HELSMAC

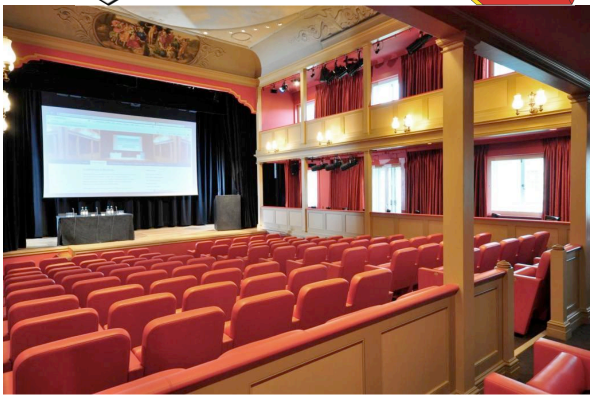
HELmholtz Symposium on Materials And Coatings for High Temperatures
7th- 8th April, 2016

HELSMAC

This Symposium will take place in Downing College, Cambridge (below), on 7th - 8th April, 2016. The main venue will be the Howard Lecture Theatre, where there is 160 m^2 of exhibition space on the ground floor, with adjacent catering facilities, and a 100-seat auditorium (right).

HELMHOLTZ
ASSOCIATION

The Gordon Laboratory



The Symposium is funded by the Helmholtz Association and supported by the Gordon Laboratory in the Materials Science Department of Cambridge University. The Symposium chairs will be Bill Clyne (Cambridge), Robert Vassen and Olivier Guillon (both FZ-Jülich).

Symposium Coverage

The focus of the Symposium will be on the processing, microstructure and performance of advanced materials and coatings designed for use in highly demanding environments - particularly at very high temperatures. The applications concerned primarily relate to the generation / handling of energy and to control of the environment, which are key areas in the research objectives of the Helmholtz Association. The programme will be divided into 5 areas, covering challenges faced in further development of: (a) gas turbine systems, (b) thermal barrier coatings, (c) energy from nuclear fusion, (d) thermal protection, particularly related to spacecraft, and (e) removal of particulate from hot gas streams.

Format of the Meeting

Attendance is by invitation only and there is no registration fee. There will be 49 delegates (all prominent in the research fields concerned), including 12 from industrial firms. There will be 25 talks (all 25 minutes duration), divided into 5 sessions spread over the two days. In addition, 19 posters will be displayed in the Exhibition area (upper right). Lunches and refreshments will also be in this location. Most delegates will be accommodated in nearby rooms in the College (lower right).

The Oral Programme

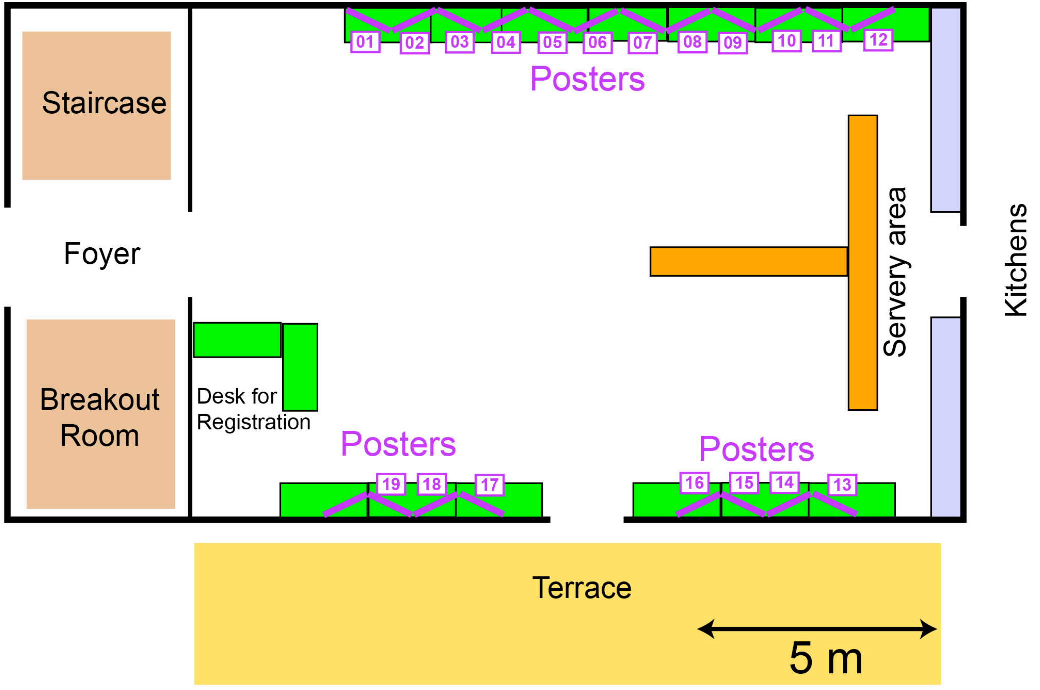
Thursday 7th April

Time	No.	Presenter	Affiliation	Title
07.45-08.45	**Breakfast**			
08.30-09.00	**Registration / Setting up of Poster Display**			
09.00-12.30	Session 1: **High Temperature Materials and Systems in Gas Turbines** (Chair: **Olivier Guillon**)			
09.00-09.25	**1**	Martin Heilmaier	KIT (Karlsruhe)	*Beyond Ni-base Superalloys: Refractory Metal Silicides for Ultra-high Temperature Structural Applications*
09.25-09.50	**2**	Robert Singer	Erlangen U.	*A Second Life for Superalloys? New Single Crystal Alloys based on Computer-Aided Design and Segregation-free Fabrication*
09.50-10.15	**3**	Christoph Leyens	IWS (Dresden)	*Advanced Coating Solutions by Thermal Spraying and Laser Cladding*
10.15-10.40	**4**	Roger Reed	Oxford U.	*Superplasticity in Ti-6Al-4V: Characterization, Modelling and Applications*
10.40-11.15	**Coffee**			
11.15-11.40	**5**	Michael Schütze	Dechema (Frankfurt)	*Mechanical Limits to the Protective Effect of Oxide Scales on High Temperature Materials*
11.40-12.05	**6**	Nitin Padture	Brown U.	*Molten Silicates (Sand, Fly Ash, Volcanic Ash) Attack of Gas-Turbine Engine Hot-Section Ceramic Coatings and its Mitigation*
12.05-12.30	**7**	Mathias Göken	Erlangen U.	*Probing the Fracture Toughness of Bond Coats and Graded NiAl Single Crystals by Micro-Cantilever Tests*
12.30-14.00	**Lunch**			
14.00-17.50	Session 2: **Stability of Thermal Barrier Coatings in Gas Turbines** (Chair: **Ram Ramamurty**)			
14.00-14.25	**8**	Tresa Pollock	UCSB (Santa Barbara)	*Design of Intermetallic Bond Coatings*
14.25-14.50	**9**	Federico Cernuschi	RSE (Milan)	*Solid Particle Erosion of Standard and Advanced Thermal Barrier Coatings*
14.50-15.15	**10**	Marion Bartsch	DLR (Köln)	*Local Strain Response of a TBC System under Thermal Mechanical Loading by in-situ Synchrotron X-ray Diffraction*
15.15-15.40	**11**	Matthias Oechsner	TU Darmstadt	*Evolution of the Crack Driving Force and/or Fracture Resistance during Thermal Cycling of TBCs*
15.40-16.10	**Tea**			
16.10-16.35	**12**	Robert Vassen	FZ Jülich	*Innovative Coatings for High Temperature Applications*
16.35-17.00	**13**	Sanjay Sampath	Stony Brook U.	*Thermal Spray as an Additive and Layered Manufacturing Technology for Applications in Energy Systems*
17.00-17.25	**14**	Ernst Affeld	MTU	*Thermo-mechanical Fatigue (TMF) Testing of Coated Nickel-based Superalloys*
17.25-17.50	**15**	Dan Roth-Fagaraseanu	Rolls Royce (Berlin)	*Enviromental Challenges in the Hot Section of Aero Engines and Surface Protection Solutions*
18.00-18.30	Special Session: (Chair: **Bill Clyne**)			
18.00-18.30	**16**	Harald Bolt	FZ Jülich	*The Helmholtz Energy Materials Characterization Platform: a Distributed Research Infrastructure of Seven Helmholtz Research Centres*
19.00-19.30	**Reception in Senior Combination Room**			
19.30-22.00	**Symposium Dinner in Hall**			

Friday 8th April

Time	No.	Presenter	Affiliation	Title
07.45-08.45	**Breakfast**			
08.45-10.00	Session 3: **Materials and Systems for Nuclear Fusion** (Chair: **Christian Linsmeier**)			
08.45-09.10	**17**	Jarir Aktaa	KIT (Karlsruhe)	*Functionally Graded Tungsten Steel Coatings for Fusion Applications*
09.10-09.35	**18**	Jan Coenen	FZ Jülich	*Materials and Components for Extreme Loads in Fusion First Wall and Divertor Applications*
09.35-10.00	**19**	Jochen Linke	FZ Jülich	*Materials for Future Fusion Reactors under Severe Stationary and Transient Thermal Loads*
10.00-10.30	**Coffee**			
10.30-11.20	Session 4: **Thermal Protection Systems for Aerospace Airframes** (Chair: **Gunther Eggeler**)			
10.30-10.55	**20**	Dietmar Koch	DLR Stuttgart	*High Temperature Stable Fibre Reinforced Composites for Thermal Protection of Spacecraft Vehicles*
10.55-11.20	**21**	Wolfgang Fischer	Airbus (Bremen)	*Airbus Safran Launchers GmbH TPS Portfolio - Status and recent Developments*
11.20-13.00	Session 5: **Particulate in High Temperature Gas Streams** (Chair: **Robert Vassen**)			
11.20-11.45	**22**	Rory Clarkson	Rolls Royce (Derby)	*Volcanic Ash, Aircraft Engines and Progress Since Eyjafjallajokull*
11.45-12.10	**23**	Giovanni Bruno	BAM (Berlin)	*A Few Aspects of the Current Understanding of Diesel Particulate Filter Materials Thermal and Mechanical Properties*
12.10-12.35	**24**	Thomas Wolff	Dinex (Bindlach)	*Highly porous SiC Substrate for Diesel Particle Filters and its Combination with Catalysts for Selective Catalytic Reduction of Nitrogen Oxide with Ammonia*
12.35-13.00	**25**	Andy Williams	Loughborough U.	*Thermal Management in Porous Ceramic Particulate Filters: Opportunities and Consequences of Plasma Technology Solutions for Particulate Filter Regeneration*
13.00-13.15	**Group Photo**			
13.15-14.00	**Lunch**			

Poster Display Layout



The Poster Programme

No	Presenter	Affiliation	Title
Materials in Nuclear Fusion Applications			
1	Christian Linsmeier	FZ Jülich	*Yttria as a Tritium Permeation Barrier in Fusion Components*
2	Sebastijan Brezinsek	FZ Jülich	*Plasma-wall Interaction with the ITER Fusion Material Mix in JET*
Processing of Materials for High Temperature Applications			
3	Dietmar Koch	DLR (Stuttgart)	*Manufacturing and Design of Nonoxide Ceramic Matrix Composites for Gas Turbine Applications*
4	Olivier Guillon	FZ Jülich	*Processing of Ceramic Composites by Field-Assisted Sintering Technology / Spark Plasma Sintering*
5	Georg Mauer	FZ Jülich	*Investigations of Novel Plasma Spray Processes by Optical Emission Spectroscopy*
6	Dimitry Naumenko	FZ Jülich	*Modeling and Predicting High Temperature Coating Damage by Oxidation and Interdiffusion*
Microstructure and Testing of Materials (for High Temperature)			
7	Rafal Dunin-Borkowski	FZ Jülich	*In Situ Transmission Electron Microscopy of Energy Materials*
8	Marion Bartsch	DLR (Köln)	*Fatigue Testing of Ni-based Superalloys for Gas Turbine Blades*
9	James Dean	Cambridge U.	*Extraction of Plasticity Parameters from Instrumented Indentation Data via Inverse FEM Modelling*
Novel Materials for High Temperature Usage			
10	Mathias Göken	Erlangen U.	*Novel Wrought γ / γ' Cobalt base Superalloys with High Strength and Improved Oxidation Resistance*
11	Joerg Adler	Fraunhofer (Dresden)	*Cellular Silicon Carbide Ceramics at High Temperature*
Thermal Barrier Coatings for Gas Turbines			
12	Daniel Mack	FZ Jülich	*Degradation of Advanced TBC systems under Thermomechanical and Corrosive Loading in Burner Rig Testing*
13	Lorentz Singheiser	FZ Jülich	*Effect of Y, Zr and O Contents in MCrAl-type Bondcoats on the Lifetime of Thermal Barrier Coatings*
14	Uwe Schulz	DLR (Köln)	*Environmental Barrier Coatings for CMCs*
15	Odile LaVigne	ONERA (Paris)	*Influence of Morphology on Thermal Properties and CMAS Resistance of Gadolinium Zirconate EB-PVD Coatings*
16	Hans-Peter Bossmann	Alstom (Baden)	*High-efficient Thermal Protection Systems for Low-cooled Gas Turbines: Increased performance and Lifetime due to Optimized Coating Parameters*
Particles in High Temperature Gas Streams			
17	Mark Peckham	Cambustion (Cambridge)	*A Standard Soot Generator for Diesel Particulate Filter Testing*
18	Alastair Houston	Cambridge U.	*Novel Diesel Particulate Filters containing Fine Ceramic Fibres*
19	Catalina Taltavull	Cambridge U.	*Effect of Volcanic Ash Characteristics on their Adhesion in Gas Turbines*

Delegates

Name <e-mail>	Affiliation	Accommodation in Downing				Car
		Tues. 5th	Wed. 6th	Thurs. 7th	Fri. 8th	
Joerg Adler <joerg.adler@ikts.fraunhofer.de>	Fraunhofer, Dresden		√	√		
Ernst Affeldt <ernst.affeldt@mtu.de>	MTU, Munich	√+1	√+1	√+1	√+1	
Jarir Aktaa <jarir.aktaa@kit.edu>	KIT, Karlsruhe		√	√		
Bryan Allcock <bryan@monitorcoatings.com>	Monitor Coatings,		√+1	√+1		√
Marion Bartsch <Marion.Bartsch@dlr.de>	DLR, Köln		√	√		
Harald Bolt <h.bolt@fz-juelich.de>	FZ Jülich			√		
Hans-Peter Bossman <Hans-Peter.Bossmann@power.alstom.com>	Alstom, Switzerland		√	√	√	
Sebastijan Brezinsek <s.brezinsek@fz-juelich.de>	FZ Jülich		√+1	√+1		√
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Federico Cernuschi <federico.cernuschi@rse-web.it>	RSE, Milan		√+4	√+4		
Rory Clarkson <Rory.Clarkson@Rolls-Royce.com>	Rolls Royce, Derby			√		√
Bill Clyne <twc10@cam.ac.uk>	Cambridge U.					
Jan Coenen <j.w.coenen@fz-juelich.de>	FZ Jülich		√+1	√+1	√+1	√
James Dean <jd362@cam.ac.uk>	Cambridge U.					√
Rafal Dunin-Borkowski <r.dunin-borkowski@fz-juelich.de>	FZ Jülich		√	√		
Gunther Eggeler <gunther.eggeler@ruhr-uni-bochum.de>	Ruhr-Universität Bochum					
Wolfgang Fischer <wolfgang.wo.fischer@airbus.com>	Airbus Safran Launchers	√+1	√+1	√+1	√+1	
Rainer Gadow <rainer.gadow@ifkb.uni-stuttgart.de>	Stuttgart U.		√	√		
Mathias Göken <goeken@ww.uni-erlangen.de>	Erlangen U.		√	√		
Olivier Guillon <o.guillon@fz-juelich.de>	FZ Jülich		√	√		
Martin Heilmaier <martin.heilmaier@kit.edu>	KIT, Karlsruhe		√	√		
Alastair Houston <ajh242@cam.ac.uk>	Cambridge U.					
Dietmar Koch <Dietmar.Koch@dlr.de>	DLR, Stuttgart		√	√		
Odile LaVigne <odile.lavigne@onera.fr>	ONERA		√	√		
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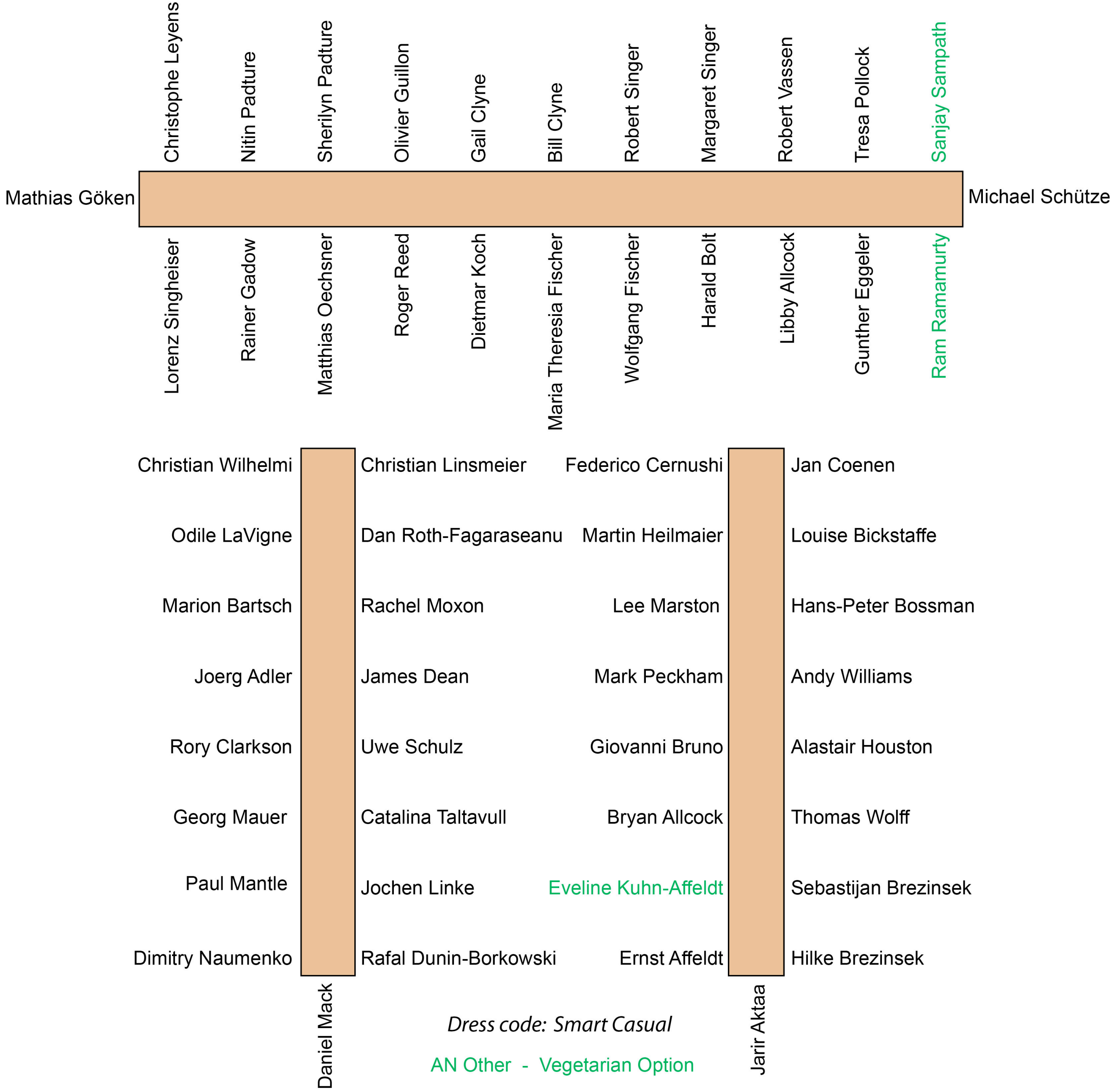
Jochen Linke < j.linke@fz-juelich.de>	FZ Jülich		√	√		
Christian Linsmeier <ch.linsmeier@fz-juelich.de>	FZ Jülich		√	√		
Daniel Mack <d.e.mack@fz-juelich.de>	FZ Jülich		√	√		
Paul Mantle <pam73@cam.ac.uk>	Cambridge U.					√
Lee Marston <Lee.Marston@dynamic-materials.com>	Fiberstone					√
Georg Mauer <g.mauer@fz-juelich.de>	FZ Jülich		√	√		
Dimitry Naumenko <d.naumenko@fz-juelich.de>	FZ Jülich		√	√		
Matthias Oechsner <oechsner@mpa-ifw.tu-darmstadt.de>	TU Darmstadt		√	√		
Nitin Padture <nitin_padture@brown.edu>	Brown U.		√+1	√+1		
Mark Peckham <msp@cambustion.com>	Cambustion, Cambridge					√
Tresa Pollock <pollock@engineering.ucsb.edu>	UCSB		√	√	√	
Ram Ramamurty <ramu@met.iisc.ernet.in>	IIS Bangalore	√	√	√	√	
Roger Reed <roger.reed@eng.ox.ac.uk>	Oxford U.					√
Dan Roth-Fagaraseanu <Dan.Roth-Fagaraseanu@Rolls-Royce.com>	Rolls-Royce Germany					√
Sanjay Sampath <sanjay.sampath@sunysb.edu>	Stony Brook U., New York		√	√	√	
Uwe Schulz <Uwe.Schulz@dlr.de>	DLR, Köln		√	√		
Michael Schütze <schuetze@dechema.de>	Dechema		√	√		
Robert Singer <robert.singer@ww.uni-erlangen.de>	Erlangen U.		√+1	√+1		
Lorenz Singheiser <l.singheiser@fz-juelich.de>	FZ Jülich		√	√		
Catalina Taltavull <ct463@cam.ac.uk>	Cambridge U.					
Robert Vassen <r.vassen@fz-juelich.de>	FZ Jülich		√	√		
Christian Wilhelmi <christian.wilhelmi@airbus.com>	Airbus Group Innovations		√	√		
Andy Williams <A.M.Williams@lboro.ac.uk>	Loughborough U.			√		
Thomas Wolff <tw@dinex.de>	Dinex, Bindlach			√		

Seating Plan for Dinner



Dress code: Smart Casual

AN Other - Vegetarian Option

Dinner Menu

Starter:	Shredded ham hock with mustard seeds, textures of piccalilli, char grilled sour dough
Main:	Braised shoulder and roast rump of lamb, boulangerè potatoes, wild mushroom and baby onions
Dessert:	Sour cherry crème brûlée, dark chocolate sorbet, hazelnut shortbread (v)
Veg. Starter:	Spiced chickpea cake, poached duck egg, pickled shallots, coriander cress
Veg. Main:	Sweet and sour Thai vegetables, crispy smoked tofu, wild rice

Abstracts – Oral Presentations

Talk 1: Thursday 7th April, 09.00-09.25

Beyond Ni-base Superalloys: Refractory Metal Silicides for Ultra-high Temperature Structural Applications

M Heilmaier

Institute for Applied Materials, Karlsruhe Institute for Technology, D - 76131 Karlsruhe, Germany

We review our current activities on developing silicide alloys for ultrahigh temperature applications. Multicomponent alloys based on the systems Nb-Si-(X) and Mo-Si-B-(X), respectively, will be addressed. Powder-metallurgical (PM) processing including mechanical alloying and field assisted sintering will be comparatively assessed against ingot metallurgy including container-less directional solidification (DS). It was found that both, PM as well as DS processing can establish very fine and homogeneous microstructures being beneficial for room temperature strength and hardness as well as for increasing the high temperature oxidation resistance in air. In addition, due to its elongated grain/phase microstructure DS samples possess substantially enhanced creep resistances. Reasons for the observed behaviors will be identified and the impact on further alloy development will be discussed.

Talk 2: Thursday 7th April, 09.25-09.50

A Second Life for Superalloys? New Single Crystal Alloys based on Computer Aided Design and Segregation-free Fabrication

RF Singer

University of Erlangen & NMF GmbH, Germany

A series of new single crystal superalloys was developed with superior temperature capability. Key for our success was the use of "redistribution elements" to push solid solution strengtheners from γ'-precipitates, where they are not effective, into the γ-matrix, where they are. The selection of promising alloy compositions for the experimental evaluation was based on the calculation of a number of criteria using our program code MultOPT [1]. Such criteria included properties like γ' volume fraction, γ-γ' misfit, heat treatment window, density, solid solution strengthening index, etc. Modern superalloys cannot be homogenized completely, i.e. even after heat treatment solid solution strengtheners are not distributed evenly. In alloy design, because of the phenomenon of instability [2], the maximum content of alloying elements is then determined by the areas with high solid solution strengtheners. Other parts of the materials are left with insufficient amount of strengtheners. We are presently working on new production methods that result in more homogeneous material, such as additive manufacturing and carbon fluidized bed cooling. Segregation-free fabrication will become the basis of a new series of further improved superalloys.

[1] R Rettig, NC Ritter, HE Helmer, S Neumeier & RF Singer, *Single-crystal nickel-based superalloys developed by numerical multi-criteria optimization techniques: Design based on thermodynamic calculations and experimental validation*, Model. Sim. Mater. Sci. Eng., **23** (2015) 035004.

[2] K Matuszewski, R Rettig, H Matysiak, Z Peng, I Povstugar, P Choi, J Müller, D Raabe , E Spiecker, KJ Kurzydłowski & RF Singer, *Effect of Ruthenium on the Precipitation of Topologically Close-packed Phases in Ni-based Superalloys of 3rd and 4th Generation*, Acta Materialia **95** (2015) 274–283.

Talk 3: Thursday 7th April, 09.50-10.15

Advanced Coatings Solutions by Thermal Spraying and Laser Cladding

C Leyens[1,2], F-L Toma[1], S Nowotny[1] & F Brückner[1]
[1] Fraunhofer IWS - Institute for Materials and Beam Technology, Dresden, Germany
[2] TU Dresden, Dresden, Germany

High-temperature coatings resisting various types of attacks from the hostile operating environment are state-of-the-art in modern gas turbines. In order to further improve performance and lifetime of costly turbine hardware, ongoing research efforts have been focussed on both, advanced coating materials and processes. The present paper will highlight recent achievements in the field of coatings produced by thermal spraying of ceramic suspensions; the coating process provides new freedom of coating design, including chemistry and microstructure control for thin (~ 10 µm) and thick (>500 µm), porous and dense ceramic coatings. Furthermore, latest results on the protection of hardware components using laser cladding of metals will be addressed. While laser cladding is typically used for 2D coating application, micro-cladding is capable of providing 3D structures that can improve adhesion of ceramic top coats very effectively. The paper will bridge scientific progress in materials science of coatings and advancing coatings methods relevant for industrial applications.

Talk 4: Thursday 7th April, 10.15-10.40

Superplasticity in Ti-6Al-4V: Characterization, Modelling and Applications

E Alabort & RC Reed
Department of Engineering Science, University of Oxford, Parks Road, Oxford, OX1 3PJ, UK

The processing regime relevant to superplasticity in the Ti-6Al-4V alloy is identified. The effect is found to be potent in the range 850 to 900˚C, at strain rates between 10^{-3} and 10^{-4} s^{-1}. Within this regime, mechanical behaviour is characterised by steady-state grain size and negligible cavity formation; electron backscatter diffraction studies confirm a random texture, leaving grain-boundary sliding as the overarching deformation mechanism. Outside of the superplastic regime, grain size refinement involving recrystallisation and the formation of voids and cavities cause macroscopic softening; low ductility results. Stress hardening is correlated to grain growth and accumulation of dislocations. The findings are used to construct a processing map, on which the dominant deformation mechanisms are identified. Physically-based constitutive equations are presented, which are faithful to the observed deformation mechanisms. Internal state variables are used to represent the evolution of grain size, dislocation density and void fraction. Material constants are determined using genetic-algorithm optimisation techniques. Finally, the deformation behaviour of this material in an industrially relevant problem is simulated - the inflation of diffusion-bonded material for the manufacture of hollow, lightweight structures.

Talk 5: Thursday 7th April, 11.15-11.40

Mechanical Limits to the Protective Effect of Oxide Scales on High Temperature Materials

M Schütze

DECHEMA-Forschungsinstitut, Frankfurt-am-Main, Germany

Besides the mechanical properties, the high temperature corrosion resistance of materials decides on their performance and life-time under operation conditions. High temperature corrosion resistance is provided by the protective oxide scales formed during high temperature exposure by the reaction of the environment with the respective alloying elements. Due to the ceramic nature of oxides, these scales show low failure strains under the effect of mechanical and/or thermal stresses, and long-term resistance can only be guaranteed if a sufficient healing capability of scale damage effects is provided. Recently, measurements of the failure strains of different oxide scales using acoustic emission recording in combination with 4-point bending testing were performed at DFI, leading to a new type of scale failure maps. These maps and the consequences resulting from these data will be discussed in detail in the paper.

Talk 6: Thursday 7th April, 11.40-12.05

Molten Silicates (Sand, Fly Ash, Volcanic Ash) Attack of Gas-Turbine Engine Hot-Section Ceramic Coatings and Its Mitigation

NP Padture

School of Engineering, Brown University, Providence, RI 02912, USA

Gas-turbine engines are used for aircraft propulsion and to generate ~20% of the world's electricity. Ceramic thermal barrier coatings (TBCs) are used to insulate and protect hot-section metallic components in these engines. However, the higher temperatures in high-efficiency engines are making TBCs prone to deposition of undesirable silicates ingested by the engines, engendering new materials issues that are becoming critical for the development of more efficient engines. The undesirable silicates (calcia-magnesia-alumina-silica glass or CMAS) can be in the form of sand and volcanic ash in the case of aircraft engines, and coal fly ash in the case of syngas-fired engines used for electricity generation. The understanding of mechanisms by which molten CMAS deposits damage conventional yttria-stabilized zirconia TBCs is presented. Demonstration and understanding of approaches to mitigate this type of CMAS-induced damage in new TBCs are also presented, together with a discussion of guidelines for the development of new TBCs. However, state-of-the-art TBC-coated superalloy components may not have the necessary high-temperature capabilities required for the next-generation engines with even higher operating temperatures and more demanding efficiency standards. Ceramic-matrix composites (CMCs), combined with environmental barrier coatings (EBCs), are being explored for future engines. But the CMAS issue will need to be addressed in the context of CMCs/EBCs. The strategies for CMAS-attack mitigation of EBCs, which are different from those used in TBCs, will be presented and discussed.

Talk 7: Thursday 7th April, 12.05-12.30

Probing the Fracture Toughness of Bond Coats and Graded NiAl Single Crystals by Micro-cantilever Tests

M Göken, R Webler & S Neumeier
Friedrich-Alexander-University Erlangen-Nürnberg (FAU), Materials Science & Engineering I,
Martensstrasse 5, D-91058 Erlangen, Germany

Testing of the local mechanical properties such as hardness, Young's modulus etc by nano-indentation is now well established. With micro-cantilevers milled by the Focused Ion Beam (FIB) technique, also the fracture toughness of very small samples can be measured. This method has been evaluated carefully on NiAl single crystals of different orientations, where also the J-integral approach has been used to obtain reliable results for the fracture toughness [1]. The micro-cantilever technique has been now adapted on NiAl single crystals with varying chemical composition and on oxidation protection bond coats on Ni-based-superalloys. Development of new advanced materials requires a very good knowledge concerning the influence of the chemical composition on the properties of the constituent phases. Therefore, combinatorial studies on diffusion couples are interesting, where the properties of many different compositions can be determined. A very simple method of generating a graded single crystalline NiAl sample consists of annealing a prior homogeneous crystal at high temperatures, since Al evaporates out and an Al-depleted zone is formed at the sample surface. By such an approach, the graded sample remains single crystalline, which is especially important for determining the highly anisotropic fracture toughness. In addition, microstructural influences are avoided, which often complicate the analysis of polycrystalline diffusion couples. The fracture toughness is then determined by FIB-milled micro-cantilevers in dependence of the chemical composition. This new approach has been used to study the properties of Al and Ni-rich NiAl single crystals, where it is found that the fracture toughness decreases with increasing Ni content from the stoichiometric composition, whereas the hardness increases with the number of constitutional defects. The results of the micro-cantilever tests are compared with nano-indentation measurements and will be discussed in terms of plastic deformation in the micro-cantilever experiments. Furthermore, the results are compared with fracture toughness measurements on different bond coats, where the micro-cantilevers were milled directly from the coating area. The results on the bond coats show the same trend as that on the combinatorial single crystal.

[1] J Ast, T Przybilla, V Maier, K Durst & M Göken, J. Mater. Res., **29**, (2014) 2129.

Talk 8: Thursday 7th April, 14.00-14.25

Design of Intermetallic Bond Coatings

TM Pollock
Materials Department, University of California Santa Barbara, USA

Bond coat interlayers in thermal barrier coating (TBC) systems must perform reliably in the complex thermal, chemical and mechanical environment of the turbine engine. To achieve higher temperatures and /or longer cyclic lives, a spectrum of intrinisic failure modes must be suppressed. Failure may occur at the bond coat – thermally grown oxide (TGO) interface, at the TGO-TBC interface or by oxidation-enhanced propagation of cracks from the coating into the substrate. Models for the failure processes suggest that bond coatings should possess improved high temperature strength (creep resistance), low oxide growth stresses and high interfacial toughnesses. Combinatorial experiments on B2-base and L12 intermetallic bond coatings reveal new failure-resistant compositional domains for further development.

Talk 9: Thursday 7th April, 14.25-14.50

Solid Particle Erosion of Standard and Advanced Thermal Barrier Coatings

F Cernuschi, C Guardamagna & L Lorenzoni
RSE – Ricerca per il Sistema Energetico, Via Rubattino, 54, 20134 Milano, Italy

The state-of-the-art of the thermal barrier coatings (TBCs), used to protect hot path components from combustion gases, is represented by yttria (partially) stabilized zirconia (YPSZ). Electron beam physical vapour deposition (EB-PVD) coatings have a columnar microstructure that guarantees high strain compliance and better solid particle erosion resistance than PS TBCs. The main drawback of EB-PVD coating is the deposition cost, which is higher than that of air plasma sprayed (APS) TBC. Nowadays, segmented APS coatings and PS - PVD™ have been developed in the frame of the UE TOPPCOAT project to improve solid particle erosion of plasma sprayed TBCs [1,2]. Combustion and cooling technology improvements, in combination with higher turbine inlet temperature, imply that the standard YSZ approaches certain limitations due to sintering and phase transformations at elevated temperatures. Moreover, under high thermal loading early failure of the coating occurs due to attack by calcium-magnesium-alumino-silicate (CMAS) deposits inducing cracking, spallation and delamination of the coating. Alternative refractory materials development, with higher performances than YSZ, was the objective of the UE project H2IGCC: within this project, the erosion resistance of porous, dense segmented YPSZ TBCs and innovative TBCs, featured with a bilayer structure, has been tested at impingement angles of 30° and 90°, representative of particle impingement on trailing and leading edges of gas turbine blades and vanes, respectively [3]. Tests were performed in a solid particle erosion jet tester at high temperatures (700°C and 1000°C). Micro-quartz and alumina were chosen as the erodents. To investigate the effect of grain size distribution, erosion rates with fine and coarse alumina powders have been studied. Furthermore, after the end of the tests, the TBC microstructure was investigated using electron microscopy to characterise the failure mechanisms taking place in the TBC. In general, TBCs with columnar-like microstructures are more resistant than standard APS TBCs.

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[2] F Cernuschi, C Guardamagna, L Lorenzoni, S Capelli, F Bossi, R Vaßen, K von Niessen, in Advanced Ceramic Coatings and Materials for Extreme Environments II, Ceram. Eng. & Sci. Proc., D Zhu, H-T Lin, Y Zhou & T Hwang (eds.), Wiley, **33**(3) (2013) 37.

[3] F Cernuschi, S Capelli, C Guardamagna, L Lorenzoni, DE Mack & A Moscatelli, Wear, in press (2016).

Talk 10: Thursday 7th April, 14.50-15.15

Local Strain Response of a TBC System under Thermal Mechanical Loading by in-situ Synchrotron X-ray Diffraction

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For stress analyses and lifetime assessments of TBC-systems, it is necessary to know the mechanical properties of each constituent, depending on the temperature and stress state. For determining comprehensive temperature- and stress-dependent mechanical properties of the thin layers of an EB-PVD coating, local strains were measured by means of high energy X-ray diffraction. Tubular coated specimens were loaded with systematically varying thermal and mechanical loads, while recording the strains in situ. Test parameters were surface temperature, applied mechanical load, and heat flux through the specimens' wall, the latter controlled by internal cooling of the tubular specimen. The topcoat surface was heated by infrared radiation up to 1000°C [1]. For capturing ageing effects associated with microstructural evolution, e.g. due to sintering or oxidation, a pre-aged specimen was investigated besides such in as-coated condition. Exemplary results of the investigations are residual strain data for the constituents as a function of temperature, gradients of elastic top coat properties across the coating thickness due to gradients in microstructure parameters such as porosity and column spacing, and data on creep behavior of the thermally grown oxide between bond coat and top coat [2].

[1] K Knipe, A Manero, SF Siddiqui, C Meid, J Wischek, J Okasinski, J Almer, AM Karlsson, M Bartsch & S Raghavan, *Strain response of thermal barrier coatings captured under extreme engine environments through synchrotron X-ray diffraction* Nat. Commun., **5** (2014) Art. 4559.

[2] A Manero, S Sofronsky, K Knipe, C Meid, J Wischek, J Okasinski, J Almer, AM Karlsson, S Raghavan & M Bartsch, *Monitoring Local Strain in a Thermal Barrier Coating System Under Thermal Mechanical Gas Turbine Operating Conditions*, JOM, **67** (2015) 1528-1539.

Talk 11: Thursday 7th April, 15.15-15.40

Evolution of the Crack Driving Force and Fracture Resistance during Thermal Cycling of TBCs

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Operational demands in future gas turbines for power generation purposes require increased cyclic durability and high temperature resistance of Thermal Barrier Coatings. Two fundamental properties have a high impact on the performance and reliability of ceramic TBCs: the planar stiffness and the fracture resistance regarding delamination cracks. Those properties are known to change during service life, i.e. when the coating is exposed over long times to high temperatures. Knowledge of those properties and their kinetics are a prerequisite to understand coating reliability and to assess coating life. Various bending methods and dynamic measurements were conducted to evaluate the influence of thermal loading on coating stiffness. The ceramic coatings were thermally treated prior to determining their stiffness isothermally, cyclically or under a thermal gradient. During thermal exposure, the coating has been either free standing or attached to a substrate material, i.e. constraint regarding its ability to shrink. The paper will discuss the evolution of coating in-plane stiffness dependent on thermal loading conditions as well as state of constraint. With respect to the in-plane fracture resistance, fracture mechanical testing has been performed to determine the evolution of the critical strain energy release rate as a function of cyclic or isothermal exposure to service relevant temperatures. The evolution of the fracture resistance at the TBC – bond coat interface, i.e. the adhesive fracture resistance, as well as the evolution of the fracture resistance within the ceramic TBC, i.e. the cohesive fracture resistance, will be discussed.

Talk 12: Thursday 7th April, 16.10-16.35

Innovative Coatings for High Temperature Applications

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Materials Synthesis and Processing (IEK-1), FZJ, 52425 Jülich, Germany

Thermal barrier coatings are widely used in both stationary and aero gas turbines to improve their efficiency by allowing an increase of the turbine inlet temperature. Standard manufacturing processes are atmospheric plasma spraying (APS) and electron beam – physical vapor deposition (EB-PVD). While the more expensive EB-PVD process is mainly used for the coating of highly loaded blades in aero engines, due to its columnar, highly strain-tolerant microstructure, APS is the deposition method applied for most of the other applications. This deposition process allows a high flexibility in the obtained microstructures, most commonly the micro-cracked, porous one with excellent thermal cycling performance. In the last decades, in addition to APS, advanced thermal spray methods have attracted much attention. One is suspension or solution plasma spraying, which allows the deposition of fine species in the sub-micrometre range, and by that the manufacture of new microstructures, as highly segmented and columnar ones. Another advanced process is plasma spray - physical vapor deposition (PS-PVD), in which powder feedstocks are evaporated and extremely strain-tolerant microstructures can be established. Besides new processes, also advanced materials beyond the standard yttria stabilized zirconia (YSZ) are studied intensively. Favorite materials are pyrochlore, such as gadolinium zirconate, or complex perovskites, which are typically applied in a so-called double layer system with YSZ underneath.

Talk 13: Thursday 7th April, 16.35-17.00

Thermal Spray as an Additive and Layered Manufacturing Technology for Applications in Energy Systems

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Thermal spraying is a directed melt spray deposition process, in which inorganic particles in the diameter range of 1-100 µm are heated, melted (in some cases partially), propelled and impacted onto a prepared substrate. A rapid sequence of events occurs including: melting, impact (in some cases shock), spreading and rapid solidification, all of which take place in microsecond timescales, enabling materials synthesis from extreme conditions. The sprayed coating is resultant from successive assemblage of such micro-scale impacted droplets (splats) producing meso-scale thick films or coatings. The coatings thus produced are anisotropic, layered structures with multiple length scales of material character and interfacial defects, with concomitant implications on properties. The layered assembly also imparts gradients in residual stresses within the thickness of the coating. These effects are in large part deemed "unintentional" and incorporated in many applications with limited manipulation. With advancements in understanding of process dynamics and the ability to control microstructures at both the splat and coating level, a fresh opportunity is available to engineer the layered assembly to provide novel through thickness properties and functionalities. In a sense, thermal spray can be considered within the context of emerging additive manufacturing concepts where the characteristics of the assembly can be manipulated across different available length scales. In this presentation, several embodiments of such concepts will be shown using the interplay among coating architecture design, materials and manufacturing. Specific examples include novel multilayer, multifunctional thermal barrier coatings, multifunctional coatings in fuel cells and thermoelectric devices. Illustrative examples of their applicability in industrial systems will also be highlighted.

Talk 14: Thursday 7th April, 17.00-17.25

Thermo-mechanical Fatigue (TMF) Testing of Coated Nickel-based Superalloys

EE Affeldt, M Rupp, J Spachtholz & J Hammer

MTU Aero Engines AG, Munich, East German Technical University, Regensburg

Thermo-mechanical fatigue is one of the critical issues for turbine vanes, which usually are coated to protect against oxidative and corrosive attack. NiAl- or platinum-modified NiAl coatings are applied as oxidation protection on single-crystalline nickel-based vanes. These coatings are ductile at high temperatures, but very brittle at lower temperatures causing coating cracks propagating into the substrate, thus reducing TMF life drastically. Thus TMF testing is essential for turbine vane design. The reference TMF life of bare single-crystalline nickel-based samples is controlled by the formation and breakage of localized oxide spikes expanding into the material by cyclic oxidation till the threshold for mechanical driven crack propagation is overcome and controls life by crack growth. This damage evolution is qualitatively well documented (e.g. [1]) and understood, whereas a quantitative calculation of the basic mechanisms e.g. of crack growth rate during TMF testing and a validation of the results would enable better design of vanes. Recent progress was published regarding the prediction of crack propagation rates under different loading condition at high temperatures [2]. It will be exemplified how this can be used to recalculate the cyclic life in the TMF tests.

[1] R Nützel, EE Affeldt & M Göken, *Damage evolution during thermo-mechanical fatigue of a coated monocrystalline nickel-base superalloy*, Int. Journal of Fatigue **30** (2008) 313-317.

[2] C Schweizer, *Evolution equations for the C(t)-Integral and the crack-tip opening displacement CTOD for elastic-viscoplastic material behavior and temperature dependent material properties*. Eng. Frac. Mech (2016) in press.

Talk 15: Thursday 7th April, 17.25-17.50

Environmental Challenges in the Hot Section of Aero Engines and Surface Protection Solutions

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Ceramic materials are used in aero engines due to their high temperature stability, low thermal conductivity and high hardness compared to the metallic materials. They are usually applied as overlay coatings to the metallic substrates and improve so the performance of metallic parts. The common applications are: abrasive liners, thermal barrier coatings, environmental barrier coatings and abradable coatings on compressor, combustor and turbine components. Thermal Barrier Coatings are in service for many decades and effectively protect the surface of the metallic parts by using their low thermal conductivity and high temperature stability. For static parts, atmospheric plasma spraying (APS) is mostly used as a process which gives a high deposition rate and relatively low production cost. For turbine blades the process used is EB-PVD (Electron Beam – Physical Vapour Deposition), which results in a coating with high strain tolerance and a good surface finish. Other applications of ceramic coatings are the so called “abradable sealing systems”, where abradability and relative high conductivity are additional challenges to the thermal protection requirements. This publication will address the challenges in using the ceramic coatings in different applications in the engine and the associated complexity during the development, manufacturing and in service performance estimation of the coatings and also provide a guide for future development targets.

Talk 16: Thursday 7th April, 18.00-18.30

The Helmholtz Energy Materials Characterization Platform: a Distributed Research Infrastructure of Seven Helmholtz Research Centres†

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The accelerated development of renewable energy technologies and the advancement of energy storage and efficient conversion technologies have become essential for achieving Germany’s goals with respect to the necessary transformation of the energy system. Basic material science is a major driver for the necessary technological development. Thus, future enhancement of efficiency, performance, and cost-effectiveness will depend critically on our capability to develop substantially improved materials and material systems, as well as on our ability to understand and to design their opto-electronic, electro-chemical, or thermo-mechanical properties. The Helmholtz Energy Materials Characterization Platform (HEMCP) is a research infrastructure supported by the Helmholtz Association and unites a unique set of instruments and analytical methods from seven research centres under one virtual roof, thus offering a wide range of options for advanced in-situ characterization of materials for energy technologies. Some details of the arrangements are available at http://www.hemcp.de/. The HEMCP concentrates on those energy technology areas where improvements are especially dependent on progress in material science: photovoltaic systems, chemical and electrochemical energy conversion and storage, as well as thermoelectric energy converters. This infrastructure provides a link between technology-oriented materials research and the development of sustainable energy systems based in the participating centers and the scientific opportunities of experiments in large-scale facilities, as well as opportunities for cooperation with universities and other research organizations or industrial partners.

† DESY, Hamburg: DLR, Köln: FZ Jülich, Jülich: HZB, Berlin: HZDR, Rossendorf: HZG, Geesthacht: KIT, Karlsruhe.

Talk 17: Friday 8th April, 08.45-09.10

Functionally Graded Tungsten Steel Coatings for Fusion Applications

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Reduced activation ferritic martensitic (RAFM) steels, e.g. EUROFER97, are to be used as structural material for the first wall (FW) of future fusion power plants. The interaction between plasma and FW, especially physical sputtering, will limit the FW lifetime under normal operation. Therefore tungsten coating is selected to protect the FW, due to its very low sputtering yield, high melting point and low activation. However, the mismatch in thermo-physical properties between tungsten and EUROFER97 can lead to large residual thermal stresses and even failure. To overcome this, erosion protective tungsten coating with tungsten/EUROFER97 functionally graded (FG) interlayer on EUROFER97 substrate are being developed and optimized. The coating, as well as the FG interlayer, are produced by vacuum plasma spraying (VPS) with parameters optimized by modelling and evaluated by means of microstructural and micromechanical investigations. In addition, residual stress measurements, thermal shock, thermo-mechanical fatigue, as well as fracture mechanical experiments, are performed on the fabricated coating systems. Thereby very promising results are obtained, revealing the good quality of the coatings with respect to desired application and verifying the success of the approach pursued.

Talk 18: Friday 8th April, 09.10-09.35

Materials and Components for Extreme Loads in Fusion First Wall and Divertor Applications

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For the first wall of a fusion reactor, unique challenges on materials in extreme environments require advanced features in areas ranging from mechanical strength to thermal properties. The main challenges include wall lifetime, erosion, fuel management and safety. Tungsten (W) is the main candidate material for the first wall of a fusion reactor, as it is resilient against erosion, has the highest melting point of any metal and shows a rather benign behavior under neutron irradiation. To overcome brittleness issues when using W, a W-fiber enhanced W-composite material (W_f/W), incorporating extrinsic toughening mechanisms, can be used. Even in the brittle regime, this material exhibits a higher tolerance towards cracking and damage than conventional tungsten. First W_f/W samples have been produced, showing extrinsic toughening mechanisms similar to those of ceramic materials [1]. These mechanisms will also help to mitigate effects of operational embrittlement due to neutrons and high operational temperatures. New manufacturing approaches and specially structured materials (e.g. Powder Injection Moulded (PIM) tungsten) may address issues of embrittlement. Addressing the safety issue, a loss-of-coolant accident in a fusion reactor could lead to a temperature rise to 1400 K, due to neutron-induced afterheat of the in-vessel components [2]. A potential problem with the use of W in a fusion reactor is the formation of radioactive and highly volatile WO_3 compounds. In order to suppress the release of W-oxide, tungsten-based alloys containing self-passivating alloying components seem feasible, as they can be processed to thick protective coatings with reasonable thermal conductivity. W-Cr-Y (with up to 80 at% of W content) already shows a 10^5-fold suppression of tungsten oxidation due to self-passivation. Developments joining W as PFM with the structural material EUROFER97 via Functionally Graded Materials (FGMs) are ongoing. They can mitigate the effect of mismatch in the thermo-mechanical properties. Furthermore, tritium management remains an issue, despite the low tritium retention in W. In order to prevent tritium loss and radiological hazards, it is important to suppress permeation through the reactor walls [3]. Permeation barriers require high reduction factors, high thermal stability and resistance to corrosion. Thermal expansion coefficients similar to those of the substrate are required for barrier layers. Finally, for the development of plasma facing components, the issues of power exhaust needs to be considered. This might require replacing copper as a heat sink, e.g. by steel, to avoid irradiation-induced deterioration, e.g. swelling [4]. However, it would impair the thermal properties and worsen the activation behavior, as is also seen when using interface materials such as oxides in composites and as permeation barriers [5].

[1] Riesch, J. et al., Physica Scripta, PFMC-14 (2014)
[2] D. Maisonnier, et al., *Conceptual Study of Commercial Fusion Power Plants*, Final Report, EFDA-RP-RE-5.0, Apr 2005.
[3] Levchuck et al., J. Nucl. Mat. **442** (2013) S592–S59.
[4] SA Fabritsiev, SJ Zinkle and B Singh, *Evaluation of Copper Alloys for Fusion Reactor Divertor and First Wall Components,* J. Nucl. Mat. **233** (1996) 127-137.
[5] Forrest, R.; *Handbook of Activation Data Calculated Using EASY-2007*, EURATOM/UKAEA Fusion Association, 2009.

Talk 19: Friday 8th April, 09.35-10.00

Materials for Future Fusion Reactors under Severe Stationary and Transient Thermal Loads

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The plasma facing components in future fusion devices such as ITER or DEMO will be exposed to severe stationary and transient thermal loads during Edge Localized Modes (type I ELMs) with a high repetition rate. In addition, also off-normal events such as plasma disruptions, vertical displacement events and others will damage the plasma facing armor. Extrapolations from existing magnetic confinement experiments confirm that under all these transient events irreversible material damage has to be anticipated. Hence, effective mitigation methods for transients are mandatory to ensure a sufficiently long lifetime of the wall armor. Due to its relatively low melting point, the use of beryllium as an armor material for the first wall in ITER has got a strong impact on the acceptable magnitude of transients [1]. The thermal shock performance of tungsten and tungsten-alloys which will be used as target material in the divertor region can be characterized by threshold values for roughening, cracking, and melting. These thresholds strongly depend on the applied thermal loads (power density and pulse duration), the number of applied pulses, the base temperature of the test samples, and the properties of the materials, which are related to its microstructure. Base temperatures below the ductile-brittle-transition temperature are unfavorable; the same applies to very high surface temperatures resulting from steady state heat fluxes where the additional energy input by ELMs may trigger surface near recrystallization effects. The thermal response of beryllium, tungsten and a number of other material candidates for the First Wall and the divertor has been evaluated in electron beam simulation experiments, which were performed in a wide parameter range. Based on these data, the prevailing damaging mechanisms have been analyzed. Further attention has been paid to synergistic effects, in particular to the growth of thermal shock induced cracks under steady state heat loads [2]. Hydrogen embrittlement, helium induced growth of tendril-like extrusions on refractory metals, and neutron induced material degradation are additional serious lifetime limiting factors for plasma facing components.

[1] B. Spilker et al, *Experimental study of ELM-like heat loading on beryllium under ITER operational conditions*, Phys. Scr. **T167** (2016) 014024

[[2] Th. Loewenhoff et al., *Impact of combined transient plasma/heat loads on tungsten performance below and above recrystallization temperature*, Nucl. Fusion **55** (2015) 123004

Talk 20: Friday 8th April, 10.30-10.55

High Temperature Stable Fibre Reinforced Composites for Thermal Protection of Spacecraft Vehicles

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Due to their high temperature stability and their adjustable oxidation resistance, ceramic matrix composites (CMCs) are promising candidates in aerospace and reentry applications. The CMCs show high durability and thermal shock resistance, high temperature capability and adjustable thermal conductivity. While for short term application, uncoated non-oxide fibre reinforced composites may be used, under longer oxidation attack either all-oxide composites have to be applied or coated non-oxide composites will be implemented. As the all-oxide composites are creep sensitive and stable only just above 1000 or 1100°C, coated non-oxide structures are preferably being used in thermal protection systems. By coating with yttria-based oxide layers, a sufficient protection against oxidation has already been proved in various experiments. Other material concepts with ultra-high temperature ceramic matrix composites (UHTCMC), or with high thermal conductive fibres, are being discussed. In the presentation, the different concepts of thermal protection systems and actual approaches being investigated and developed at DLR will be shown.

Talk 21: Friday 8th April, 10.55-11.20

Airbus Safran Launchers GmbH TPS Portfolio - Status and recent Developments

W Fischer

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Airbus Safran Launchers GmbH at Bremen has focussed recently on further maturation of its comprehensive TPS portfolio and the application on missions currently under preparation. Within the European demonstrator programmes, the blanket based/oxide ceramic TPS was developed to PDR maturity. The metallic TPS MERIT, based on beta-Ti alloy, was further developed in the frame of the FLPP materials & structures programme. For metallic & oxide ceramic TPS, a demonstrator has been designed, manufactured and tested on Germanys SHEFEX I & II C/SiC, SPFI and metallic TPS experiments have been flown. For the SHEFEX III vehicle, an oxide-based CMC TPS on the leeward side has been prepared. Within the frame of EU projects, a UHTC based TPS concept and a hybrid TPS concept have been studied. Currently, a heat shield for the ORION aft bumper is being prepared, based on blanket type thermal protection, in combination with medium temperature polyimide and high temperature metallic multi-layer insulation. This paper summarizes the recent activities concerning maturation (ground/flight testing) and application of blanket-based TPS, metallic TPS, oxide/silicon carbide CMC based and UHTC/Hybrid TPS.

Talk 22: Friday 8th April, 11.20-11.45

Volcanic Ash, Aircraft Engines and Progress Since Eyjafjallajokull

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The Icelandic eruption of 2010 and its impact on aviation highlighted to the wider world a problem that a small number of people had been grappling with since the early 1980s; jet engines can be easily damaged by volcanic ash and for safety and economic reasons it was advisable to keep aircraft well clear of ash clouds. This presentation outlines how, qualitatively, volcanic ash damages gas turbine engines and explains how relatively little is known about how much ash it takes to damage an engine. It then covers the commercial, wider socioeconomic and regulatory picture that has evolved since 2010, including a selection of aviation affecting eruptions to illustrate the points made. The key question of how much improvement in the engine damage quantitative understanding would be needed to significantly reduce the socioeconomic impacts is discussed. Finally a summary is given of the research and engine events that are starting to improve the quantitative understanding.

Talk 23: Friday 8th April, 11.45-12.10

A Few Aspects of the Current Understanding of Diesel Particulate Filter Materials Thermal and Mechanical Properties

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Bi-continuous porous ceramics for filtration applications possess a particularly complicated microstructure, whereby porosity and solid matter are intermingled. Moreover, they very often display a micro-crack network, resulting from the strong anisotropy of the microscopic coefficient of thermal expansion (CTE). Mechanical, thermal, and filtration properties all strongly depend on the morphology of both solid matter and porosity, and on the degree of micro-cracking (also, the micro-crack density), which is in its turn linked to the grain size. Recent industrial and academic research has enormously progressed in understanding the microstructure-property-performance relationships existing in these complicated materials:

- *Using 3D computed tomography (CT) at different resolutions, and several X-ray refraction-based techniques, porosity and pore orientation could be quantitatively evaluated (in the example of cordierite).*
- *Neutron and X-ray diffraction have been instrumental to disclose a) the non-linear character of the stress-strain response, and b) the negative CTE of these materials, and its consequences on the materials properties.*
- *Analytical and numerical models have been elaborated to rationalize these behaviours in terms of microcracking and microstructural features.*

Here these results will be reviewed, and an overview of (some of the) outstanding problems will be given.

Talk 24: Friday 8th April, 12.10-12.35

Highly Porous SiC Substrate for Diesel Particle Filters and its Combination with Catalysts for Selective Catalytic Reduction of Nitrogen Oxide with Ammonia

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Wall flow Diesel Particle Filters (DPF) are the established solutions for particle number reduction efficiencies up to 99.99%, to comply with the European emission regulations for on-road Diesel engines. SiC is known to be one of the most robust materials used in these filter applications. With the Euro 6 emission standard, the integration of NO_x reduction functionality in DPFs becomes more and more important. For this purpose, high porous SiC filters have been developed [1,2]. A new type of a DPF substrate, based on reaction-formed SiC, has recently been developed and its combination with different catalysts for the Selective Catalytic Reduction (SCR) of nitrogen oxides with ammonia was investigated [3]. The characteristic features of this highly porous SiC, and the impact by the coating with SCR catalysts based on Fe-β-zeolites, Cu-zeolites and their combination with mixed metal oxides, have been further studied. The aim of this paper is to give an introduction to this new material and to present the recent progress in this development. Results for the soot filtration, and its passive regeneration with NO_2 parallel to the SCR reaction, will be presented. Finally, we will show the performance of a complete heavy duty exhaust after treatment with such a SCR on DPF as the key component.

[1] K Nakamura, N Vlachos, A Konstandopoulos, H Iwata & O Kazushige, *Performance Improvement of Diesel Particulate Filter by Layer Coating*, SAE J. Engineers, 2012-01-0842.

[2] K Ogyu, T Ogasawara, H Sato, K Yamada & K Ohno, *Development of High Porosity SiC-DPF, which is Compatible with High Robustness and Catalyst Coating Capability for SCR Coated DPF Applications*, SAE J. Engineers, 2013-01-0840.

[3] T Wolff, R Deinlein, H Christensen & L Larsen, *Dual Layer Coated High Porous SiC – A New Concept for SCR Integration into DPF*, SAE J. Engineers, 2014-01-1484.

Talk 25: Friday 8th April, 12.35-13.00

Thermal Management in Porous Ceramic Particulate Filters: Opportunities and Consequences of Plasma Technology Solutions for Particulate Filter Regeneration

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We remain dependent on combustion sources for many of our essential energy systems, continuously improving technologies to minimise the negative impacts of the energy use on our environment. Local air quality in urban areas is of particular concern and has led to increasingly stringent legislation being applied to the energy sector. Reduction of particulate emissions from combustion sources is being effectively tackled through pre-combustion approaches (e.g. fuel quality), through combustion optimisation and by implementing exhaust gas aftertreatment systems such as monolithic ceramic particulate filters. Although a wide range of types of particulate filters exist, they all require cleaning to avoid excessive pressure drops across the substrate as the amount of trapped particulates increase. Typically this is done through oxidation of the trapped particles, requiring filters that are capable of withstanding high temperatures, high temperature gradients and both reducing and oxidising environments. Significant opportunities exist within the industry to improve vehicle efficiency and reduce cost by developing new and improved regeneration systems. Medium (>1000 K) and high temperature (>10,000 K) plasma technologies for particulate filter regeneration are introduced with a particular focus on their interaction with porous ceramic substrates. When used effectively, no observable damage is present. However, there exists engineering conflicts between minimising energy consumption, achieving fast regeneration and maintaining substrate durability. This conflict is presented showing the limits of current technology. It identifies two clear opportunities. Firstly, the recent application of pulsed plasmas to cordierite substrates demonstrates the opportunities for developing lower thermal requirement (and potentially lower cost substrates). Secondly, how advances in local substrate thermal characteristics can enable significant improvements in efficacy of oxidative plasma solutions.

Abstracts – Poster Presentations

Poster 1

Yttria as a Tritium Permeation Barrier in Fusion Components

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The development of tritium permeation barriers (TPB) is crucial for a safe reactor operation. Thin oxide coatings, such as Al_2O_3 and Er_2O_3, are promising candidates for TPB, due to their high thermal stability and corrosion resistivity, and their reasonable hydrogen permeation reduction factors. Their hydrogen permeation reduction factors are in the range of one to three orders of magnitude [1,2]. Due to the more favorable neutron activation behavior of Y compared to Al and Er, Y_2O_3 is produced as a TPB on Eurofer97 substrates. 1 µm thick layers are deposited on both substrate sides by RF magnetron sputter deposition. After annealing the cubic crystal structure is verified by X-ray diffraction and the microstructure is investigated by scanning electron microscopy. The permeation reduction factor is determined in gas-driven deuterium permeation experiments with a newly developed setup at FZ Jülich. First measurement results suggest that the permeation reduction factor is in the same order of magnitude than for Er_2O_3. Since the permeation reduction depends heavily on the microstructure of the barrier layer, layers with different microstructures are prepared and the reduction factors are compared.

[1] F Koch, R Brill, H Maier, D Levchuk, A Suzuki, T Muroga & H Bolt, *Crystallization behavior of arc-deposited ceramic barrier coatings*, J. Nuclear Materials **329-333** (2004) 1403–1406.

[2] T Chikada, A Suzuki, Z Yao, D Levchuk, H Maier, T Terai & T Muroga, *Deuterium permeation behavior of erbium oxide coating on austenitic, ferritic, and ferritic/martensitic steels*, Fusion Eng. Design **84** (2009) 590 - 592.

Poster 2

Plasma Wall Interaction with the ITER Fusion Material Mix in JET

S Brezinsek[1], V Philipps[1], Ph Mertens[1], JW Coenen[1], A Huber[1], G Sergienko[1], A Kirschner[1], S Wiesen[1], Ch Linsmeier[1], R Neu[2], M Rubel[3] & GF Matthews[4]
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Since installation of the JET ITER-Like Wall [1], there has been >30 h of plasma operation with the inertial-cooled full tungsten divertor, designed and developed by FZJ [2], and the Be first wall. The divertor plasma-facing components PFCs successfully handled harsh Tokamak conditions, with (i) surface temperature excursions passing the ductile-to-brittle transition and recrystallisation temperatures many times, (ii) ITER-relevant steady-state and peak power loads due to more than 1.5 million transients (edge-localised modes or ELMs), (iii) combined impact of deuterium and intrinsic impurities (C, Be, O), as well as extrinsic impurities like He, Ne, Ar, N_2 and Xe, and (iv) multiple complex conditioning cycles with baking, deuterium glow discharges and ion-cyclotron-wall conditioning. Routinely, monitoring discharges have been applied to characterise the impurity content in the plasma and the performance of the tungsten divertor and the first wall. Overall, the bulk divertor components showed no impact of damage and only moderate damage of the W-coating CFC tiles. The main wall bulk Be tiles showed massive damage at dedicated contact points, from melting and erosion due to high steady state heat flux (mid-plane limiters in limiter configuration) and high transient heat flux (upper dump plate during disruptions). We present an overview of findings from operation with full tungsten divertor and beryllium first wall, including in-situ observations and post-mortem analysis of extracted tiles. These include erosion and deposition characteristics [3], material migration and mixing, fuel retention and outgassing [4], as well as power handling [5]. A brief insight into plasma compatibility and performance will be given and conclusions drawn for the next step fusion device ITER [6].

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[3] S Brezinsek et al, Nucl. Fusion. **55** (2015) 063021.

[4] S Brezinsek et al, Nucl. Fusion. **53** (2013) 083023.

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Poster 3

Manufacturing and Design of Nonoxide Ceramic Matrix Composites for Gas Turbine Applications

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Non-oxide silicon carbide fibre reinforced silicon carbide matrix composites (SiC/SiC and SiC/SiCN) show good thermal shock resistance, a low coefficient of thermal expansion and excellent physical properties as well as chemical stability at elevated temperatures. They are therefore regarded as promising candidates for various applications in the turbine section of jet engines or in stationary gas turbines. The manufacturing process of such composites begins with creating a SiC-fibre preform in any shape by a layup of fabrics or filament winding. To create the matrix, two different routes are applied: liquid silicon infiltration (LSI) in case of the SiC/SiC composites and polymer infiltration and pyrolysis (PIP) in case of the SiC/SiCN composites. LSI is a technique characterised by short processing times to obtain composites with low porosity in a three step process: infiltration of fibre preforms with adapted phenolic resins and thermal curing, pyrolysis and siliconisation. The aim is to obtain a high carbon yield during pyrolysis and a maximised carbon conversion between the SiC fibres to near stoichiometric SiC. To protect the SiC fibres from the attack of the liquid silicon and to simultaneously provide a weak fibre matrix bonding, a Si-BN/SiC fibre coating has shown to be suitable. On the other hand, in the PIP manufacturing process the fibre preforms are infiltrated with polysilazanes, cured and pyrolysed to obtain an amorphous SiCN matrix. The resulting shrinkage of the polysilazanes leads to porosity in the matrix. Depending on the fibre volume content and ceramic yield of the polymer, this porosity can be reduced by repeating the process until the required porosity is reached. In dependence of the chosen fibre coating and fibre architecture, bending strengths of over 500 MPa for PIP composites and over 200 MPa for the LSI composites have been achieved. To increase the stability of the composites at gas turbine conditions, a tailored yttrium silicate environmental barrier coating is developed

Poster 4

Processing of Ceramic Composites by Field-Assisted Sintering Technology / Spark Plasma Sintering

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Field-Assisted Sintering Technology (FAST) / Spark Plasma Sintering (SPS) is widely used to consolidate new multi-functional and composite materials, due to unique combinations of processing parameters. High heating rates (> 100 K/min), uniaxial pressure (typically up to 100 MPa) and short dwell time (~ few minutes) are among the main characteristics of FAST/SPS, leading to fully dense ceramic matrix composites (CMCs) that cannot be produced by other sintering techniques. The fast heat treatment prevents chemical reactions between the different components or their decomposition, whereas the applied pressure and the current flow promote the densification of the CMCs at lower temperatures. In addition, FAST/SPS allows obtaining dense materials with limited – or even inhibited - grain growth or highly textured compounds. In this work, three different CMCs processed by FAST/SPS are presented: (i) 8 mol.% fully yttria-stabilized zirconia (8YSZ) containing different amounts of carbon nanotubes, (ii) ZrB_2 reinforced with SiC particles, and (iii) a novel composite based on Cr_2AlC-MAX phase containing SiC fibers. Processing, sintering behavior and resulting microstructures will be described in detail.

Poster 5

Investigations of Novel Plasma Spray Processes by Optical Emission Spectroscopy

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For thermal barrier coating systems (TBCs), there are two major development directions: the improvement of the materials on the one hand and the investigation of new manufacturing techniques on the other hand. They are closely related to each other and must be both considered correspondingly [1]. This poster focuses on the investigation of two novel manufacturing processes for TBCs by optical emission spectroscopy (OES). Plasma Spray-Physical Vapor Deposition (PS-PVD) is a new technology operating at low pressure and high plasma power. At such condition, vaporization even of high-melting oxide ceramics is possible enabling the formation of columnar structured coatings from condensates and nano-sized clusters. These unique plasma conditions were characterized by OES [2] to improve the understanding of the process. Suspension plasma spraying (SPS) is a novel method to process submicron-sized feedstock powders which are not sufficiently flowable to feed them in dry state. Such finely grained materials are generally prone to partial evaporation under plasma spray conditions. Furthermore, this evaporation can be inhomogeneous so that the stoichiometry of the deposits might be affected. This was quantitatively investigated by OES [3].

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Poster 6

Modeling and Predicting High Temperature Coating Damage by Oxidation and Interdiffusion

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Protective metallic coatings are commonly used to enhance the oxidation and corrosion resistance of the underlying high temperature materials. One of the widely used high temperature coating systems are MCrAlY (M = Ni, Co) overlay coatings which ensure the growth of a slowly growing adherent alumina scale and thus protect the underlying substrate from rapid oxidation attack. Aluminium from the bondcoat is lost as a result of the growing external alumina scale on the coating surface and to the substrate by interdiffusion resulting in dissolution of the β-NiAl phase in the coating. The performance of a coated material depends on the intrinsic oxidation properties of the coating as well as the compatibility of a given type of coating with its base material. In general practice, the lifetime estimates are based on extensive experimental testing programs providing data in terms of the depletion of the β-NiAl phase. A promising alternative to this tedious and time consuming practice is the development of a CALPHAD-based thermodynamic-kinetic modelling. In the present study, two types of coated systems were considered:

- MCrAlY coating on commercially available nickel base alloys
- MCrAlY coating on model single-crystal Ni-Cr-Al-X (X = Co, Ta, W) alloys.

Element concentrations and phase distributions in coated specimens after exposure at various temperatures were obtained by scanning electron microscopy (SEM). Phases were identified by energy/wavelength dispersive X-ray spectroscopy (EDX/WDX) and electron backscatter diffraction (EBSD). Average element concentrations as function of distance from the coating surface were obtained using glow discharge optical emission spectroscopy (GDOES). The microstructural development in the coated systems was modelled by considering simultaneously occurring oxidation and interdiffusion processes. Using available thermodynamic and kinetic data for all occurring phases from Thermo-Calc, the current work differs from contemporary modelling methodologies. For the various coated systems studied, good agreement was found between the measured and computed phase fractions and phase distributions after specific time intervals.

Poster 7

In situ Transmission Electron Microscopy of Energy Materials

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Aberration-corrected transmission electron microscopes offer a wide variety of powerful techniques for characterising the local microstructure, crystallography and chemical composition of materials. Recent developments in microscope, specimen holder and detector technologies, as well as in methodology, software and data handling, now provide new opportunities for in situ studies of dynamic processes and functional properties in materials in the presence of external stimuli, such as elevated and reduced specimen temperature, electrical and mechanical probes, liquids, gases and applied magnetic fields. This presentation will provide an overview of recent research in this area in the Ernst Ruska-Centre in Forschungszentrum Jülich, with a specific focus on applications to energy materials. Topics will include studies of supported catalysts at elevated temperature [1], the oxidation and reduction of metal nanoparticles, changes in the structure, chemistry and electrical properties of thin films and nanocrystals that are of interest for energy-efficient resistive switching and photovoltaic applications and studies of the magnetic properties of novel ferromagnetic alloys and spintronic devices. The ability to reconstruct the three-dimensional crystallographic structure of a material from a single high-resolution image with atomic spatial resolution [2] will also be presented and prospects for achieving atomic resolution tomography during in situ experiments discussed.

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Poster 8

Fatigue Testing of Ni-based Superalloys for Gas Turbine Blades

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Single crystal Ni-base superalloys are used for turbine blades in aero engines and stationary gas turbines, where they operate under complex loading conditions, i.e. high temperature and complex stress state. The microstructure that provides high strength and high resistance against creep and fatigue is the well-known γ / γ' microstructure with cubic γ'-precipitates separated by γ-channels, which is achieved by adding alloying elements and a stepwise solid solution annealing treatment. While in the γ'-phase Al, Ti, and Ta segregate, forming Ni_3Al (Ni_3Ti), solid solution strengthening of the γ-channels is provided by enrichment of Co, Cr, Re, and W [1,2]. During longer exposure at high temperatures, these strengthening elements also have the tendency to form undesired brittle phases, such as the so called TCP (topologically closed packed) phases namely the σ, μ, or Laves phase. TCP phases can have a deleterious effect on the creep properties of superalloys [3] and influence the fatigue properties (in thermal mechanical fatigue) due to the depletion of the γ matrix of strengthening elements in the vicinity of the TCP-phases [4]. However, observations made in high temperature fatigue experiments indicate that formation of TCP-phases may have beneficial effects on the evolution of fatigue damages. In this contribution, the influence of TCP phases on the crack propagation during high temperature fatigue tests has been investigated and will be discussed.

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Poster 9

Extraction of Plasticity Parameters from Instrumented Indentation Data via Inverse FEM Modelling

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A methodology is presented for inferring the yield stress and work-hardening characteristics of bulk metallic materials from indentation data. It involves FEM modeling (building on previous “manual” convergence procedures [1]), with predicted outcomes (load-displacement plots and residual indent shapes) being systematically compared with experimental data. The “correct” property values are found by searching for the combination giving the maximum value for a “goodness of fit” parameter (*g*), which characterizes the level of agreement between experimental and predicted outcomes (and ranges from 0 for no agreement to 1 for perfect agreement). This is done by using a matrix of property values as input data for the FEM model. With one unknown property (yield stress, with no work hardening), its “correct” value can be found from the indentation outcome (load-displacement plot) with a single indenter shape (plastic strain field), since it will give the largest (closest to 1) value of *g*. With two unknown property values (yield stress and linear work hardening coefficient), a family of combinations of them is likely to produce similarly high values of *g* (close to 1), for a given indenter shape. For a significantly different indenter shape, however, the set of combinations is likely to be different, such that only one combination (the “correct” one) gives a high value of *g* for both cases. This concept can be extended to the case of three unknown property parameters (yield stress, work hardening coefficient and work hardening exponent), with the possibility of three indenter shapes being needed to obtain the correct (or unique) combination of parameter values. These ideas point towards an algorithm requiring relatively little computational effort and leading, not only to inferred property values, but also to an indication of the associated level of confidence in them. The methodology is illustrated using experimental data for extruded copper. Similar procedures could be employed to extract other types of property, such as creep characteristics.

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Poster 10

Novel Wrought γ/γ' Cobalt base Superalloys with High Strength and Improved Oxidation Resistance

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Co-base superalloys hardened through γ’ $Co_3(Al,W)$ precipitates with $L1_2$ crystal structure have attracted much attention since their discovery in 2006. They exhibit identical microstructures as γ/γ’ Ni-base superalloys and very promising properties. Due to the higher melting point of Co, they have a higher solidus and liquidus temperature and show less segregation than Ni-base superalloys. The creep properties are similar to first generation Ni-base superalloys and they have a comparable or even higher flow stress above 900°C. Moreover, the lower solvus temperature of the γ’ phase compared to Ni-base superalloys in combination with a high γ’ volume fraction at application temperature makes them very interesting high temperature structural materials produced by conventional cast and wrought methods. In this work, two newly-developed cast and wrought γ/γ’ Co-base superalloys with good oxidation resistance are investigated with respect to microstructure, deformation mechanisms, yield strength and creep properties. Both alloys possess a polycrystalline microstructure with a high γ’ volume fraction. The lattice misfit between the γ’ and γ/ phase is positive which has been determined by high energy X-ray diffraction. The yield strength up to a temperature of 800°C is similar to that of the Ni-base superalloys Waspaloy and Udimet 720LI. The creep strength of both Co-base superalloys is significantly better, which shows the potential of this new type of precipitate strengthened superalloys. Oxidation tests indicate that the oxidation resistance is comparable to commercial Ni-base superalloys.

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Poster 11

Cellular Silicon Carbide Ceramics at High Temperature

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Because of high thermal conductivity, low coefficient of thermal expansion and good thermal shock and corrosion resistance, cellular silicon carbide ceramics are of particular interest for applications at high temperatures, e.g. in volumetric burners or CSP plants. Out of different typical high temperature materials like silicon infiltrated silicon carbide, Alumina and a FeCrAl-alloy, especially pressureless sintered silicon carbide (SSiC) has been identified as the most promising material for such applications. A durability of the material over a long period of time, up to 10,000 hours or even more, is essential. In order to assess durability, the behavior of SSiC cellular ceramic foams at temperatures up to 1550°C for short and 1250°C for long operation times, at medium and high gas velocities and under the influence of various amounts of oxygen, water vapor and impurities has been investigated. In comparison to SiSiC material, a significantly higher oxidation resistance of our recently new developed SSiC was obtained. Based on identified degradation mechanisms, the durability of SSiC foams can be estimated.

Poster 12

Degradation of Advanced TBC Systems under Thermomechanical and Corrosive Loading in Burner Rig Testing

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Degradation of thermal barrier coatings (TBCs) in gas-turbine engines due to calcium-magnesium-alumino-silicate (CMAS) glassy deposits from various sources has been a persistent issue for many years. Understanding of the mechanism of CMAS-induced degradation of TBC, as well as approaches for mitigating CMAS attack by means of advanced TBC compositions, have grown remarkably. For an appropriate modelling of coating lifetimes, as well as for the design of TBCs with improved persistence, it is essential to characterize the interaction with CMAS in conditions close to actual service in an engine. A burner rig facility has been used for evaluation of TBC performance, where a thermal gradient is applied across the TBC, with simultaneous injection of CMAS to simulate the relevant conditions, while preserving full control over important degradation-limiting parameters. The paper summarizes the impact of load parameters, including composition and deposition rate of CMAS, surface temperature, temperature gradient, and high temperature dwell time on the microstructural degradation and cyclic lifetimes. Tests have been performed on the state of the art material YSZ, as well as on advanced TBC systems comprising top coats from pyrochlores, garnets or hexa-aluminates.

Poster 13

Effect of Y, Zr and O Contents in MCrAl-type Bondcoats on the Lifetime of Thermal Barrier Coatings

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The effect of minor reactive element (RE) additions of yttrium and zirconium as well as that of oxygen impurity in MCrAl (M=Ni,Co) type bondcoats on the cyclic oxidation lifetimes of electron-beam physical vapour deposited (EB-PVD) and atmospheric plasma sprayed (APS) thermal barrier coatings (TBC) systems has been studied. The EB-PVD TBC system, having an oxygen content of 0.05 wt.% in the MCrAlY bondcoat (0.3 wt.% Y) showed five times longer cyclic oxidation lifetime compared to nominally the same TBC system with 0.2 wt.% oxygen in the bondcoat. In the latter bondcoat, the minor yttrium addition was tied up into fine precipitates of yttrium aluminates. Thereby the beneficial RE-effect of yttrium on the adherence of the alumina based thermally grown oxide (TGO) was significantly reduced. The critical TGO thickness at failure was, by about a factor of two, lower for the high oxygen bondcoat than for the low oxygen bondcoat. Contrary to EB-PVD TBC systems, in APS-TBC systems a different failure mechanism is operative, whereby the lifetime is mainly determined by the rate of crack propagation through the ceramic topcoat. Consequently, no detrimental effect of increasing oxygen content on the lifetime of APS-TBC-systems with MCrAlY-bondcoat was found. The effect of Zr addition to MCrAlY bondcoat appeared to be positive in the EB-PVD TBC systems by shifting the crack propagation path from the TGO/bondcoat interface towards the TGO/topcoat interface and within the TGO. For APS-TBC-systems, the Zr-addition to MCrAlY-bondcoat had a negative effect of the locally enhanced TGO growth in the bondcoat concave regions, which promoted crack linking in the above topcoat regions, effectively shortening the lifetime. In summary, the lifetime of TBC-systems was observed to depend on the RE-reservoir, determined by the RE and O contents. Indications were found that for EB-PVD TBC systems an optimum RE-reservoir for extended lifetime exists, which provides a compromise between improved scale adherence and increased oxidation rate. In contrast, for APS-TBC systems with optimized bondcoat roughness profile, the RE-effect of improving TGO adherence seems to be only of minor importance for the lifetime.

Poster 14

Environmental Barrier Coatings for CMCs

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Ceramic matrix composites (CMCs) are promising materials for components in the hot section of gas turbines. They can withstand higher service temperatures than the currently used Ni-based superalloys. However, non-oxide CMCs have inadequate oxidation resistance, especially under the presence of rapidly flowing water vapor, as is present in combustion atmospheres. SiC-based CMCs suffer from volatilization of silicon hydroxide, which leads to severe surface recession. Therefore, environmental barrier coatings (EBCs) are required that protect the underlying CMC. In this study, SiC-based CMCs were coated by magnetron sputtering with silicon as the bond coat, and additionally with multilayers consisting of $Y_2Si_2O_7$ and Y_2SiO_5 or combinations thereof. The coating architecture was designed namely to minimize chemical interactions among different layers and to have a strain tolerant microstructure. Samples were tested up to 1250°C in air in a furnace cycle test or under severe thermal gradient conditions in a burner rig, respectively. All coatings showed no spallation after up to 100 h of testing and improved the oxidation resistance of the CMC. While the uncoated substrate suffered from severe degradation under flowing water vapor and showed rapid loss of the matrix material after only 1 h of testing, the EBC considerably lowered the mass loss and provides a good protection of the CMC in this test. The evolution of the microstructure of the systems during testing, interfacial reactions, and phase formation will be additionally addressed.

Poster 15

Influence of Morphology on Thermal Properties and CMAS Resistance of Gadolinium Zirconate EB-PVD Coatings

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The continued search for thermal barrier coatings with low thermal conductivity and good resistance to attack by CMAS (Calcia, Magnesia, Alumina and Silica), for high pressure turbine blades, is a technological and economical challenge for engine manufacturers seeking to increase turbine efficiency and component lifetime. Gadolinium zirconate could be a possible alternative candidate to standard yttria-stabilised zirconia. Coatings of such composition have been manufactured using industrial EB-PVD (Electron Beam Physical Vapour Deposition) equipment, with process parameters selected to tailor the coating morphology. The thermal conductivity has been found to be largely independent of the coating pore architecture, while thorough optimisation of the coating columnar structure is required to provide efficient resistance to CMAS infiltration. As a consequence, this last aspect should be addressed, in addition to the ceramic/melt interaction issue when developing new CMAS-resistant coatings.

Poster 16

High-efficient Thermal Protection Systems for Low-cooled Gas Turbines: Increased performance and Lifetime due to Optimized Coating Parameters

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In the past, combustor and turbine parts have often been TBC coated, to reduce the temperature of the metallic walls and get longer life. In case of TBC spallation, many parts could stay operational for long times. To increase the GT efficiency in future, the firing temperature will be increased and the amount of cooling will be reduced. Especially the combustor and first stage of the turbine will be affected. The thermal protection system on these parts must be optimized concerning: (i) materials properties and manufacturing tolerances, (ii) material degradation and failure mechanisms, and (iii) heat transfer and cooling air pick-up for long cooling channels. A statistical model has been developed, based on mean and standard deviation of lab test data, manufacturing processes and part-specific thermal boundary conditions. In a first model, thermally activated failure mechanisms, like low cycle fatigue of the base material, oxidation and interdiffusion of the bondcoat, and cyclic life of TBC, have been considered. Based on this, the stress/strain has been determined in a second model. The used Monte Carlo simulation reveals the most critical parameters for lifetime.

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Poster 17

A Standard Soot Generator for Diesel Particulate Filter Testing

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Diesel Particulate Filters (DPFs) are the preferred method for meeting Diesel emissions legislation for road vehicles. As a result, a great deal of test and development work on DPFs is now in progress for a variety of applications. A clear need has emerged for a cost-effective and repeatable technique to test DPFs without the need for an engine or chassis dynamometer. Engine and vehicle facilities are not only expensive, but it can be very difficult to obtain good repeatability in such an environment. Further, independent adjustment of soot loading rate (g/hr), loading temperature and loading flow rate may be difficult without access to engine control unit variables and calibration. This poster describes a new instrument to generate soot which is representative of a Diesel engine exhaust, to regenerate (thermally clean) DPFs, to map their thermal stresses, to load with ash and assess its effects in a controlled and repeatable manner via control of: Soot rate (g/ hr), Soot load temperature (C) and Exhaust flow rate (kg/hr). The burner is configured such that the soot generation is stable and repeatable (both in terms of concentration and composition) independent of the soot load on the DPF.

Poster 18

Novel Diesel Particulate Filters containing Fine Ceramic Fibres

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Ongoing concerns about adverse health effects [1] of carbon particulate in Diesel engine exhausts continue to drive the quest for improvement performance from Diesel Particulate Filter (DPF) systems for their removal. Two of the main areas in which improvements are being sought are enhanced removal of very fine particles (<~50 nm), particularly during the period immediately after regeneration (removal of accumulated particulate via combustion), and improved thermo-mechanical stability - especially in terms of resistance to thermal shock (during regeneration). The latter is focused partly on raising the fracture toughness of the materials concerned [2]. One approach to achieving these aims is to create novel composite materials via the introduction of (ceramic) fibres. This has the potential both to enhance the fracture toughness, mainly by promoting fibre pull-out, and to improve the filtration efficiency by creating “hybrid” (multi-scale) structures [3], with some gas flowing through very fine channels, while the presence of other (relatively coarse) pathways ensures that the overall permeability remains acceptably high. For DPFs, the latter requirement corresponds to the specific permeability being no lower than about $\sim 10^{-12}$ m^2. This presentation covers the creation of novel DPF structures containing fine ceramic fibres and measurement of their porosity and permeability. Work is also presented on tomographic capture of DPF structures (using a *Simpleware* package) and simulation of the flow through them of hot gas containing fine carbon particulate (using *COMSOL* packages). It is concluded that there is scope for significant improvement in overall DPF performance via the incorporation of fine fibres.

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Poster 19

Effect of Volcanic Ash Characteristics on their Adhesion in Gas Turbines

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Deposition of ingested volcanic ash (VA) within gas turbine aeroengines presents an increasing level of hazard as turbine entry temperatures (TET) continue to be raised, and can cause severe engine damage. The key issue is whether ingested particulate adheres to surfaces inside the engine, with the low softening temperature of many VAs making this more likely. Such adhesion has been studied both in a small turbojet aeroengine [1] (using a borescope) and in a customized plasma torch-based set-up designed to simulate a turbine combustion chamber [2]. Numerical modelling has been used to predict particle flight histories in the customized set-up and correlations established with observed rates of particle deposition [3]. Particle size is important, since the Stokes number of small (<~5 µm) particles is such that they do not impact solid surfaces, whereas large (>~40 µm) particles remain relatively cool. Unfortunately, VA particles in the intermediate size range commonly reach the turbine. The composition of VA, which varies significantly between different volcanoes, is also important, particularly insofar as it affects the glass transition temperature, T_g, the glass content and the viscosity of the glass. Many VAs have low softening temperatures (<~700˚C), particularly when compared with TET values of up to 1400˚C. In this study, four Icelandic VAs have been studied and correlations established between these features and observed deposition characteristics. The ashes examined fall into two groups of two, one (high silica) pair from strato-volcanoes (Hekla & Askja) and one (low silica) pair from a region where lower viscosity magma is produced (Laki and Eldgja). High speed photography of ash pellets projected against a substrate using a gas gun showed that the former were much more viscous than the latter and this is correlated with powders of the latter exhibiting much higher rates of adhesion. Establishing whether a particular VA cloud represents a serious hazard to air traffic is thus likely to require in situ sampling, probably using drones, and measurement of ash composition.

[1] M Shinozaki, KA Roberts, B van de Goor & TW Clyne, *Deposition of Ingested Volcanic Ash on Surfaces in the Turbine of a Small Jet Engine*, Adv. Eng. Mats. **15** (2013) 986-994.

[2] C Taltavull, J Dean & TW Clyne, *Adhesion of Volcanic Ash Particles under Controlled Conditions and Implications for Their Deposition in Gas Turbines*, Adv. Eng. Mats. (2016) DOI:10.1002/adem.201500371.

[3] J Dean, C Taltavull & TW Clyne, *Influence of the Composition and Viscosity of Volcanic Ashes on their Adhesion within Gas Turbine Aeroengines*, Acta Mater. (2016) **109** (2016) 8-16.