as that of region far away from the weld zone in the rest of the areas including the deformed region. The influence of post weld heat treatments on integrity of weld was carried out. Profuse faulting and twinning and planar arrangement of dislocations were observed in the deformed region and in the areas close to fusion interface in the HAZ, dissolution of γ' particles has occurred. The present observations are rationalized in terms of the temperature seen in the HAZ zone and also the residual strain generated due to heating and microstructural changes during welding.

9:00 PM

A Comparison of the Precipitation Kinetics of γ" Particles in Virgin and Re-Solutioned Alloy 625: *Sundararaman Mahadevan*[1]; Hrishikesh Chidanand Pai[1]; [1]Bhabha Atomic Research Centre

Alloy 625 is used as superheater tubes and ammonia cracker tubes in many ammonia plants and in chemical industries. The components, made of this alloy are expected to have a life of about 100,000 hours at an operating temperature in the range of 450°C to 700°C. Since the availability of nickel is scarce and the alloy is very expensive, attempts are being made to resolution the material which has seen its service life and use it again. The data about the ageing behaviour of the resolutionised material under service conditions is necessary to determine the expected life of the component. The results of a detailed investigation on the kinetics of precipitation of intermetallic phases in the resolutioned material as well as virgin alloy are reported in this paper. The ageing behaviour of virgin and resolutioned material was found to be quite different. The distribution of γ' precipitates was non-uniform and the precipitation was found to occur heterogeneously on dislocations in the resolutioned specimens. These observations are discussed in the light of redistribution of different alloying elements during service and their effect on subsequent precipitation kinetics of resolutioned material.

9:15 PM

Notched Low Cycle Fatigue of Alloy 718: *A Sridhar*[1]; Vikas Kumar[2]; A. K. Gogia[1]; [1]Project Office (Materials); [2]Defence Metallurgical Research Laboratory

Low Cycle Fatigue (LCF) damage is the life-limiting factor for rotating components in advanced gas turbines. LCF tests in laboratory are generally conducted in strain control using smooth cylindrical specimens and smooth geometry may not represent actual component, as LCF life can be significantly influenced by notches present in components and the latter is not accounted by the data based on smooth specimens. Most of the data available in literature is generated using circumferential or single or double edge notch. Use of circumferential notch may not be entirely appropriate for comparison with smooth fatigue specimens, because of difference in their diameters, as there is a decrease in volume or surface area of the specimen as the diameter decreases, and this is of significance, since fatigue failures usually start at the surface. In the present study tangential slot notch was used to investigate the effect of slot notch on LCF behavior of Alloy 718 as it removes a very small percentage of the specimen cross-sectional area and does not cover entire circumference. So comparison can be made between the smooth and tangential notch specimens without much variation in their surface areas or volume. Effect of tangential slot notch on fatigue behavior of Alloy 718 is studied at ambient temperature and 650°C and comparison is made with smooth specimen data. Results indicate that tangential slot notch also reduces significantly the fatigue life of alloy 718 though it removes only a small amount of material from the gauge portion.

Wednesday AM, October 5, 2005
Processing Effects and Properties

Session Chairs: Joe Lemsky, Ladish Company, Inc.; Kevin E. Kloske, Pratt & Whitney

8:30 AM

Characterization of Residual Stresses in Turbine Discs by Neutron and High-Energy X-Ray Diffraction: Ulrike Cihak[1]; Helmut Clemens[1]; Peter Staron[2]; *Martin Stockinger*[3]; Johann Tockner[3]; Jens Homeyer[4]; [1]University Leoben; [2]GKSS Research Center; [3]Bohler Schmiedetechnik GmbH & Company KG; [4]HASYLAB at DESY

Knowledge of the evolution of residual stresses developing during fabrication of industrial components is steadily gaining importance. Therefore, the prevailing residual stresses in a number of identical, hot-forged, water quenched turbine discs made of nickel-base alloy IN718 have been studied by neutron diffraction. Simultaneously, independent finite element simulations (FEM) have been performed characterizing different quenching rates. The trend of these simulations agrees with that obtained from diffraction measurements. Although the (311) peak was used, which is generally recommended for fcc materials, the results exhibit an offset compared to the FEM results. To clarify this discrepancy further investigations, using an alternative peak, were carried out and a geometrically simple model plate of IN718 applying identical heat treatment conditions was studied. The results, received from the thin model plate and the thick commercial part, are compared with FEM predictions, which are based on detailed measurements of the heat transfer velocity during quenching.

8:50 AM

Residual Stresses in IN718 Turbine Disks: *Christian Krempaszky*[1]; Ewald Werner[1]; Martin Stockinger[2]; [1]TU-Munich; [2]Böhler Schmiedetechnik GmbH & Company KG

To obtain materials/components covering a wide range of conditions with characteristic mechanical properties, quenchings in connection with special heat treatments are of particular engineering importance. In addition to strength demands, reduction of production costs of forged parts by eliminating processing steps is essential. In this course a direct age version of IN718 has been proposed, for which an increase of strength is possible by precipitation strengthening during cooling from the forging temperature. The mechanical and thermal treatments inevitably result in residual stresses and distortions in the treated parts, which result either from coupled thermo-mechanical interactions during the usually rapid cooling from sufficiently high temperatures down to room temperature. Due to the macroscopic portion of the residual stress state (residual stresses of the 1st kind), machining of slender forged components may lead to severe distortion of the component. In the worst case, the dimensional accuracy of pre-finished components can not be achieved. Within the scope of this paper, residual stresses in forged, axisymmetric, plate-like components, e.g. turbine disks, of Ni-base superalloy IN718 are investigated with the focus on the distortion of the component during machining. To predict residual and thermal stresses which occur during quenching and their redistribution due to machining, appropriate semianalytic and finite element based models are set up and discussed. To verify the theoretical predictions of the residual stress state and the corresponding distortion resulting from machining, both (the residual stress state and the component distortion) are determined by experiment.

9:10 AM

Effect of Grain Size/Tensile Strength on the Low Cycle Fatigue at Elevated Temperature of Alloy 718 Cogged by Open Die Forging Press: *Y. S. Song*[1]; M. R. Lee[1]; J. T. Kim[1]; [1]Doosan Heavy Industry Company

Alloy 718 was prepared through Triple melting process utilizing VIM/VAR/VAR to get the high cleanliness with low inclusion contents and then cogged by open die forging press (1600T) precisely. The grain size was controlled from ASTM No. 9.0 to 4.0 by cogging condition, not heat treatment like solution treatment, respectively. Tensile strength test was investigated at elevated temperature from R.T to 649°C. Low cycle fatigue test was carried out at R.T,621° to 649°C with strain control; Total strain range was 0.6% to 1.4%. As expected, at higher strain range, lower fatigue lives were exhibited at higher temperature. In case that the grain size was ASTM No. 8, low cycle fatigue lives were remarkably improved compared with coarse grain size that has ASTM No. 4. In case of the coarse grain size, the difference value between the ultimate tensile strength and yield strength was closer, strain was to impose above the ultimate tensile strength. However, In case of the fine grain size, the difference value between the tensile strength and yield strength was bigger than the coarse grain size, observation of the microstructure and fracture surface by SEM was carried out to evaluate the direct relationship among the grain size, inclusion distribution and low cycle fatigue behavior.

9:30 AM

Effect of Portevin-Le Châtelier Instabilities on the Sensitivity of Alloy 718 to Oxidation Assisted Intergranular Cracking at High Temperatures: *Eric Andrieu*[1]; Jean Marc Cloue[2]; Bernard Viguier[1]; Veronique Garat[2]; [1]CIRIMAT- ENSIACET; [2]Framatome-ANP

The sensitivity of alloy 718 to O.A.I.C (Oxidation Assisted Intergranular Cracking) in the 500-700°C temperature range was investigated versus strain rate and environment (air or hydrogenated argon). In an inert atmosphere (ArH2), the fracture mode is ductile transgranular over the whole temperature and strain rate range explored, independently of the occurrence of Portevin-Le Châtelier (P.L.C) type instabilities. On the other hand, when the tests are run in an oxidizing atmosphere, a fracture mode transition (ductile transgranular to brittle intergranular) occurs concurrently with the disappearance of the flow instabilities. This experimental finding confirms what had been seen at lower temperature by other authors. Further imposed-load experiments seem to show that the disappearance of the intergranular fracture mode is not due to mechanical unloading of the structure, but rather to phenomena localized on the grain scale.

9:50 AM

High Temperature Intergranular Oxidation of Alloy 718: Eric Andrieu[1]; *Julien Deleume*[2]; Veronique Garat[2]; Jean Marc Cloue[2]; [1]CIRIMAT- ENSIACET; [2]Framatome ANP

Alloy 718 samples were oxidized in air in conditions close to those encountered during high-temperature heat treatments (shaping: about 1000°C) or in service (turbomachine disks: 650°C). The main objective of the study was to evaluate the impact of these treatments on oxygen penetration into the grain boundaries and, hence, to assess the harmfulness of these penetrations in terms of defect initiation and propagation. The method relies mainly on the SIMS-based imaging technique. This technique, which supplements those applied in previous studies, uses a series of basic maps to locate within the volume the oxygen in free or combined state, in relation with the microstructural features (grain boundaries, grains, delta phase, etc). The results point to intergranular oxidation for both exposure conditions without clearly demonstrating the existence of atomic oxygen penetrations. The affected depths seem sufficient both to form preferential initiation sites (oxidation at 1000°C) and to assist the intergranular propagation of defects and/or cracks (oxidation at 650°C).

10:10 AM

Modelling the Material Properties and Behaviour of Ni and Ni-Fe Based Superalloys: *Nigel John Saunders*[1]; Zhanli Guo[2]; Alfred Peter Miodownik[1]; Jean-Philippe Schille[2]; [1]Thermotech Ltd; [2]Sente Software Ltd.

Over the past decade thermodynamic models have become increasingly used for Ni- and NiFe-based superalloys. However, their applicability often falls short from directly providing the information that is actually required. To overcome such limitations a new computer programme has been developed, called JMatPro, an acronym for Java-based Materials Properties software. The properties which can be calculated are wide ranging, including thermo-physical and physical properties (from room temperature to the liquid state), TTT/CCT diagrams, coarsening of γ' and γ", and mechanical properties. It should be noted that the mechanical properties are calculated as a function of temperature and strain rate up to the melting point. Stress/strain diagrams at any given temperature and strain rate can also be generated. The creep properties that JMatPro can provide include steady creep rate, rupture life and rupture strength. A feature of the new programme is that the calculations are based, as far as possible, on sound physical principles rather than purely statistical methods. Thus many of the shortcomings of methods such as regression analysis can be overcome. It allows sensitivity to microstructure to be included for many of the properties and also means that the true inter-relationship between properties can be developed, for example in the modelling of creep and precipitation hardening. The purpose of the present paper is to describe the technical background behind the new programme, giving extensive examples of its application and use for superalloys of the 718, 625, 706 and derivative types.

10:30 AM Break

10:50 AM

Effects of Cyclic Solution Treatment on the Microstructures and Mechanical Properties of Alloy 718: *Jaekeun Hong*[1]; Jihong Park[1]; Nhokwang Park[1]; Seongjun Kim[2]; Chungyun Kang[2]; [1]Korea Institute of Machinary and Materials; [2]Pusan National University

Effects of solution treatment on the microstructure and mechanical properties in wrought Alloy 718 were investigated. For the improvement of tensile and fatigue properties of the alloy, a cyclic solution treatment, heating at 1000° for 3 minutes followed by furnace cooling at the rate of 3°/minute and holding at 985° for 8 minutes, was proposed. The cyclic treatment was performed repeatedly 3 times and the samples were air-cooled to room temperature. After the cyclic solution heat treatment, Alloy 718 was subject to the standard aging treatment, holding at 718° for 8 hours followed by cooling at 55°/hour and holding at 620° for 8 hours, and finally air cooling to room temperature. For comparison purposes, a standard heat treatment was also performed by solution treatment at 954° followed by aging. The microstructures of the heat-treated samples were analyzed by optical microscopy and scanning electron microscopy (SEM). Cyclic solution treatment resulted in the formation of small spherical shaped δ-phases without grain growth. However, the δ-phases of the standard heat-treated specimen showed needle-like morphologies. Tensile and low cycle fatigue tests were performed on both cyclic heat-treated and standard heat-treated specimens at room temperature and 650°. Low cycle fatigue tests on the cyclic treated specimens showed promising results without reduction of strength.

11:10 AM

The Role of Oxygen Grain-Boundary Diffusion during Intercrystalline Oxidation and Intergranular Fatigue Crack Propagation in Alloy 718: Ulrich Krupp[1]; *Philip E.-G. Wagenhuber*[1]; Vicente Braz da Trindade Filho[1]; William M. Kane[2]; Charles J. McMahon Jr.[2]; [1]University of Siegen; [2]University of Pennsylvania

The design of new high-efficient gas turbines is closely associated with the need to increase the service temperature of its components. Today, the applicability of the polycrystalline Ni-base superalloy alloy 718, e.g., for gas turbine disc applications, is limited by its susceptibility to intergranular cracking during low-cycle fatigue in combination with hold times at maximum tensile stress and high temperatures typically of 650°C. Static 4-point bending tests and fatigue tests with and without hold times in a temperature range between 650°C and 1000°C and in various atmospheres have revealed that this kind of intergranular cracking is not due to the formation of massive oxidation products along the grain boundaries, at least at the lower temperature (650°C). At the lower temperature of 650°C, it can be attributed rather to the mechanism of "dynamic embrittlement" at a nanoscale, i.e., diffusion of elemental oxygen into highly stressed grain boundaries ahead of a growing crack, followed by decohesion. By microstructural evaluation of the mechanical tests and the oxidation experiments using electron microscopy in combination with electron back-scatter diffraction (EBSD), it became evident that only some of the grain boundaries are prone to oxygen-induced attack. This observation gave rise to apply a grain-boundary-engineering-type treatment to the as-received alloy 718 material, resulting in an increase in the fraction of low-sigma CSL grain boundaries. These special boundaries seem to have a high resistance to oxygen grain boundary diffusion, resulting in a decrease in the crack-propagation rate below 650°C and a less-pronounced intercrystalline oxidation attack at higher temperatures.

11:30 AM

A New Alloy Designed for Superheater Tubing in Coal-Fired Ultra Supercritical Boilers: *Brian A. Baker*[1]; [1]Special Metals Corporation

Future increases in the demand for clean and efficient electrical power production will be unrelenting. Meeting the coming challenges will require power generating systems capable of operating with increased boiler pressures and temperatures. In turn, meeting the demands of the application will also require materials which can withstand these extreme conditions. This paper describes a new nickel-base tubing alloy, INCONEL alloy 740, developed for the purpose of meeting this challenge. This material possesses a unique combination of elevated temperature strength properties and resistance to coal ash corrosion required by the application. The material was developed to fulfill the minimum s tress rupture requirement of 100,000 hour rupture life at a stress of 100 Mpa and at a temperature of 750°C. In addition, metal loss of less than 2 mm in 200,000 hours was defined as the target corrosion resistance for this material. The mechanical properties of this new material will be described, in addition to its coal-ash and steam corrosion resistance and weldability. Thermal stability will also be discussed, focusing upon microstructural features of long-term exposed samples. Early methodology utilized to arrive at the current chemical composition will also be presented.

11:50 AM

Metallurgical Effects on Machinability of Wrought Inconel 718: *Maria Krook*[1]; Viktor Recina[2]; Birger Karlsson[1]; [1]Chalmers University of Technology; [2]Volvo Aero Corporation

This work presents a study on how the properties of the work material affect the machinability of Inconel 718. The first part of the study was performed in a controlled production environment, where the effect of microstructural properties on tool wear was investigated. The wear on cemented carbide tools from turning operations was measured and correlated to material characteristics such as chemical composition, grain size, strength and hardness. The variation in these parameters was however too small and their effects partly conflicting. Yet, the results showed that carbide-forming elements such as carbon, titanium and molybdenum increase the tool wear. The second part of the study was to study the effect of microstructure on machinability. The machining experiments were performed on tailored material in a well-defined environment. Three turning trials were conducted on four ring rolled forgings obtained from the same melt, but with different forging parameters and heat treatments leading to variations in microstructure, strength and hardness. The tools used were standard cemented carbide inserts. The results show that increasing grain size leads to increased notch wear. The wear appearance is most likely due to deformation hardening of the work piece originating from the previous cutting passage. Since the movement of the dislocations will be hindered by the grain boundaries, the deformation depth becomes deeper in a material with larger grain size which could cause increased tool wear. These factors are investigated in the present contribution.

Wednesday PM, October 5, 2005
Weldability and Applications

Session Chairs: Xishan Xie, University of Science and Technology Beijing; Edward A. Loria, Consultant

1:30 PM
Design and Manufacture of a Very Large Hot-Gas Expander Impeller in Alloy 718 for Highly Corrosive Off-Gas: Volker Schulte[1]; *Sharad Chandra*[1]; Klaus Mohr[1]; Dieter Bokelmann[2]; Karl-Heinz Schoenfeld[2]; Joerg Poppenhaeger[2]; [1]MAN Turbo AG; [2]Saarschmiede Freiformschmiede GmbH

The present paper focuses on metallurgical issues and the manufacturing of impellers for an integrally geared 2-stage expander for corrosive hot-gas application. The design employs the largest single piece forging in Alloy 718 material for use in the low pressure stage impeller. The expander was specified to operate up to temperatures of 500°C and to be subjected to a highly corrosive off-gas. The design had to comply with the requirement of avoiding condensation of the off-gas under any operating conditions. First the material for the impeller and a number of other parts was chosen to be Alloy 718 because this guaranties best corrosion resistance. Since the diameter of the low pressure impeller was the largest ever build by MAN TURBO and another requirement was to go for a single piece forging, the largest ever produced free-form forging in Alloy 718 resulted as far known. The production of the low pressure impeller, which weighs over 6000 kgs in the rough forged machined condition, is a metallurgical challenge. The melting of the required block in VIM-ESR-VAR technique, the forging process and subsequent NDT of the finished forged and heat treated cylinder shows some possible boundaries of manufacturing such impellers. The new design enables integrally geared expanders to be able to be applied to very large machinery trains for basic industry and comparable service for very hot and corrosive off-gas conditions.

1:50 PM
Mixed INCONEL® Alloy 718 Inertia Welds for Rotating Applications — Microstructures and Mechanical Properties: *Olaf Roder*[1]; Dietmar Helm[1]; Stephanie Neft[1]; Joachim Albrecht[2]; Gerd Luetjering[2]; [1]MTU Aero Engines GmbH; [2]Technical University Hamburg-Harburg

IN718 is the work-horse nickel-iron-chromium alloy for a variety of parts for aero-engine applications such as disks, shafts, blades, vanes, casings and fasteners due to a good combination of relevant mechanical properties, good corrosion resistance, easy fabricability and reasonable cost. The conditions in aero-engines often require to join rotating parts which are made out of different materials, for example due to temperature limitations of one material. Besides the possibility of bolting the parts together, welding can lead to some advantages and is used in the compressor and high-pressure turbine section of aero-engines. For joining nickel-super-alloys and especially different nickel-alloys inertia welding represents often the only available possibility. The following work summarises investigations of inertia welding IN718 with alloys INCOLOY® alloy 909, UDIMET® 720LI, René® 88 and itself. Specimens of fully heat-treated material are joined by inertia welding. The microstructures in the welded zones is investigated by optical microscopy and transmission electron microscopy. Post-weld heat-treatments are performed and the finally chosen PWHT is characterised by its tensile, creep and some low cycle fatigue properties. The results of the mechanical tests are described in terms of the microstructural changes observed in the welded zone.

2:10 PM
Mechanical Properties of 718 Inertia Weld and Its Comparison with EBW: *P. V. Neminathan*[1]; T. Mohandas[2]; [1]Kaveri Engine Programme; [2]Defence Metallurgical Research Laboratory

Nickel base superalloy 718 is extensively used in aero gas turbine for critical rotating assemblies such as discs and shafts. These assemblies are subjected to severe service conditions at high temperature. Some of the engine builders employ electron beam welding process for joining of these rotating assemblies. However, fusion welds of nickel base superalloys are prone to microfissuring in the heat affected zone. Those defects arise due to solidification cracking as a result of liquation along the grain boundaries. This inherent metallurgical problem in EB welding process can adversely affect the mechanical properties, particularly fatigue. Solid state bonding processes. viz. Inertia friction welding, are known to mitigate this problem. Keeping this in view, inertia welding studies on this alloy were taken up. This paper reports mechanical properties of inertia weld of 718 alloy in addition to microexamination results. Effect of post weld ageing treatment is also incorporated. Microstructural examination revealed that the heat affected zone or weld zone are free from microfissures. The weld zone microstructure is much finer than the base metal. Tensile strength and ductility [at RT. 300°C and 650°C] as well as R I LCF lives obtained on lnertia welds, in PWHTd condition, were at par with the corresponding parent material in STA condition. A comparative study on EBW indicated that the tensile strength [at RT and 300° C] is comparable to that of parent material, but the ductility and LCF lives of EBW of 718 alloy were below that of the corresponding parent material.

2:30 PM

Single Point Turning Process Optimization of Fine Grain Processed 718: *Brian Hann*[1]; Dan Greving[1]; Harry Kington[1]; Derek Rice[1]; [1]Honeywell Engines, Systems & Services

The 718 family of nickel-base superalloys is used extensively in the design of critical aerospace components, namely in the hot section disks of gas turbine engines. The reliability of such components is often dependent upon, among other factors, their as-machined surface integrity. Surface integrity is often related to tool-surface interactions. The interactions may result in varying degrees of carbide cracking (possibly resulting in matrix cracking), carbide pull-outs, surface tearing, surface roughness, and grain distortion. The very properties that make materials in the 718 family of nickel-base superalloys attractive for critical applications also make these materials difficult to machine. Among these properties are high temperature strength, poor thermal conductivity, and high work hardening rate. Conventional carbide tools tend to wear due to the increased temperature at the tool edge. This wear leads to an increasing required tool load, resulting in increased depth of grain distortion. Ceramic machining tools have shown promise for machining alloys in the 718 family, owing to their inherent high temperature strength and wear resistance. In addition to improved surface integrity, ceramics tools also offer significant improvement in machining throughput. Through the design and analysis of factorial experiments, varied factors (feeds, speeds, depths of cut, tool types) are correlated with various response factors, including surface roughness, surface quality, depth of grain distortion, as well as microhardness and residual stress profiles.

2:50 PM

Development of Forgeable Ni-Base Alloys for USC Steam Turbine Applications by Microstructure Simulation and Formability Tests: *X. Li*[1]; R. Kopp[1]; M. Wolske[2]; [1]RWTH Aachen University; [2]Hydro Aluminium Deutschland GmbH

For the industrial production of large safety components such as turbine discs and turbine shafts, FEM coupled microstructure modeling offers a possibility to describe the microstructural changes such as recrystallization and grain growth during forming. Therefore, the material performance during the production process can be judged by understanding of the microstructure information. In this project, the microstructure evolution and the formability during the industrial processes were investigated with the help of FEM simulations. For numerical investigation of a forging process, compression tests, stress relaxation tests and annealing tests were carried out. After the analysis of the experimental results and the metallographic research on the immediately quenched specimens, microstructure models for simulating recrystallization and grain growth on the basis of empirical-phenomonological equations were developed for each alloy. The models were verified and fitted by means of 3-step compression tests. Finally, a sequence of upsetting and hammer forging operations were simulated via FEM coupled microstructure simulation. To determine and compare the formability of the investigated Ni-alloys, compression tests were performed with specimens of flange geometry. The research was firstly forcused on the commercial alloys Inconel 706, Inconel 617 and Waspaloy, to identify the best material candidate for the industrial processing and application of stationary steam turbine components. Based on these results, two novel alloy variants, “DT706” and “DT750”, were developed and studied again with the above described approaches.

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3:30 PM

A Method of Optimizing Chemical Composition to Obtain Both Higher Strength and Higher Plasticity for Alloy IN718C: *Ping Yan*[1]; [1]Central Iron & Steel Research Institute

The influence of electron vacancy number of main chemical elements on the properties in alloy In718C was investigated in this paper. The electron vacancy number has been successfully used to predict the tendency of TCP phases precipitation. In general, the TCP phases appear in the temperature range of 700~900°, which is not the working temperature of IN718C. The basic concept of electron vacancy number, meaning that the higher the electron vacancy number, the lower the non-bonded free electrons in the alloy. It is well known that the main difference between metals and nonmetals is the former composing a number of unbounded “free” electrons. Furthermore, the more the unbounded “free” electrons existed in the metals, the stronger metallic character the metals have. Therefore, it is possible to design a metals’ composition with lower electron vacancy number and stronger metallic character which will result in both higher strength and higher plasticity. In this study, some lower electron vacancy number composition within the range of IN718C specification were consciously designed. The alloys with higher strength and higher plasticity were obtained, as compared with higher electron vacancy number one with lower strength and lower plasticity . From the experiment results, it is supposed that there is an implication relation between mechanical properties and electron vacancy number for alloy IN718C, even if no TCP phase and microstructure difference appeared.

3:50 PM

Creep-Testing Foils and Sheets of Alloy 625 for Microturbine Recuperators: *Neal D. Evans*[1]; Philip J. Maziasz[1]; John P. Shingledecker[1]; [1]Oak Ridge National Laboratory

Microturbines are an attractive alternative for both distributed power generation and combined heat and power applications. Recuperators are compact, high efficiency heat-exchangers which improve the efficiency of microturbines and smaller gas turbines. However, recuperators are also costly and challenging components of such systems which limit maximum operating temperature and lifetime. Because thinner foils make such heat exchangers more compact and efficient, foils on the order of 0.076 – 0.254 mm (0.003 – 0.010 in.) are needed and used for this application. The processing necessary to produce fine-grained foils makes them quite different compared to traditional, heavier section wrought products, with the initial as-processed foil microstructures (e.g. grain size, precipitate morphology, precipitate distribution, etc.) determining the creep properties of such foils during service. For this study, creep-rupture tests in air at 750°C and 100 MPa are being performed on: lab-scale processed 0.102 mm (0.004 in.) thick foil, 0.102 mm commercial fine-grain foil and 0.254 mm commercial sheet of alloy 625. These creep-test results, where form-dependent behavior is observed, will be correlated to microstructures of both as-processed and creep-tested specimens, as characterized by analytical electron microscopy. Research supported (NDE, PJM, JPS) by the Office of Distributed Energy and Electricity Reliability under the Assistant Secretary for Energy Efficiency and Renewable Energy, and the Division of Materials Sciences and Engineering (ORNL SHaRE User Facility), U.S. Department of Energy, under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

INDEX

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