

AEROMAT | 2025

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CONTENTS

Scroll to the title and Click on it to link to the paper. After viewing the paper, use the browser's back button to return to the beginning of the Contents.

View Mobile App for the most up-to-date technical program details.

..... **Session: Thermal and Environmental Barrier Coatings for Gas Turbines I**

Bending Behavior and Microstructural Evaluation of Yttria-Stabilized Zirconia Thermal Barrier Coating Deposited via Suspension Plasma Spray and Solution Precursor Plasma Spray for Advanced Turbine Applications

*Dr. Taki Aissou, Dr. Patrick Dubois, Prof. Mathieu Picard, and Prof. Jocelyn Veilleux
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Cord Plasma Spray: A New Robust Process with the Potential to Produce Advanced Coating in Industrial Gas Turbine and Aero Applications

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Environmental Barrier Coatings Applied by Suspension Plasma Spraying

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The Influence of Particle Size Distribution for Homogeneity of Ytterbium Silicate Cating Prepared by Atmospheric Plasma Spraying

Kohei Seki, Takaya Masuda and Hiroyuki Ibe; Fujimi Incorporated, Kakamigahara, Gifu, Japan

..... **Session: Thermal and Environmental Barrier Coatings for Gas Turbines II**

Pull Adhesion Testing of Hafnium Oxide Coatings

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CONTENTS

Optimization of Heat Treatment Parameters for Yb-Disilicate Environmental Barrier Coatings

Dr. Peyman Khamsepour¹, Dr. Parul Parul¹, Prof. Ana C. Tavares¹, Prof. Daniel Guay¹, Prof. Kenneth Beyerlein¹, Dr. Bruno Guerreiro², and Dr. Rogerio S. Lima²

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Exploring the Microstructure and CMAS Resistance of Yb₂Si₂O₇ Environmental Barrier Coatings Deposited by Axial and Radial Injection Plasma Spraying

Mr. Farzam Arhami and Prof. Christian Moreau; Concordia University, Montreal, Quebec, Canada;

Ytterbium Disilicate Environmental Barrier Coatings: Processing and Combined Steam and Calcium Magnesium Alumino-Silicate Corrosion

Prof. Tanvir Hussain, University of Nottingham, Nottingham, United Kingdom

Parameter Exploration of Yb₂Si₂O₇ Coatings Prepared by Plasma Spray Physical Vapor Deposition

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Session: Thermal and Environmental Barrier Coatings for Gas Turbines III

Microstructure, Mechanical and Thermal Properties of Ytria-Tantala-Stabilized Zirconia Coatings Prepared from Suspension Plasma Spraying

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High-Resolution Synchrotron μ XRD and μ XRF for Detailed Phase and Elemental Analysis in Suspension Plasma Sprayed Environmental Barrier Coatings

Dr. Chinmayee Nayak¹, Mr. Arman Hasani¹, Dr. Malgorzata Grazyna Makowska², Mr. Ebenezer Owusu³,

Prof. Tanvir Hussain³, Dr. Sneha Goel⁴, Prof. Antti Salminen¹, Dr. Ashish Ganvir¹, and Mr. Vinay Gidla^{1,6}

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High Temperature (1100 °C) Isothermal Exposure of Plasma Sprayed Al₂O₃-YSZ -CNT Composite Bimodal Coatings

Mr. Shiven Ponnappureddy¹, Mr. Shubhendra Shivam Maurya²,

Prof. Anup Kumar Kesari², and Prof. Kantesh Balani¹

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(2) Indian Institute of Technology Patna, Bitha, Bihar, India

CONTENTS

100 KW High Power Cascade Debye Larmor Plasma Torch for APS and VPS Applications

Dr. Armando Salito¹, Dr. Geoffrey Darut², Mr. Christian Adam², Prof. Hanlin Liao³, Prof. Marie-Pierre Planche², Mr. Manfred Roesli¹, and Mrs. Myriam Sleiman²;

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Self-Healing Thermal Barrier Coatings: How Microchanges Influence the Overall Coating Durability

Dr. Pawel Sokolowski, Wrocław University of Science and Technology, Wrocław, Poland

Session: Cold Spray Coatings for Aerospace Applications

ID-Nova Warm Spray Process

Mr. Alan W. Burgess, SprayWerx Technologies Inc., North Vancouver, British Columbia, Canada

New Achievements in Cold Spraying of Aluminum Alloys for Structural Repair Applications Using Nitrogen as Propelling Gas

Mr. Jan Kondas, Dr. Reeti Singh, and Mr. Leonhard Holzgassner

Impact Innovations GmbH, Rattenkirchen, Germany

Deposition of Laser Ablation Resistant Coating on Carbon Fiber-Reinforced Polymers by Cold Spray

Mr. Saiful Wali Khan, Dr. Ekta Singla, and Prof. Harpreet Singh

Indian Institute of Technology Ropar, Rupnagar, Punjab, India

Cold Spray Aluminum: A Cutting-Edge Solution for the Restoration of Gas Turbine Low-Pressure Compressor Components

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Session: Thermal and Environmental Barrier Coatings for Gas Turbines IV

Comparative Oxidation Performance of NiCoCrAlY Coatings Deposited by High-Velocity Air Fuel and High-Velocity Oxy Fuel for Thermal Barrier Applications

Mr. Aravind Kumar Thoutam¹, Mr. Murilo Sergio Lamana¹, Dr. Fadhel Ben Ettouil¹, Prof. Ali Dolatabadi², and Prof. Christian Moreau¹

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(2) University of Toronto, Toronto, Ontario, Canada

CONTENTS

Study of the High-Temperature Oxidation Performance of MCrAlY Bond Coats Deposited by Thermal Spray and Cold Spray Processes

Mr. Murilo Sergio Lamana¹, Mr. Aravind Kumar Thoutam², Dr. Fadhel Ben Ettouil¹, Prof. Ali Dolatabadi³, and Prof. Christian Moreau¹

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Influence of Reactive Elements on Next-Generation Bond Coats in Thermal Barrier Coating Systems Using High Entropy Alloys

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Oxidation Behavior of AlCrFeNiSi-Based High Entropy Alloy Bond Coat Designed with the CALPHAD Approach

Mr. Michael Boschen¹, Dr. Ashok Meghwal¹, Mr. Ecio Bosi¹, Prof. Soon Jik Hong², Prof. Christopher C. Berndt¹, and Prof. Andrew Ang¹;

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Session: Surface Preparation, Load Bearing, Tribology, Corrosion, Abradable and Repair I

Microstructural Study of Nickel Chromium Coating with Complex Composition for High-Performance Application

*Ms. Nadia Akter, Ms. Grace Wagner, Prof. Fardad Azarmi, and Prof. Ying Huang
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Study on Corrosion Properties of Aluminum-Bronze Sealing Coating

Mr. Tong Liu^{1,2}, Mr. Jianming Liu¹, Prof. Yueguang Yu¹, Ms. Dan Guo¹, and Prof. Deming Zhang^{1,2}

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Session: Surface Preparation, Load Bearing, Tribology, Corrosion, Abradable and Repair II

A Comprehensive Review of High-Temperature Ceramic Abradable Coatings Used in Aero and Industrial Gas Turbines

*Mr. Masih Ghorban, Northwest Mettech Corp., Surrey, British Columbia, Canada
Concordia University, Montreal, Quebec, Canada*

High Temperature Sliding Abrasive Wear Performance of High-Velocity Oxygen Fuel-Sprayed Cr₃C₂-NiCr Coatings: Oxidation Induced Behavior and Mechanism

Dr. Xinqing Ma and Mr. Peter Ruggiero, Curtiss-Wright Corporation, East Windsor, Connecticut, USA

CONTENTS

Development of Repair Methods for Single Crystal Components Using Thermal Spray Processes

Ms. Maïke Létang¹, Dr. Jens Gibmeier², Dr. D. Sebold¹, Prof. Olivier Guillon^{1,3} and Prof. Robert Vaßen^{1,4}

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High-Temperature Tribological Performance of Chromium Oxide: NiMoAl-Based Coating Applied by Atmospheric Plasma Spray

Mr. Andre Renan Mayer¹, Mr. Kaue Bertuo², Francisco R.R. Enriquez³, Dr. Firuze Soltani-Kordshuli⁴, Dr. Gopal Dwivedi⁴, and Prof. Pantcho Stoyanov⁵

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Session: Thermal and Environmental Barrier Coatings for Gas Turbines V

Impact of Plasma Parameters on the Deposition of Environmental Barrier Coatings

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The Mechanism of Rapid Interdiffusion Bonding During Air Plasma Spraying of Thermal-Environmental Barrier Coatings for Future Ceramic Turbine Components

Dr. Edward Jonas Gildersleeve V, Dr. Emine Bakan, and Prof. Robert Vaßen

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Session: Thermal and Environmental Barrier Coatings for Gas Turbines VI

The Influence of YSZ Powder Morphology and Microstructure on the Surface Roughness of Thermal Barrier Coatings Applied in Industrial Gas Turbines)

Prof. Giovanni Bolelli¹, Dr. Simone Bursich², Ms. Margherita Cescon¹, Mr. Alessandro Lanzi², Prof. Luca Lusvarghi¹, Mr. Francesco Masciarelli¹, and Dr. Stefania Morelli¹

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Isothermal Oxidation Behavior of Multilayered Thermal Barrier Coatings

Arezoo Sezavar Seyedijandaghi, Ferdowsi University of Mashhad, Mashhad, Islamic Republic of Iran

CONTENTS

Session: Thermal and Environmental Barrier Coatings for Gas Turbines VII

Laser Treatment of Columnar YSZ Coatings Produced by Suspension Plasma Spraying

Mr. Peyman Saffarzade¹, Dr. Amit Roy¹, Dr. Fadhel Ben Ettouil¹, Dr. Rogerio Lima², Prof. Martin Pugh¹, and Prof. Christian Moreau¹

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Dynamic Behavior of CMAS Droplets on Laser-Glazed Thermal Barrier Coatings

Dr. Amit Roy¹, Dr. Fadhel Ben Ettouil¹, Mr. Peyman Saffarzade¹, Dr. Rogerio Lima², Prof. Martin Pugh¹, Prof. Pantcho Stoyanov¹, and Prof. Christian Moreau¹

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Development of Multicomponent Stabilized Zirconia as Ultrahigh Temperature Thermal Barrier Materials

Mr. Sairam Ramachandran and Prof. Ashutosh S. Gandhi, Institute of Technology Bombay, Mumbai, India

Session: Thermal and Environmental Barrier Coatings for Gas Turbines VIII

Developing Oxidation-Resistant ZrC-Based Coating via Plasma Spraying for Advanced Thermal Protection Systems

Dr. Niroj Maharjan^{1,2}, Mr. Michael Boschen², Dr. Duy Quang Pham², Dr. Sam Meure¹, and Prof. Andrew Ang^{1,2}

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Boride and Carbide Coating by Plasma Spraying: Manufacturing and Assessment at Temperatures High than 2000 K

Dr. Arthur Charrue¹, Dr. Aurélie Quet¹, Dr. Charlotte Gregis², Mr. Vincent Génissel¹, and Dr. Marianne Balat-Pichelin³

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(2) ArianeGroup SAS, Le Haillan, France

(3) PROMES-CNRS, Font-Romeu-Odeillo, France

Cold Spray Additive Manufacturing of Satellite Propellant Tanks Using Ti-6Al-4V Alloy

Dr. Philip McNutt and Dr. Dibakor Boruah, TWI Limited, Cambridge, United Kingdom

Study on the Type II Hot Corrosion of MCrAlY

Mr. Zhaoran Zheng, BGRIMM Technology Group, Beijing, China

CONTENTS

Session: Surface Preparation, Load Bearing, Tribology, Corrosion, Abradable and Repair III

Automating Metal Component Refurbishment: How Can the Power of Digital Tools Boost Quality, Productivity and Safety?

*Dr. Alejandro Vargas Uscategui, Mr. Hans Lohr, and Dr. Peter C. King
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Coatings for Fluid Erosion Protection

*Dr. Juan Manuel Mendez¹, Mr. Steve Guetre¹, Mr. Marcio Duffles², Dr. Stefan Tzanev¹, Mr. Michael Patterson¹,
Ms. Marissa MacLean, P. Eng¹, and Mr. Jason Lee¹
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Revolutionizing Manufacturing: The Role of Laser Cleaning in Thermal Barrier Coatings Deposition and Removal.

Dr. Dmitri Novikov, IPG Photonics, Marlborough, Massachusetts, USA

Session: Thermal and Environmental Barrier Coatings for Gas Turbines IX

Suspension Plasma Spray versus Electron-Beam Physical Vapor Deposition Yttria-Stabilized Zirconia Thermal Barrier Coatings: Durability under Thermal Cycle in Thermal Gradient Environment

Dr. Rogerio S. Lima and Dr. Bruno Guerreiro, National Research Council of Canada, Boucherville, Quebec, Canada

Axial Plasma Spraying of Solution Precursors: Adding a New Dimension to Future Thermal Barrier Coatings Development?

*Thomas Hervy¹, Nicholas Curry², Mr. Stefan Björklund³, Dr. Frantisek Lukac⁴, Dr. Rahul Jude Alroy³ and
Prof. Shrikant Joshi³
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Isothermal Oxidation Performance of High-Entropy Zirconate as an Advanced Topcoat for Thermal Barrier Coatings

*Ms. Hamideh Vakilifard¹, Prof. Martin Pugh¹, Dr. Rogerio S. Lima², and Prof. Christian Moreau¹
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Data-Driven Design and Rapid Evaluation of Novel Thermal Barrier Coatings

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CONTENTS

The Performance Comparison of APS and PS-PVD Environmental Barrier Coatings

*Prof. Xiaofeng Zhang, Prof. Min Liu, Dr. Ziqian Deng, Prof. Chunming Deng, and Prof. Changguang Deng
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Session: Additive Manufacturing I

Direct Energy Deposition and Selected Laser Melting Processing Applications at MT Aerospace

Mr. Michael Windisch, MT Aerospace, Augsburg, Germany

Modeling Microstructure of Additive Manufactured Metal Parts

*R Sambathkumar, X Gao, R Avil, O Stryzhyboroda, C Huang, and J Jakumeit
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Developing Additively Manufactured Engine Parts for Small Launch Vehicles and Reusable Launch Vehicles

*Dr. Keum-Oh Lee¹, Dr. Hyeonjun Kim¹, Mr. Jaesung Shin¹, Mr. Byoungjik Lim¹, and Dr. Yong-Oh Noh²
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Developing Aerospace High-Strength Aluminum Additive Friction Stir Deposition Process for Critical Defense Parts

*Mr. Jacob Swanson, Mr. Noah Barnhill, Mr. Mitchell Keeler, and Mr. Joey Wheeler
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Session: Light Alloy Technology I

Scandium Additions in High-Performance Aluminum Alloys for Aerospace Applications

*Dr. Timothy A. Langan¹, Henk Vander Laan¹, and Mr. Frank Palm²;
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The Fatigue Properties of Anodized Aluminum Alloys

*Ms. Ashley Kobylinski¹, Prof. Omar S. Es-Said¹, Dr. Michael Hahn², Mr. Michael Niedzinski³, Mr. Xiaodong Sun¹,
Kade Cochran¹, Joey Slaybaugh¹, Sarah Leka¹, and Dr. Ricky Whelchel⁴
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The Utilization of Extrusions for Aerospace Applications

*Steven Babaniaris¹ and Dr. Justin Lamb²
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(2) Universal Alloy Corporation, Canton, Georgia, USA*

CONTENTS

2074 Aluminum Sheet: Next Generation Low Density AIRWARE® Sheet for Fuselage Applications

Mr. Scott Buchwald¹, Dr. Hélène Godin², Mr. K. Paul Smith¹, and Mr. Peter Bittner³

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Development of a Stretch Forming Process for 2055 Aluminum Lithium Fuselage Frames

Mr. Jonathan Beckman¹ and Mr. Aaron Lam²

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Revolutionizing Aluminum Alloys: AMAG's Path to Unrestricted Innovation with AMAG CrossAlloy®

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Use of High-Performance Materials by Smart Assembly and Forming Techniques

Mr. David Chartier¹ and Dr. Frank Eberl²

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Session: Sustainability and Recycling I

Aluminum Solutions to Improve Sustainability in the Aerospace Industry

Dr. Sabine Spangel, Philipp Rumpf, Dr. Andreas Bach, Christian Tussing, Sasi Chinnasamy and Dr. Achim Bürger

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Digital Material Passports: Key Enabling Elements to Improve Quality, Sustainability and Circular Economy

Dr. Achim Hofmann, Advanced-Materials-Concepts GmbH, Bavaria, Germany

Data and Decision Science-Driven Assessment of Sustainable Materials for Thermal Protection in Aerospace

Dr. Tanjore Jayaraman, United States Air Force Academy, Colorado Springs, Colorado, USA

Adhesive Bonding in Cryogenic Conditions

Dr. Antonio Pagliuca, 3M Aerospace, Bracknell, United Kingdom

Materials Challenges for Sustainability in Reusable Space Launch Systems

Mr. Thomas N. Ackerson, Enterprise Engineering, Blue Origin, Merritt Island, Florida, USA

The Future of Aerospace Manufacturing and the Role of Advanced Materials

Mr. Tim Gaur, Airbus, Herndon, Virginia, USA

CONTENTS

Effect of Sustainable Aviation Fuel on the Volume Variation of Nitrile Elastomers

Ms. Erika Kano de Oliveira and Ms. Suelen Salih Teixeira Navarro, Embraer SA, São José dos Campos, São Paulo, Brazil

Session: University of British Columbia and The German Aerospace Center Biogenic Structural and Functional Materials

Biomass Derived Antimicrobial Cellulose Aerogels as an Alternative to Fossil-Based Plastic Materials and Theoretical Studies of Gel Structure Formation

Prof. Barbara Milow¹, Mrs. Nina Borzecka¹, Mr. Bruno Goncalves¹, Mrs. Sam Yeo², Prof. Ameya Rege¹, Dr. Kathirvel Ganesan¹, and Prof. Sepideh Pakpour²

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Development of Organic Aerogels Containing Chitosan Biopolymer from European Green Crab Shells

Dr. Lukas Bichler¹, Mr. Mitchell Barrett¹, Dr. Marina Schwan²,

Prof. Barbara Milow², Dr. Adam Dzierbinski², Dr. Martin Sgraja², Ms. Crysta Stubbs³, and Mr. Ryan Chamberland³

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Impact of Weak Organic Acids as Coagulants on Tailoring the Properties of Cellulose Aerogel Beads

Prof. Barbara Milow, Mr. Diogo Costa and Dr. Kathirvel Ganesan,

The German Aerospace Center, Cologne, Germany

Porous Carbon Materials for Electrochemical Applications

Dr. Marina Schwan¹, Ms. Jessica Kröner¹, Prof. Barbara Milow¹, Mr. Mitchell Barret² and Dr. Lukas Bichler³

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Session: Additive Manufacturing II

Exploring Gradient Aerospace Alloys: Modeling, Manufacturing, and Evaluation

Mr. Matt Dolde, Mr. Thomas Ales and Dr. Peter Collins;

Iowa State University, Ames, Iowa USA

Metal Additive Manufacturing for Critical Aerospace and Defense Components

Dr. Prabir K. Chaudhury, Education and Consulting LLC, Phoenix, Arizona, USA

CONTENTS

Performance of Rolled Threads on 3D Printed Inconel 718 and 17-4PH Stainless-Steel Hex Head Fasteners

Dr. Noel P. Greis^{1,2}, Dr. David Willens², Mr. Alex Deneault², and Mr. Daniel Barmakian²

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Session: Advances in Coatings and Surface Modification I

A Novel Approach for Applying 2K Coatings to Improve Outcomes and Reduce Cost

Mr. Michael R. Bonner, Saint Clair Systems, Inc., Washington, Michigan, USA

Evaluation of Mechanical Properties of Thermal Spray Coatings Using Micropillar Compression Test

Mr. Yeon Woo Yoo¹, Prof. Sung-Gyu Kang², Mr. Yong-Jin Kang¹, Mr. Youngjin Park¹, and Dr. Sunghun Lee¹

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Antimicrobial and Advance Coatings for the Aerospace Industry

Dr. Alfred Mitchell, Luminore CopperTouch, Houston, Texas, USA

Session: Light Alloy Technology II

Aluminum Alloys for High-Temperature Application

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Terran R Relativity's Space Heavy Lift Space Launch Vehicle

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Session: University of British Columbia and The German Aerospace Center Accelerated Sustainable Materials Design I

Transforming Mechanical Test Labs into Autonomous Knowledge Discovery Hubs

Dr. Eric Breitbarth, Mr. Florian Paysan, Mr. Eric Dietrich, Dr. David Melching, Mr. Manuel K uch,

Ms. Vanessa Sch one, Mr. Ferdinand D omling, and Prof. Guillermo Requena

The German Aerospace Center, Cologne, Germany

CONTENTS

High-Throughput Computational Screening of Aluminum Alloys from Scraps

Katrin Bugelnig, KB¹, Silvana Tumminello¹, Dr. Tobias Strohmam¹, Maike Becker¹, Nuria Navarrete¹, Florian Kargl¹, M. Kolbe¹, Janis Ganzenmüller¹, Julie Villanova², and Prof. Guillermo Requena¹

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Rapid Assessment of the Recyclability of Aluminum Alloys as a Function of Iron Content

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Session: Additive Manufacturing III

Printable, High Strength, Burn-Resistant Nickel Superalloy Designed Using ICMD Software

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Improving Manufacturing Readiness of Additive Friction Stir Deposition for Ferrous and Nickel-Base Materials

Mr. Lukas Dean¹, Mr. Dallin Gariety¹, Dr. Chase Cox², Mr. Wes Downs², Mr. Russell Steel³, and Dr. Yuri Hovanski¹

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Alloy Prototyping in Additive Manufacturing Using the Flexibility of Ultrasonic Atomization

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Break Through in Metallic Properties by Additive Manufacturing

Dr. Youping Gao, Castheon Inc, Thousand Oaks, California, USA

Session: Composite Materials and Structures

Hydroxy Functional Co-Curable Polyurethane Films for Composite Surfacing

Mr. Ron Fattal, Films, AkzoNobel, Waukegan, California, USA

Monitoring Damage Development in Laminated Composites Using Acoustic Emission During High Cyclic Shear Loading

Dr. Hamza Segnidi, University of Hassan II, Casablanca, Ben M'Sick, Morocco

CONTENTS

Strength Prediction for Composite Parts Utilizing the Material Modeling Approach

Ms. Amanda N Baranowski, Mr. Seth A Yakel, Ms. Cosette A Geesey, Ms. Catherine M Parra, and Dr. Mahesh Chengalva
BCA Product Development, Boeing, Everett, Washington, USA

Session: High Temperature and Gas Turbine Materials I

Novel Cr-Si Slurry Coatings for High-Temperature Materials

Mr. Michael Kerbstadt, Dr. Emma White, and Dr. Mathias Galetz
DECHEMA-Forschungsinstitut, Frankfurt am Main, Germany

Investigating the Influence of Calcium Chloride on the Nitridation Behavior of Silicon Powder

Mr. Ahsan Ali, National University of Sciences and Technology, Islamabad, Pakistan

Benefits of Multichamber Vacuum Heat Treatment with High-Pressure Gas and Oil Quenching

Mr. Thomas Hart, SECO/VACUUM, Meadville, Pennsylvania, USA

Influence of Hot Deformation Parameters on the Tensile Properties of VDM Alloy 780

Dr. Masood Hafez Haghghat¹, Dr. Bodo Gehrman¹, Dr. Helena Alves¹, and Bill MacDonald²
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(2) VDM Metals USA, LLC, Florham Park, New Jersey, USA

Session: Modeling and Simulation of Manufacturing Processes

Digital Twins for Accelerated Materials Innovation

Dr. Surya R. Kalidindi, Georgia Institute of Technology, Atlanta, Georgia, USA

Accelerating Material Development with Computational Insights from FLOW-3D Additive Manufacturing

Mrs. Allyce Jackman and Garrett Clyma, Flow Science Inc., Santa Fe, New Mexico, USA

Digital Forgings: Application of ICME and Digital Twins for the Development of Aerospace Forgings

Mr. Thomas Witulski and Mrs. Angela Quadfasel, M&P Development, Meinerzhagen, Germany

Advancing Precision Welding Through Computational Modeling with FLOW-3D Weld

Mrs. Allyce Jackman, Flow Science Inc., Santa Fe, New Mexico, USA

Artificial Intelligence and Simulation-Based Optimization of Turbine Blade Manufacturing

J Jakumeit¹, Y Bami², T Bähr¹, G Zheng¹, R Laqua¹, S Chatterjee¹, C Nicolae¹ and J Schievenbusch¹
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(2) Access e.V., Wisconsin, USA

CONTENTS

Session: University of British Columbia and The German Aerospace Center Accelerated Sustainable Materials Design II

In-Situ Defect Detection in Electron Beam Powder-Bed Fusion via Surface Height Reconstruction from Backscattered Electron Signals

Mr. Meet Upadhyay, University of British Columbia, Vancouver, British Columbia, Canada

Laser Powder Bed Fusion of Titanium Aluminide Ti48-2-2: Manufacturing and Testing of Highly Loaded Compressor Wheels

*Dr. Jan Haubrich¹, Dr. Joachim Gussone¹, Prof. Guillermo Requena¹,
Mr. Ralf Heber², Dr. Holger Gödecke², A. Stark³, and Dr. Norbert Schell³;
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(2) G+L innotec GmbH, Laupheim, Germany
(3) Helmholtz-Zentrum Hereon, Geesthacht, Germany*

Incorporating Nonlinear Effects in Fast Semi-Analytical Thermal Modeling of Powder-Bed Fusion

*Mr. Shaun Cooke, Prof. Chad W. Sinclair, and D.M. Maijer
The University of British Columbia, Vancouver, British Columbia, Canada*

Session: Additive Manufacturing IV

Utilizing Computational Materials Modeling and Big Data to Develop Printable High Gamma Prime Superalloys for Additive Manufacturing

*Mr. Jonathon Bracci, Mr. James Vecchio, and Dr. Kevin Kaufmann;
Oerlikon Metco (U.S.) Inc., San Diego, California, USA*

Properties of AA7075 Produced with Additive Friction Stir Deposition: Graphite Free

*Mr. Michael Merrell¹, Mr. Jacob Hansen¹, Mr. Lukas Dean¹, Mr. Scott Rose², Mr. Noah Barnhill, Mr. Mitchell Keeler³,
and Dr. Yuri Hovanski¹;
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(2) The Boeing Company, Berkeley, Missouri, USA
(3) ASTRO America, Moline, Illinois, USA*

Novel True 3D Printing Method for Serial Production of Highly Performant Components up to 100,000 Pounds

Mr. Isaac Valls, MetalPrint3D-XXL, Berlin, Germany

Increasing the Ductility of an Al-Cu-TiB₂ Composite by Additive Manufacturing

*Prof. Xiaoming Wang¹ and Dr. Tao Wang²
(1) Purdue University, West Lafayette, Indiana, USA
(2) PSW Group, Chicago, Illinois, USA*

CONTENTS

Additive Manufacturing Aluminum Alloy Matrix Composites without a Strength-Ductility Trade-Off

Prof. Xiaoming Wang¹, Mr. Huan Li¹, Mr. Jerome Fourmann², Dr. Paul Rometsch³, and Dr. Alexandre Bily⁴

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(2) Rio Tinto, Chicago, Illinois, USA

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Flexural Behavior of Ti-6Al-4V Triply Periodic Minimal Surface Lattice Sandwich Structure Produced by Electron Beam Powder Bed Fusion

Mr. Eric Bol and Prof. M Ramulu; University of Washington, Seattle, Washington, USA

Martensitic Stainless Steel with Precipitation Hardening and High Mechanical Strength for Additive Manufacturing.

Dr. Tiphaine Giroud¹, Dr. Solange Vivès², Mr. Loïc Michel¹, Ms. Alicia Nigon¹, and Dr. Laury-Hann Brassart¹

(1) Aubert & Duval, Les Ancizes-Comps, France

(2) Aubert & Duval, Paris, France

Session: Advances in Coatings and Surface Modification II

Characteristics of the Porous Anodic Oxide Film Formed on Aerospace 7xxx Aluminum Alloy

Yudie Yuan, Y. Lin, J. Qin, F. Liang, J. Wu, Z. Wang, and G. Tian;

Novelis Zhenjiang, Jiangsu, China

Composite Laser Ablation Surface Preparation to Replace Manual Processes in Aerospace Applications

Mr. Adam Hicks, Air Force Research Laboratory, Wright-Patterson Air Force Base, Ohio, USA

Patterned Peening for Strength and Ductility Optimization

Dr. Mark Atwater, Liberty University, Lynchburg, Virginia, USA

Session: High Temperature and Gas Turbine Materials II and Residual Stress for AeroSpace Components

Low-Cost Design Validation of Turbine Components Using High-Temperature Steel AISI 422 for Small Gas Turbine Engine

Mr. Nhat-Minh Hoang, Mr. Quoc-Huy Nghiem, Mr. Duy-Lanh Chu, and Mr. Phi-Minh Nguyen

Viettel Aerospace Institute, Hanoi, Vietnam

Influence of Long-Term Thermal Ageing on Mechanical Properties for In718 and In625

Mr. Zacharie Obadia, Airbus Commercial Aircraft, Toulouse, Occitanie, France

CONTENTS

Session: Tribology and Wear of Aerospace Materials: Low-Cost Manufacturing and Affordable Structures

Gear-Steel: Novel Material for Aircraft and Helicopter Drivetrain Parts

Dr. Gregory Vartanov, Advanced Materials Development Corp., Oakville, Ontario, Canada

The Astonishing Diversity in the World of 2D Materials: Lessons Learned From MXenes and Transition Metal Carbo-Chalcogenides for Solid Lubrication

Prof. Carsten Gachot; Technische Universität Wien, Vienna, Austria

Influence of WC₁₂Co on the Microstructure and Tribological Performance of High-Velocity Air Fuel Sprayed AlCoCrFeNi High-Entropy Alloy Coating

Dr. Payank Patel¹, Dr. Ashok Meghwal², Mr. Stefan Björklund³, Prof. Shrikant Joshi⁴, Prof. Paul Munroe⁵, Prof. Christopher C. Berndt², Prof. Andrew Ang², Prof. Christian Moreau¹, and Prof. Pantcho Stoyanov¹

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(3) University West, Trollhättan, Sweden

(4) University West, Trollhättan, Västra Götaland, Sweden

(5) University of New South Wales, Sydney, Australia

Military Steel: Novel Material for Deep Penetrating Bombs

Dr. Gregory Vartanov, Advanced Materials Development Corp., Oakville, Ontario, Canada

Session: The University of British Columbia and The German Aerospace Center Safe and Competitive Composites Aerostructures I

Challenges in Predicting the Energy Absorption of Composite Materials under Axial Crush Loading

Prof. Reza Vaziri¹, Dr. Matthias Weimer², Dr. Johannes Reiner³, Dr. Thomas Feser², Prof. Heinz Francois Voggenreiter², Prof. Anoush Poursartip¹, and Dr. Nathalie Toso²

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(2) The German Aerospace Center, Stuttgart, Germany; 3Deakin University, Geelong, Australia

Investigation of Crystallization Kinetics of Thermoplastic Composites

Prof. Anoush Poursartip¹, Mr. Daniel Fricke², Ms. Ines Mössinger², Dr. Ashley Chadwick², Mr. Tristan Wiedmann^{1,2}, Dr. Kamyar Gordnian³,

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(3) Convergent Manufacturing Technologies Inc., Vancouver, British Columbia, Canada

CONTENTS

Towards Model-Based Continuous Resistance Welding of Carbon Fiber Specimens

Julieta Barroeta Robles¹, Steven Roy¹, Marc Palardy-Sim¹, Marc-André Octeau¹, Jakub Stanczak¹, Francois Ferland¹, Henri Roger Junior Elame¹, Philippe Gaudreault-Crawley¹, Hugo Laurin¹, Ali Yousefpour¹, Stephen Atkinson², Scott Nesbitt², Prof. Reza Vaziri², Prof. Anoush Poursartip², Dr. Lars Larsen³, Manuel Endraß³, and Prof. Michael Kupke³

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Session: Welding and Joining I

Evaluation of Polycrystalline Diamond Materials for Friction Stir Welding Tooling

Mr. Scott Rose¹, Dr. Michael Shemkunas², Mr. Russell Steel³, and Mr. Murray Mahoney³

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Ultrahigh Speed Friction Stir Lap Welding of Aluminum Alloys

Dr. Yuri Hovanski¹, Mr. Todd Lainhart¹, Mr. Joshua Sheffield¹, and Mr. Dale Fleck²

(1) Brigham Young University, Provo, Utah, USA

(2) Mazak MegaStir, Provo, Utah, USA

Multiprincipal Element Alloy Fillers for Brazing Gas Turbine Engine Components at Two Distinct Temperature Ranges

Dr. Benjamin T. Schneiderman^{1,2}, Mr. Aric Adamson¹, Dr. Warren Miglietti³, and Dr. Zhenzhen Yu^{1,2}

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(3) Prince and Izant Company, Cleveland, Ohio, USA

Compositionally Complex Alloy as Brazing Filler Metal for Joining Honeycomb Sealing Systems

Mr. Jonas Vogler¹, Dr. Benjamin T. Schneiderman², Dr. Zhenzhen Yu², Dr. Rainer Völkl¹, and Prof. Uwe Glatzel¹

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Enabling Friction Stir Process Improvements through Specifications

Mr. Scott Rose¹ and Dr. Michael Shemkunas²

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(2) The Boeing Company, Everett, Washington, USA

Session: Emerging Materials and Processes I

The Role of HOCUT® 4260 in Overcoming Aerospace Machining Challenges

Mr. Ron Weigel, Quaker Houghton, Shawnee, Kansas, USA

CONTENTS

Manufacturing of Radio Frequency Metasurfaces for Radar Applications

*Dr. Melissa Riley¹, Mr. Andrzej Tabecki¹, Mr. Frank A.S. Nolan¹, Mr. Charlie Borley¹, Dr. Andy Wilson¹,
Dr. Kirsten Dyer², Dr. Cameron Gallagher³, Prof. Alastair P Hibbins⁵, and Prof. J.R. Sambles⁵*

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(3) The University of Exeter, Exeter, Devon, United Kingdom

Session: The University of British Columbia and The German Aerospace Center Safe and Competitive Composites Aerostructures II

.....

Towards Tool-Less Thermoplastic Carbon-Fiber Reinforced Polymer Manufacturing Processes Using a Cooperating Robot System

Mr. Matthias Beyrle¹, Mr. Dominik Deden¹, Dr. Michael Vistein¹,

*Mr. Maximilian Janek¹, Dr. Lars Larsen¹, Mr. Julien-Mathieu Audet², Mr. Gabriel Côté², Mr. Yves Fortin², and
Bruno Monsarrat²*

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(2) National Research Council Canada, Montréal, Quebec, Canada

Improving Quality Inspection in Automated Fiber Placement: A Data-Efficient, Unsupervised Anomaly Detection Framework

Assef Ghamisi, Todd Charter and Homayoun Najjaran, University of Victoria, Victoria, British Columbia, Canada

Vacuum Bag Leak Detection Using Machine Learning with Simulated Data from an Analogous Electric Circuit

Yussuf Reza Esmaeil and Homayoun Najjaran; University of Victoria, Victoria, British Columbia, Canada

Session: Emerging Materials and Processes II

.....

Material Properties of Precipitation Hardening Stainless Steel Ferrium® PH48S™

Mr. Nobuyuki Takahashi¹, Mr. Yoshiki Kumagai¹, Dr. Yoshihiko Koyanagi¹, and Mr. Kerem Taskin²

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(2) QuesTek Innovations LLC, Evanston, Illinois, USA

Decision Science-Driven Assessment of Magnetocaloric Materials for Thermal Management Systems

Dr. Tanjore Jayaraman; United States Air Force Academy, Colorado Springs, Colorado, USA

Industrial Internet of Things, Industry 4.0, and AI: What Process Parameters Should I be Watching and Which Should I be Controlling?

Mr. Michael R. Bonner, Saint Clair Systems, Inc., Washington, Michigan, USA

Intermetallic Matrix Alloys for Metal Cladding Application

Dr. C. Paul Qiao, L.E. Jones Company, Menominee, Michigan, USA

CONTENTS

Lost Core Nanomaterial Electroforming Process for the Low-Cost Manufacture of Complex High-Strength, Lightweight, High-Temperature Service Components

*Dr. Jonathan McCrea, Mr. David Kim, and Dr. Gino Palumbo;
Integran Technologies Inc, Mississauga, Ontario, Canada*

Scalium™: A New High-Strength Aluminum Alloy to be Used from Skis to Aerospace

Mr. Felix Lapointe; Ferreol Technologies, Québec, Canada

Predicting Material Properties and Its Validation Methodology

Mr. Marco Pelissero; Total Materia AG, Zurich, Zurich, Switzerland

Corrosion Resistance Comparison of Two Maraging Stainless Steels for Aerospace Application

*Dr. Laury-Hann Brassart¹, Mr. Jérémie Rougier¹, Dr. Charles Declairieux¹, and Dr. Solange Vivès²
(1) Aubert & Duval, Les Ancizes, Puy-de-Dome, France;
(2) Aubert & Duval, Paris, France*

Session: Materials Characterization and Failure Analysis

Small-Scale Alloy Development and Industrial Scale-Up Enabled by Complementary Characterization Methods Based on the Example of a PH-Steel

Dr. Manfred Stadler; voestalpine BÖHLER Edelstahl, Kapfenberg, Styria, Austria

Profilometry-Based Indentation Plastometry: A Novel Method to Support Failure Analysis in Aerospace

*Dr. Henry Begg¹, Dr. Oliver Morris¹, Dr. Zak Barrett², and Ms. Coral Smith²
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Microstructural Changes and Negative Creep of Inconel 783

*Mr. Konstantin Mueller¹, Dr. Benedikt Albert², Dr. Rainer Völkl¹, and Prof. Uwe Glatzel¹
(1) University of Bayreuth, Bayreuth, Germany;
(2) MTU Aero Engines AG, Munich, Germany*

Influence of Sample Preparation on Metallographic Examination of Thermal Spray Coatings

Ewa Bobala, GE Aerospace Poland, Warsaw, Poland

Imagining New Dimensionalities in Imaging of Elasticity

Mr. Thomas Ales and Dr. Peter Collins; Iowa State University, Ames, Iowa, USA

Buckling Strength Analysis and Effect of Local Welds in Isogrid Cylinder Structure

*Dr. Joon Tae Yoo, Mr. Sanghoon Lee, Dr. Yeonhee Jung, Dr. Chunghee Park,
Mr. Mincheol Shin, and Dr. Jong Hoon Yoon
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CONTENTS

Space Materials and Process Engineering, Selection, Validation and Application

Paresh R. Modi, Engineering Consulting Services, LLC, Fort Worth, Texas, USA

Session: The University of British Columbia and The German Aerospace Center Sensor Technology

Advanced Modeling Techniques for Next-Generation Polymer-Based Acoustic Nondestructive Testing Transducers

*Dr. Martin Angerer, Mr. Jonas Welsch, Prof. Edmond Cretu, and Prof. Robert Rohling
The University of British Columbia, Vancouver, British Columbia, Canada*

Front-End Amplified polyCMUTs for Acoustic Emission Sensing of Carbon Fiber-Reinforced Polymer

*Mr. Jinhao Lu, Dr. Martin Angerer, Mr. Jonas Welsch, Prof. Robert Rohling, and Prof. Edmond Cretu
The University of British Columbia, Vancouver, British Columbia, Canada*

Implementation of polyCMUT-Based Ultrasound Arrays in the Manufacturing Process of Lightweight Composite Structures

*Mr. Dominik Görick¹, Mr. Jonas Welsch², Prof. Michael Kupke¹, Prof. Heinz Francois Voggenreiter³, Prof. Edmond Cretu², and Prof. Robert Rohling²
(1) The German Aerospace Center, Augsburg, Bavaria, Germany;
(2) The University of British Columbia, Vancouver, British Columbia, Canada,
(3) The German Aerospace Center, Stuttgart, Baden-Württemberg, Germany*

Monitoring the Curing of Epoxy Resin Accelerated by Ultrasonication via Impedance Measurements

*Mr. Daniel Csehngeri, Prof. Edmond Cretu, Prof. Anoush Poursartip, and Prof. Robert Rohling
The University of British Columbia, Vancouver, British Columbia, Canada*

Quality Assurance of Vacuum Assisted Resin Infusion Manufacturing Processes via Acoustic Monitoring with polyCMUTs

*Mr. Jonas Welsch¹, Dr. Martin Angerer¹, Mr. Jinhao Lu¹, Mr. Dominik Görick²,
Prof. Robert Rohling¹, and Prof. Edmond Cretu¹
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Session: Titanium Alloy Technology

ATI Titan 27®: Leveraging Slip to Improve Performance for Aerospace

*Dr. Bhuvni Nirudhodi¹, Dr. Ming Li¹, Dr. John Foltz², D.A. Shaner¹, Erik Rogoff², and Dr. Andrew J. Temple²
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(2) ATI, Monroe, North Carolina*

CONTENTS

Development of Low-Cost Titanium Sheet via a Combination of Field Assisted Sintering Technology and Hot Rolling (FAST-roll)

*Dr. Samuel Lister, Dr. William Pulfrey, and Prof. Martin Jackson;
University of Sheffield, Sheffield, South Yorkshire, United Kingdom*

High-Temperature Titanium Alloy Development for Aerospace Applications: ATI Titan 171™ Alloy

*Dr. David Brice, Mr. John V. Mantione, and Dr. Matias Garcia-Avila
ATI, Monroe, North Carolina*

Effect of High Temperature on Ti-6Al-4V Annealed Material Tensile Properties Between 900 and 1800 °F

*Ms. Magdalena Michalowska and Mr. Jonathan Beckman;
(1) Gulfstream Aerospace, Savannah, Georgia, USA*

High-Temperature Titanium Alloy Development for Aerospace Applications: ATI Titan 1200™ Alloy

Dr. David Brice and Mr. John V. Mantione; ATI, Monroe, North Carolina, USA

Novel Stainless Steel Substitutes Aerospace Titanium Alloys

Dr. Gregory Vartanov, Advanced Materials Development Corp., Oakville, Ontario, Canada

Session: Welding and Joining II

Improving Production Performance of Refill Friction Stir Spot Welding

*Dr. Yuri Hovanski, Ms. Ruth Belnap, Mr. Damon Gale, and Ms. Taylor Smith
Brigham Young University, Provo, Utah, USA*

How Much Can Grain Refining Reduce the Solidification-Cracking Susceptibility?

Prof. Sindo Kou, University of Wisconsin, Madison, Wisconsin, USA

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A front-facing view of an F-35 fighter jet inside a large hangar. The jet is dark grey and has its wings swept back. The cockpit canopy is visible, and the aircraft is positioned on a runway or taxiway. The background shows the structural beams of the hangar. The image is overlaid with a yellow vertical stripe on the left and a blue vertical stripe on the right.

**2025 ABSTRACT
PROCEEDINGS**

Session: Thermal and Environmental Barrier Coatings for Gas Turbines I

Bending Behavior and Microstructural Evaluation of Yttria-Stabilized Zirconia Thermal Barrier Coating Deposited via Suspension Plasma Spray and Solution Precursor Plasma Spray for Advanced Turbine Applications

Dr. Taki Aïssou, Dr. Patrick Dubois, Prof. Mathieu Picard, and Prof. Jocelyn Veilleux; Université de Sherbrooke, Sherbrooke, Quebec, Canada

The efficiency and durability of gas turbines rely heavily on the performance of thermal barrier coatings (TBCs), which protect components from extreme temperatures and mechanical stresses. yttria-stabilized zirconia (8YSZ) is well-established for its effectiveness in TBC applications, yet its mechanical behavior, when deposited using emerging techniques like suspension plasma spray (SPS) and solution precursor plasma spray (SPPS), remains underexplored, particularly in novel inside-out ceramic turbine (ICT) configurations. This work bridges that gap by examining the bending performance of 8YSZ coatings deposited via SPS and SPPS on titanium substrates, with a particular focus on microstructural control. Both dense and columnar microstructures were tailored through systematic manipulation of key process parameters, including plasma conditions, solvent composition, and feedstock concentration. The resulting microstructures were characterized in detail using SEM, XRD, and Raman spectroscopy. To simulate real-world operational conditions of the innovative turbine designs, a custom-designed four-point bending test was employed, subjecting the coatings to combined tensile and compressive stresses at elevated temperatures. This approach provided insights into the strain tolerance and delamination resistance of the TBCs. The study offers a comparative analysis of SPS and SPPS of 8YSZ and establishes a novel framework for assessing TBC performance under complex, application-specific stress conditions.

Cord Plasma Spray: A New Robust Process with the Potential to Produce Advanced Coating in Industrial Gas Turbine and Aero Applications

Mr. Dominique Billières¹, Dr. Geoffrey Celeste¹, Prof. Shrikant Joshi² and Mr. Stefan Björklund²; ¹Saint-Gobain Coating Solutions, Avignon, France; ²University West, Trollhättan, Sweden

Plasma spray technology has demonstrated impressive flexibility, enabling DVCs, columnar TBCs with SPS, and high-performance abradable coatings. Due to the process complexity, however, a key challenge for the IGT and aerospace industries is to achieve a robust process at industrial scale. This can be further complicated when attempting to use SPS technology or when co-spraying dissimilar materials due to the additional challenges inherent in these processes. This presentation will introduce a breakthrough technology in thermal spraying: cord plasma spray (CPS). The authors obtained a variety of interesting microstructures by combining specifically developed YSZ cords (containing very fine powders) with the axial injection torch AXIAL III[®] (from **Northwest Mettech Corp.**). The expected advantages of this new approach will be presented along with potential industrial applications in the IGT and aerospace turbine markets.

Environmental Barrier Coatings Applied by Suspension Plasma Spraying

Madhura Bellippady¹, Nicholas Curry², Lisa Pin³, Stéphane Raffy⁴, Andreas Ottosson⁵, Olav Norheim⁶, Prof. Nicolaie Markocsan¹, and Prof. Shrikant Joshi¹; ¹University West, Trollhättan, Västra Götaland, Sweden; ²Northwest Mettech Corporation, Vancouver, British Columbia, Canada; ³Safran Ceramics, Le Haillan, Nouvelle-Aquitaine, France; ⁴Saint-Gobain Research Provence, Cavaillon, Provence-Alpes-Côte d'Azur, France; ⁵GKN Aerospace Sweden AB, Trollhättan, Västra Götaland, Sweden; ⁶Thermal Spraying & Engineering AB, Malmö, Skåne, Sweden

Environmental barrier coatings (EBCs) are protective ceramic coatings applied on ceramic matrix composites to prevent surface recession in steam and corrosive environments. Ytterbium disilicate (YbDS) has garnered significant attention as a promising topcoat material for EBCs due to its high thermomechanical stability, as well as resistance to oxidation and corrosion in harsh environments. In this work, a systematic study was conducted to assess the process parameter impact on the

microstructure of suspension plasma sprayed YbDS coatings on silicon carbide substrates with a silicon-bond coat, by varying plasma power and total gas flow rate. The results showed that these process parameters have a significant influence on phase constitution, microstructure and porosity of the YbDS coatings. The effect of thermal post-treatment on the above was also investigated. In addition, the YbDS coatings were subjected to long-term thermal exposure to ascertain the corresponding changes in microstructure and thermally grown oxide layer.

The Influence of Particle Size Distribution for Homogeneity of Ytterbium Silicate Cating Prepared by Atmospheric Plasma Spraying

Kohei Seki, Takaya Masuda and Hiroyuki Ibe; Fujimi Incorporated, Kakamigahara, Gifu, Japan

Environmental barrier coatings are applied for higher temperature operated turbine engine using SiC-based ceramic matrix composites to prevent reducing the thickness by oxidation-volatilization cycle in high-temperature and water vapor environments. Although Yb₂Si₂O₇ has attracted attention in terms of the similar coefficient of thermal expansion (CTE) to the SiC and excellent high-temperature steam resistance, and the Yb₂Si₂O₇ coatings which has vertical cracks running through the thickness are reported. These cracks are caused by the high thermal stresses attributed to formation of Yb₂SiO₅ which has higher CTE than that of the Yb₂Si₂O₇ and SiC. Since Yb₂SiO₅ is formed due to the volatilization of SiO₂ in Yb₂Si₂O₇ during the melting, it can be suppressed by reducing the heat energy into the feedstock adjusting the spray conditions, but which may entrap the unmelted particles into the coating.

In this study, we focused on the particle size distribution (PSD) of feedstock, and investigated the relevance of the PSD of Yb₂Si₂O₇ feedstock, the volatilization amount of SiO₂, and the Yb₂SiO₅ formed in the coating. It is confirmed that volatilization of SiO₂ tends to occur in specific particle size. Subsequently, we examined and discussed the optimal PSD of feedstock to obtain homogeneity Yb₂Si₂O₇ coating.

Session: Thermal and Environmental Barrier Coatings for Gas Turbines II

Pull Adhesion Testing of Hafnium Oxide Coatings

Ms. Andrea Vozar¹, Dr. Reza Sarrafi-Nour¹, Dr. Bryan J. Harder², and Jonathan Salem²; ¹GE Aerospace Research, Niskayuna, New York, USA; ²NASA Glenn Research Center, Cleveland, Ohio, USA

The introduction of silicon carbide/silicon carbide (SiC/SiC) ceramic matrix composites (CMCs) into aviation turbine engine hot section enabled increased inlet temperature and reduced cooling requirements. Environmental barrier coatings (EBCs) are required to achieve the durability needs of CMC aerospace turbine components. Future EBC oxide topcoats will need to provide sufficient thermal capability to support turbine inlet temperatures in excess of 1650 °C (3000 °F), thermal barrier function and acceptable mechanical properties such as adhesion strength. Hafnium oxide (HfO₂) has been evaluated as a prospective oxide topcoat material and can be deposited in a pseudocolumnar structure for increased in-plane compliance to better manage the thermal expansion mismatch stresses with Si-based ceramics, thus, to help adhesion to Si-based ceramics. Coatings were applied using two different processing methods on bulk α-SiC substrates to compare the properties of the two deposition methods. Samples were exposed to aging heat treatment from 1371–1538 °C (2500–2800 °F) in air and mechanical pull testing was conducted at room temperature to track the adherence with aging. The pull adhesion test results revealed sensitivities to the strength of the monolithic SiC substrate and potential confounding effects associated with bonding adhesive layer and preparation conditions.

Optimization of Heat Treatment Parameters for Yb-Disilicate Environmental Barrier Coatings

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In aircraft engines, environmental barrier coatings (EBCs) are responsible for protecting ceramic matrix composites (CMCs) from the corrosive effects of water vapor at elevated temperatures. In this work, ytterbium disilicate (YbDS) was plasma-sprayed using optimized spray parameters that avoid silicon evaporation, without any substrate pre-heating, resulting in a partially amorphous EBC. A series of heat treatments were used to crystallize the YbDS-based EBC and bring its CTE closer to the CTE of the SiC CMC substrate. This project aimed to optimize the heat treatment for the as-sprayed EBCs by in-depth analysis of the effect of time and temperature on the phase formation and crystallinity of Yb-disilicate coatings. For this purpose, heat treatment was carried out at 1100, 1200 and 1300 °C for 2 to 10 hours. Metastable phases are formed during the crystallization process at 1100 °C. To achieve around 94-97% YbDS as the major crystalline phase, it is necessary to increase the heat treatment time at 1100 °C or increase the temperature to 1200 or 1300 °C. The microstructure and porosity measurements were performed on the cross section of the as-sprayed, heat treated with stable phases, and heat treated with both stable and metastable phases EBCs.

Exploring the Microstructure and CMAS Resistance of Yb₂Si₂O₇ Environmental Barrier Coatings Deposited by Axial and Radial Injection Plasma Spraying

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Yb₂Si₂O₇ environmental barrier coatings (EBCs) were sprayed under three conditions using two plasma torches with radial and axial injection, varying torch power and plasma gas composition. The 91 kW axially injected EBC with reduced N₂ and H₂ (A1) was ~90% crystalline as-sprayed, with ~25 wt.% Yb₂SiO₅ as a secondary phase and small, uniformly distributed porosities. Increasing N₂ and H₂ by 5% (A2) improved particle melting and densified the microstructure, but resulted in an amorphous as-sprayed state with higher silicon evaporation. The 30 kW radially injected EBC (R1) was also amorphous as-sprayed, and 75 wt.% Yb₂SiO₅ was crystallized after annealing at 1300 °C for 24 hours. Under CMAS exposure at 1350 °C, R1 formed a dense apatite reaction layer, altering CMAS composition and hindering infiltration after 96 hours. The Yb₂Si₂O₇-rich EBC (A1) showed CMAS infiltration through its thickness after 72 hours but showed no blistering or damage. A2's denser structure with minimal porosity further resisted CMAS infiltration.

Ytterbium Disilicate Environmental Barrier Coatings: Processing and Combined Steam and Calcium Magnesium Alumino-Silicate Corrosion

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As efficiency gains are sought within gas turbines through ceramic matrix composites (CMCs), ytterbium disilicate coatings, as both abrasion and environmental barriers, are seriously considered to achieve the desired performance. This paper will present how SPS and APS abrasion and EBC coatings perform when exposed to steam, molten calcium magnesium alumino-silicates (CMAS) and combined steam and CMAS. Three ytterbium disilicate (Yb₂Si₂O₇ or YbDS) abrasion EBCs containing 8, 15, and 22 % porosity by area were deposited using atmospheric plasma spraying. These coatings were then exposed to steam, CMAS (35 CaO – 10 MgO – 7 Al₂O₃ – 48 SiO₂ mol. %) and combined steam and CMAS at 1350 °C for 100 hours. Exposure to steam caused the formation of a thin ytterbium monosilicate (Yb₂SiO₅ or YbMS) reaction layer. Reaction with the CMAS occurred by a dissolution-precipitation mechanism, with a reprecipitated ytterbium disilicate phase and Yb-apatite (Ca₂Yb₈(SiO₄)₆O₂) crystals noted as the only reaction products. After the combined exposure, the CMAS infiltration depth was higher than that observed in the standalone CMAS exposure. Also, an increased amount of Yb-apatite formation was observed within with YbMS reaction layer, and an ytterbium aluminum garnet (Yb₃Al₅O₁₂ or YbAG) phase was also observed.

Parameter Exploration of Yb₂Si₂O₇ Coatings Prepared by Plasma Spray Physical Vapor Deposition

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Ytterbium Disilicate (Yb₂Si₂O₇) coatings were prepared utilizing NASA GRC's plasma spray-physical vapor deposition rig with a recently installed XY motion stage. Parameters studied include primary and secondary gas flow rates, carrier gas composition and optimization and electric power settings. Special emphasis was given to torch motion for validation and optimization of the new equipment as well as the variability in microstructure and composition as they relate to spray parameters, including inter-run variability. Environmental barrier coatings (EBCs) exhibited a range of compositions from a mixture of monosilicate/disilicate to disilicate with excess SiO₂. Single and dual-layer EBCs were evaluated with x-ray diffraction and scanning electron microscopy. Steam oxidation was performed at high temperature in 90% H₂O/O₂ to determine durability of these coating systems.

Session: Thermal and Environmental Barrier Coatings for Gas Turbines III

Microstructure, Mechanical and Thermal Properties of Yttria-Tantala-Stabilized Zirconia Coatings Prepared from Suspension Plasma Spraying

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This study focuses on the development of innovative solutions of new material coatings using plasma spraying for thermal barrier coating (TBC) applications. The purpose of this work is to explore the feasibility of generating an in-situ ZrO₂-YO_{1.5}-TaO_{2.5} (YTZ) system in the t'-phase during the deposition process of a mechanically activated oxide mixture of the ternary system by suspension plasma spraying). The oxide mixture compositions and plasma spraying parameters were varied to study their effects on the amount of YTZ t'-phase as well as their corresponding physicochemical properties. Characterization of the coatings was carried out by x-ray diffraction, scanning electron microscopy, microhardness, and thermal conductivity, which was measured by laser flash analysis. The results show that the coating properties are strongly affected both by the spray distance and the ratio of the gases that promote plasma formation.

High-Resolution Synchrotron μ XRD and μ XRF for Detailed Phase and Elemental Analysis in Suspension Plasma Sprayed Environmental Barrier Coatings

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The suspension plasma spray (SPS) technique is revolutionizing the development of thin, high-performance environmental barrier coatings (EBCs) for next-gen aero engines. SPS enables the creation of thinner coatings with finer microstructures compared to conventional atmospheric plasma spray, allowing precise control from micrometer to nanometer scales, greatly enhancing EBC performance. This fine-tuning is vital for optimizing the multilayered EBC structure, including bond and top coats. Detailed microscale analysis, especially at layer interfaces, is key to preventing localized degradation under extreme conditions, which can lead to coating failure.

Localized characterization is essential due to the heterogeneity of SPS coatings and their interfaces. Conventional methods like XRD and XRF provide only broad overviews, missing critical local details. To address this, we introduce advanced synchrotron μ XRD and μ XRF techniques for detailed local analysis at $1\mu\text{m}^2$ resolution. Our case study on SPS-produced EBCs (yttrium disilicate top coat, silicon bond coat, and silicon carbide substrate) demonstrates this method's effectiveness. Using focused ion beam milling, we prepared thin samples and found a uniform distribution of phases and elements, revealing the impact of environmental exposure like calcium magnesium aluminosilicates. These results highlight the importance of localized analysis for enhancing coating performance.

High Temperature (1100 °C) Isothermal Exposure of Plasma Sprayed Al_2O_3 -YSZ-CNT Composite Bimodal Coatings

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Plasma-sprayed nanostructured coatings with bimodal microstructure have gained traction due to their property to counteract the effects of densification. The current study investigates and compares the microstructural and mechanical properties of isothermal exposed plasma sprayed coatings at 1100 °C for 100 hours (in Ar) made from conventional Al_2O_3 ($\mu\text{-Al}_2\text{O}_3$) powders and a bimodal particulate composite of nano Al_2O_3 reinforced with nano YSZ (3/8 mol%) and CNTs. Nanoreinforcements of YSZ provide insulation and toughness, whereas CNTs improve in-plane thermal conductivity, thus reducing localized hot spots. Post-exposure analysis reveals that $\mu\text{-Al}_2\text{O}_3$ coatings exhibited extensive mud cracks on the surface and completely delaminated, whereas composite coatings remained adherent to the substrate with finer mud cracks. This adherence was achieved by mitigating the strain-due mismatch in thermal expansion via nanostructure regions and improved toughening using YSZ. Phase analysis revealed $\gamma\text{-Al}_2\text{O}_3$ has completely transformed to $\alpha\text{-Al}_2\text{O}_3$ and a small amount of monoclinic ZrO_2 (~3-5 vol%) phase. Raman analysis demonstrated CNTs were retained with a reduction in $I_{\text{D}}/I_{\text{G}}$ (~20-25%). Further, statistical analysis of nanohardness, Young's modulus, fracture toughness of composite coatings was carried. The results show that Al_2O_3 -3YSZ bimodal composite coatings perform better than Al_2O_3 , indicating their potential as a thermal barrier coating for gas turbine applications.

100 KW High Power Cascade Debye Larmor Plasma Torch for APS and VPS Applications

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This paper summarizes the characterization of a 100 KW high power Debye Larmor Cascade plasma torch for APS and VPS application. The study focuses on analyzing the effect of the arc length and the diameter of the cascade tunnel and optimizing the shape of the output anode nozzle. We will report the first study of plasma fluctuation depending on plasma current, argon and hydrogen plasma gas mixture for APS and VPS conditions. With such a high-power plasma system we will report on first results of ZrO_2 TBC coating.

Self-Healing Thermal Barrier Coatings: How Microchanges Influence the Overall Coating Durability

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The concept of self-healing thermal barrier coatings (TBCs) centers on their ability to recover from microstructural damage caused by extreme thermomechanical loads and to autonomously restore functional properties to a near-initial state. In other words, the microstructural effects should enable macrostructural benefits, necessitating rather complex coating systems. This work presents the flexibility and adaptability of various plasma spray approaches for producing self-healing TBCs. Silicon carbide (SiC) was used as a healing agent and integrated into the state-of-the-art YSZ top coat. Different spray routines and various feedstocks were employed to carefully control the coating structure, limit the in-flight oxidation of SiC, and promote the so-called oxidation-driven self-healing capability. The microstructural evolution of the coatings under high-temperature conditions,

specifically isothermal oxidation and thermal cyclic fatigue, was evaluated using high-resolution scanning electron microscopy, energy-dispersive spectroscopy, and electron backscatter diffraction methods. The evolution of thermal transport properties resulting from the addition of SiC was also studied. This research facilitates a discussion on how the incorporation of carbide-based self-healing agents influences coating architecture and overall durability of TBC systems.

Session: Cold Spray Coatings for Aerospace Applications

ID-Nova Warm Spray Process

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ID-Nova warm spray is the addition of nonreactive gases such as nitrogen, argon or carbon-dioxide into HVOF processes to reduce temperature and increase particle velocity. Warm spray can be used to enhance coating properties by decreasing porosity and oxide content in metal coatings. The technique of adding "inert gas" to the combustion stream causes an increase in the number of gas molecules which increases the gas velocity for a given temperature. This provides another parameter to enhance coating properties. This paper will examine the coating properties of using different auxiliary gases with ID-Nova HVOF process.

New Achievements in Cold Spraying of Aluminum Alloys for Structural Repair Applications Using Nitrogen as Propelling Gas

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Aluminum alloys, such as AA6061 and AA7050 are widely used in the aircraft industry. Therefore, cold spraying has high potential in the field of repairs of worn-out parts. However, many repair applications are limited to using expensive helium as a propelling gas to achieve the desired mechanical properties and adhesion strength. The latest developed hardware solution and cold spray parameters were investigated in relation to the mechanical properties of the deposited aluminum alloys. Flat and round tensile specimens were extracted from the thick cold sprayed deposits to measure the tensile properties and adhesion strength. The results indicate significant improvements, e.g. in case of Al7050 adhesion strength >230 MPa, tensile strength >360 MPa and elongation >3.5%.

Deposition of Laser Ablation Resistant Coating on Carbon Fiber-Reinforced Polymers by Cold Spray

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Carbon fiber-reinforced polymers (CFRPs) are increasingly utilized in aerospace due to their lightweight characteristics, however, their susceptibility to laser-based directed energy weapons poses a significant risk to defense equipment. Cold spray metallization offers a potential solution to enhance the laser resistance of these materials. However, achieving continuous metal coatings on CFRPs is challenging, primarily due to substrate erosion and poor adhesion. This study explores a bond layer strategy aimed at improving adhesion and promoting uniform metal deposition. Aluminum (Al) was deposited on the bond layer under various process conditions to achieve consistent and successful coatings. Laser ablation tests were conducted to evaluate the effectiveness of these coatings in enhancing the laser ablation resistance of CFRPs. The findings suggest that, while complete uniformity remains difficult, the introduction of a bond layer significantly improves coating adhesion and uniformity. Optimized deposition parameters also enhance the laser resistance of the aluminum-coated CFRP, offering a potential method for improving the durability of CFRPs in high-energy environments.

Cold Spray Aluminum: A Cutting-Edge Solution for the Restoration of Gas Turbine Low-Pressure Compressor Components

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The restoration of gas turbine low-pressure compressor (LPC) components is critical for maintaining operational efficiency and prolonging the lifespan of turbine systems. This paper explores the innovative application of cold spray aluminum technology as a cutting-edge solution for repairing LPC components subjected to wear and erosion corrosion. Cold spray, a solid-state deposition process, offers significant advantages over traditional repair methods, including minimal thermal distortion, enhanced adhesion, and the ability to apply coatings with tailored microstructures. We present a comprehensive analysis of the cold spray process, detailing its mechanics, material properties, and the resulting performance enhancements in restored components. Experimental results demonstrate the efficacy of cold spray aluminum in improving wear resistance and operating performance, alongside case studies illustrating successful restorations in operational settings. The findings highlight cold spray aluminum as a viable and effective strategy for the maintenance of gas turbine LPC components, promoting operational reliability and cost-effectiveness in aerospace and industrial applications.

Session: Thermal and Environmental Barrier Coatings for Gas Turbines IV

Comparative Oxidation Performance of NiCoCrAlY Coatings Deposited by High-Velocity Air Fuel and High-Velocity Oxy Fuel for Thermal Barrier Applications

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High-velocity air fuel (HVAf) and High-velocity oxy fuel (HVOF) are advanced thermal spray techniques developed to produce dense, oxidation-resistant coatings. These methods are particularly important for thermal barrier coating (TBC) applications in the aerospace industry. HVAf, in particular, has shown greater potential for producing dense bond coats with minimal in-flight particle oxidation, making it ideal for TBC systems. In this study, NiCoCrAlY coatings were deposited on Hastelloy-X substrates using both HVAf and HVOF techniques, and their oxidation performance was evaluated at an elevated temperature over varying durations. This approach provided insights into the oxidation mechanisms and kinetics as they evolved over time. Deposition parameters were thoroughly characterized using AccuraSpray diagnostics, while the microstructure and oxide formation were examined using scanning electron microscopy and energy-dispersive x-ray spectroscopy. Oxidation tests revealed that HVAf-deposited coatings have greater potential than those deposited via HVOF, demonstrating superior oxidation resistance. These findings highlight the effectiveness of HVAf for producing high-performance bond coats for TBC applications, particularly in environments requiring long-term oxidation resistance.

Study of the High-Temperature Oxidation Performance of MCrAlY Bond Coats Deposited by Thermal Spray and Cold Spray Processes

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Bond coats are an essential element in the aerospace industry, as they ensure the structural integrity and thermal efficiency of engines operating in extreme environments. The high-temperature oxidation performance of bond coats is an indicator of the durability and thermal resistance of thermal barrier coating (TBC) systems used in gas turbines. Several deposition methods have been used to deposit bond coats for TBCs, including high-velocity oxygen fuel (HVOF), high-velocity air fuel (HVAf) and cold spray (CS). These deposition methods significantly influence the microstructure and adhesion characteristics of the bond coats, which impact their

resistance to high-temperature oxidation. The main objective of this study is to analyze how the deposition process affects the oxidation kinetics and the integrity of the oxide layer. To that end, a low-temperature HVAf torch and a cold spray system are used to deposit MCrAlY coatings on a superalloy substrate. Isothermal oxidation tests are performed and the formation and evolution of the thermally grown oxide layer are assessed. The microstructure of the coatings is assessed by scanning electron microscopy and the oxidation is quantified on a field-emission scanning transmission electron microscope equipped with energy dispersive spectroscopy.

Influence of Reactive Elements on Next-Generation Bond Coats in Thermal Barrier Coating Systems Using High Entropy Alloys

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Increasing demands for higher operating temperatures and improved efficiency reveal the limitations of conventional bond coat materials like MCrAlX, which are susceptible to oxidation and degradation. This study investigates FeCoNiCrAlYHf and FeCoNiCrAl HEAs as alternative bond coat materials to overcome these limitations. The bond coats were applied using low-temperature spray techniques, including high-velocity oxygen fuel (HVOF), high-velocity air fuel (HVAf), to assess the impact of spray temperature on coating microstructure and performance. All samples underwent isothermal oxidation testing at 1150 °C for 200 hours to measure mass gain, both before and after vacuum heat treatment (conducted at 1050 °C for 4 hours), to evaluate the behavior of the TGO layer in response to the presence of reactive elements and heat treatment. The results show that HEA bond coats, with and without reactive elements, successfully formed dense, continuous, and uniform protective Al₂O₃ layers without mixed oxide formation. In contrast, mixed oxide formation was observed in the MCrAlX benchmark sprayed with HVOF. No significant difference in TGO formation was found between HEA coatings with reactive elements, demonstrating superior oxidation resistance. Additionally, vacuum heat treatment reduced TGO growth by approximately 40%, which is considered to be a promising result.

Oxidation Behavior of AlCrFeNiSi-Based High Entropy Alloy Bond Coat Designed with the CALPHAD Approach

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High-entropy alloy (HEA) coatings have demonstrated significant potential for high-temperature applications, outperforming conventional bond-coat materials like thermal-sprayed NiCoCrAlY used in thermal barrier coatings (TBCs). Key properties including oxidation resistance, phase formation, and mechanical behavior are highly dependent on the specific elemental composition of the HEA, where careful selection and balance of alloying elements are crucial to achieving optimal performance. However, the vast compositional space of HEAs presents challenges in optimizing ideal compositions. Calphad-based computational approach offers a powerful method to streamline this process. In this study, equilibrium and non-equilibrium (Scheil) solidification phase diagrams were simulated to identify an optimized AlxCrFeNiSi_y HEA composition aimed at promoting simple solid-solution phases while minimizing undesirable intermetallics. The selected composition was synthesized via gas atomization and subsequently deposited on additively manufactured Ni-base superalloy substrates using the high-velocity oxygen fuel (HVOF) process. A TBC system incorporating AlxCrFeNiSi_y HEA as a bond coat and YSZ top coat was fabricated. The coating's isothermal oxidation resistance was evaluated at 1100 °C, assessing its suitability as a bond-coat material in TBCs. Furthermore, the microstructure, mechanical properties and phase composition of the coatings were analyzed and compared with simulation predictions, providing valuable insights into the material's performance and potential for future oxidation resistant materials.

Session: Surface Preparation, Load Bearing, Tribology, Corrosion, Abradable and Repair I

Microstructural Study of Nickel Chromium Coating with Complex Composition for High-Performance Application

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In this study, the high-velocity oxygen fuel (HVOF) spraying technology has been used to deposit NiCrSiBMoFeCuC coating. The microstructural characterization was carried out on the coating sample using optical microscopy, scanning electron microscopy (SEM), energy dispersive spectroscopy, transmission electron microscopy (TEM), and x-ray diffraction (XRD). The coating microstructure exhibited low-porosity content approximately $3.17 \pm 0.93\%$, which is in acceptable range for an anticorrosion protective coating. However, the SEM analysis showed some microcracks at the interfacial region between the substrate and the coating that indicates low cohesion that could be due to high-temperature gradient resulting in the formation and concentration of thermal stress. Notably, a high density of dislocations within the grain core has been observed in TEM micrographs, which accounts for the increased hardness of the coating. The XRD analysis of the coating has identified the major peaks as expected but coating sample showed formation of some extra phases during HVOF process that may alter thermomechanical properties of the coating. The need for this study can be justified due to the unique composition of the coating that makes it suitable to be used as a protective layer for corrosion protection in harsh environments for industrial parts and components.

Study on Corrosion Properties of Aluminum-Bronze Sealing Coating

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Abradable seal coatings are widely employed in the gas turbine of aero engine, which is not only strong enough to resist the impact of external particles and airflow, but also excellent wear resistance. In the current study, we concentrate on APS sprayed aluminum-bronze abradable coating that can be used in turbo engines both for seals and clearance control. A high temperature and speed test rig has been developed by BGRIMM for testing the CuAl abradable seal coating and Ti-6Al-4V dummy blade. Impact velocities between 250 and 400 m·s⁻¹ and incursion rates between 5.0 and 500 μm·s⁻¹ have been applied. In addition, the erosion behavior at room temperature of the CuAl coating was investigated. The erodent material was 50 μm alumina and the impact angles were 20° and 90°. The erosion performance of the different conditions in this study was ranked based on the coating depth and weight loss after wear testing. The coating microstructures and phase compositions were evaluated via scanning electron microscopy and x-ray diffraction. The erosion mechanisms of the coating were compared by analyzing the cross-sectional and top-surface microstructures of the as-sprayed and eroded coatings.

Session: Surface Preparation, Load Bearing, Tribology, Corrosion, Abradable and Repair II

A Comprehensive Review of High-Temperature Ceramic Abradable Coatings Used in Aero and Industrial Gas Turbines

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As global efforts intensify to curb carbon emissions, optimizing fuel efficiency has become increasingly crucial. Abradable coatings, utilized in aero and industrial gas turbines, play a significant role in enhancing fuel efficiency by minimizing the clearance between turbine blade tip and the casing. This reduction in clearance leads to lower specific fuel consumption, translating into substantial fuel savings and decrease in carbon emissions. While there are different types of abradable

coatings, those used in the high-pressure turbine section should have a friable structure and be mechanically stable in the high temperatures (> 1,100 °C) of the turbine. These coatings are based on modified ceramic that can withstand these extreme requirements. Despite their critical role, there is a lack of comprehensive reviews about these coatings. This literature review addresses this gap by presenting an overview of current advancements in high-temperature abradable ceramic coatings. It explores recent developments in material systems, examines various thermal spray deposition techniques, and discusses testing methodologies for evaluating coating performance. A particular emphasis will be placed on the abradability and wear mechanisms of these coatings. This study aims to provide a consolidated understanding of the state-of-the-art in high-temperature ceramic abradable coatings.

High Temperature Sliding Abrasive Wear Performance of High-Velocity Oxygen Fuel-Sprayed Cr₃C₂-NiCr Coatings: Oxidation Induced Behavior and Mechanism

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Currently, high-velocity oxygen fueled-formed Cr₃C₂-NiCr coating is widely used due to its excellent resistance to thermal-induced wear degradation at temperatures up to 850 °C. Our previous research focused on comparing different feedstock materials to determine the optimal Cr₃C₂-NiCr coatings for sliding abrasive wear at room temperature. This ongoing study aims to investigate the sliding abrasive performance of these optimal coatings under oxidation-induced conditions. Experimental analysis involves characterizing the in-situ tribological behaviors of the coating at high temperatures and evaluating the wear performance of pre-oxidized coating specimens. The goal is to understand how oxidation and abrasion factors influence the sliding abrasive wear behavior of the coatings. Various test methods, such as pin-on-disk test, Taber wheel test, and disk rotating test, were used to characterize the abrasive wear behavior. Additionally, detailed studies on abrasive wear mechanisms were conducted through x-ray diffraction, scanning electron microscopy morphologies, TGA, and surface profile analyses of the test samples. Special attention was given to the effect of TGO layers on the wear behavior, the impact of feedstock materials on coating microstructures, TGO growth, and abrasive tribological behavior to identify the optimal coating for enhanced sliding abrasive wear resistance at high temperatures.

Development of Repair Methods for Single Crystal Components Using Thermal Spray Processes

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Repairing single-crystal turbine blades is critical due to their complex manufacturing and high material costs. Effective repair solutions are essential for extending the lifespan and performance of high-temperature components in gas turbines, leading to a growing interest in repair technologies. Therefore, this study investigates three thermal spray processes — cold gas spraying, high-velocity air-fuel spraying, and vacuum plasma spraying — for their potential to repair single-crystal CMSX-4 substrates using CMSX-4 powder. Each process underwent parameter optimization, and the resulting coatings were evaluated for density and oxygen content, critical factors for repair applications. Single splat experiments were conducted to study microstructure formation. Additionally, residual stresses in the coatings were measured using the incremental hole-drilling method to provide insights into stress distribution of the coatings. Adhesion properties were assessed through pull-off testing to evaluate the mechanical integrity of the coating-substrate bond. The optimized polycrystalline coatings were subjected to a controlled heat treatment in which the samples were intentionally passed through a high temperature zone. The aim of this process was to promote directional grain growth starting from the underlying single-crystal substrate. After the heat treatment, the resulting grain structures of the coatings were analyzed by electron backscatter diffraction.

High-Temperature Tribological Performance of Chromium Oxide: NiMoAl-Based Coating Applied by Atmospheric Plasma Spray

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As the aerospace industry advances to meet new regulations, the operating conditions inside gas turbine engines become increasingly demanding. Consequently, next-generation aircraft components require development and testing of advanced materials. Thermally sprayed coatings are commonly used to improve wear resistance, with different approaches depending on the operating conditions. Varying temperatures and contact pressures are encountered within these turbines, making the precise definition of applied solutions critical for a smooth engine operation. The recent development of chromium oxide – NiMoAl-based coatings, which offers exceptional strength, creep resistance, and oxidation stability, shows to be a promising material for these extreme aerospace conditions. However, limited tests were performed under extreme conditions. Therefore, this study focuses on the high-temperature tribological performance of chromium oxide – NiMoAl-based coatings applied using atmospheric plasma spray. Different thicknesses were sprayed and tested using a reciprocating flat-on-flat tribometer configuration. Relevant sliding distances and temperatures were selected for testing against Waspaloy flat counterfaces. In addition, different surface finishes were used to simulate the conditions that these surfaces are exposed to. Differences as a function of the coating thickness, initial roughness, and temperature have been assessed.

Session: Thermal and Environmental Barrier Coatings for Gas Turbines V

Impact of Plasma Parameters on the Deposition of Environmental Barrier Coatings

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Environmental barrier coatings (EBCs) are essential for enhancing the performance of advanced gas turbine components that employ ceramic matrix composites. Plasma spraying remains the primary technique for applying these coatings. Currently, rare earth silicate materials are preferred for the barrier layer; however, their processing presents unique challenges compared to zirconia-based thermal barrier coatings. These challenges include silica volatilization during spraying and the formation of amorphous and metastable phases upon deposition. This paper examines the deposition of ytterbium disilicate and explores the effects of various plasma spray parameters—including gas mixture, flow rate, and net power—on particle in-flight properties. We will also discuss how these parameters influence the resulting coating structure. The findings aim to provide insights into optimizing the processing conditions for rare earth silicate EBCs, ultimately contributing to the advancement of gas turbine technology.

The Mechanism of Rapid Interdiffusion Bonding During Air Plasma Spraying of Thermal-Environmental Barrier Coatings for Future Ceramic Turbine Components

Dr. Edward Jonas Gildersleeve V., Dr. Emine Bakan, and Prof. Robert Vaßen;
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Previously, we have demonstrated an abnormally high CTE mismatch for a multi-layered ceramic coating system, despite that it is possible under certain circumstances to fabricate zirconia-based thermal barrier oxides atop rare-earth disilicate environmental barrier coatings. Past results have demonstrated these thermal-environmental barrier coatings (T-EBCs) are not only durable upon fabrication, but also withstand thermal shock both in isothermal as well as thermal gradient conditions. To date, there have been only hypotheses presented for the exact mechanism governing this surprisingly-enhanced bonding mechanism between 8YSZ and $\text{Yb}_2\text{Si}_2\text{O}_7$. This presentation will demonstrate, through multiple ultrahigh-resolution characterization methods: FIB-SEM, STEM/EDS, EBSD, and atom probe tomography, the mechanism that takes place during initial fabrication of 8YSZ thermal barrier coatings atop amorphous $\text{Yb}_2\text{Si}_2\text{O}_7$ environmental barrier coatings. The counter example of plasma-spraying 8YSZ atop crystalline $\text{Yb}_2\text{Si}_2\text{O}_7$ will also be shown, for reference, to demonstrate what has inhibited past research from successfully fabricating such T-EBCs. The results from these unique characterization techniques all converge on a single conclusion: nanoscale interdiffusion reactions take place at the microsecond timescale during rapid solidification of the molten 8YSZ droplets – forming a chemical bond between the 8YSZ and $\text{Yb}_2\text{Si}_2\text{O}_7$ that exceeds traditional mechanical interlocking adhesive strengths of thermally sprayed coatings.

Session: Thermal and Environmental Barrier Coatings for Gas Turbines VI

The Influence of YSZ Powder Morphology and Microstructure on the Surface Roughness of Thermal Barrier Coatings Applied in Industrial Gas Turbines)

Prof. Giovanni Bolelli¹, **Dr. Simone Bursich²**, Ms. Margherita Cescon¹,
Mr. Alessandro Lanzi², Prof. Luca Lusvardi¹, Mr. Francesco Masciarelli¹, and
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The primary ceramic material used in thermal barrier coatings is yttria-stabilized zirconia (YSZ), typically containing 7-8 wt.% yttria. Original equipment manufacturers generally require that the surface roughness of the ceramic top coat meets specific targets to ensure optimal turbine efficiency and aerodynamic performance. Achieving the desired roughness after spraying is uncommon, requiring manual or automated finishing. Powder manufacturing and coating microstructure are known to affect the ceramic top-coat's tribological properties and surface roughness.

This study aimed to examine the surface roughness of single-layer ceramic coatings in both as-sprayed and finished conditions. These coatings were deposited using atmospheric plasma spraying (APS) with an advanced cascade plasma torch. Standard 7–8% YSZ powders from different manufacturing processes were employed, resulting in both porous and dense-vertically cracked coating microstructure. All coatings were applied on Hastelloy-X substrates with an HVOF + APS “Flash” NiCoCrAlY bond coat.

The surface roughness of the samples, both in their as-sprayed state and after the finishing process, was evaluated using a profilometer and a roughness measuring device. Furthermore, the FEG-SEM technique was utilized to analyze all coating systems, offering insights into the mechanisms that could affect their roughness characteristics.

Isothermal Oxidation Behavior of Multilayered Thermal Barrier Coatings

Arezoo Sezavar Seyedijandaghi, Ferdowsi University of Mashhad, Mashhad, Islamic Republic of Iran

Isothermal oxidation behavior of multilayered thermal barrier coatings isothermal oxidation behavior of two multilayered thermal barrier coatings (MLTBCs) has been investigated. Moreover, the property of the produced coatings was compared with a conventional bilayered TBC. For this purpose, nanostructured and micro YSZ were used as ceramic powder feedstocks and TBCs were deposited by air plasma spray procedure. The first multilayered TBCs consisted of 100 wt% NiCrAlY, micro YSZ as the second layer (thickness: 100 μm), nanostructured YSZ as the third layer (thickness: 200 μm), and micro YSZ as the final layer (thickness: 100 μm). Although the composition of layers for the two kinds of MLTBCs were the same, in the second coating, the thicknesses of nanostructured YSZ layer and final layer were 100 and 200 μm , respectively. Isothermal oxidation was carried out at 1100 $^{\circ}\text{C}$ in the atmospheric furnace. Microstructure evaluation, elemental and phase analysis were performed. The results showed that MLTBCs have lower TGO growth rate compared with the bilayer conventional one, and also MLTBC with the thicker nanostructured layer has the lowest TGO growth rate compared to the other coatings.

Keywords: Multilayer thermal barrier coating; nanostructured coating, high-temperature oxidation.

Session: Thermal and Environmental Barrier Coatings for Gas Turbines VII

Laser Treatment of Columnar YSZ Coatings Produced by Suspension Plasma Spraying

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Thermal barrier coatings (TBCs) protect turbine engine components allowing them to operate at high temperatures, significantly improving turbine power and fuel efficiency. Suspension plasma spraying (SPS), a modern coating technique, is gaining attention for its ability to create columnar microstructures that balance porosity, reduce thermal stresses, and lower thermal conductivity. However, the columnar structure can also facilitate the penetration of calcium-magnesium-alumino-silicates (CMAS), which leads to TBC deterioration. To mitigate this, a laser post-treatment process has been proposed to remelt the top layer of TBCs, forming a barrier that prevents or reduces CMAS infiltration. In this study, columnar yttria-stabilized zirconia (YSZ) top coats were deposited by SPS. A laser treatment was used to create a remelted layer at the surface of the SPS coatings. The influence of key laser parameters, such as scanning speed and laser power, on the microstructure of the remelted top layer of the columns in the SPS coatings was investigated. It is hypothesized that such a process could significantly improve the durability and performance of SPS deposited TBCs by minimizing CMAS penetration.

Dynamic Behavior of CMAS Droplets on Laser-Glazed Thermal Barrier Coatings

Dr. Amit Roy¹, **Dr. Fadhel Ben Ettouil¹**, Mr. Peyman Saffarzade¹, Dr. Rogerio Lima², Prof. Martin Pugh¹, Prof. Pantcho Stoyanov¹, and Prof. Christian Moreau¹; ¹Concordia University, Montréal, Quebec, Canada; ²National Research Council of Canada, Boucherville, Quebec, Canada

Calcium-magnesium-alumino-silicates (CMAS) are ingested by gas turbine engines and deposited on and infiltrate thermal barrier coatings (TBCs) during high-temperature operation. When exposed to temperatures above 1200 $^{\circ}\text{C}$, the CMAS infiltrates the TBC, compromising its stress tolerance and leading to premature failure. Researchers have employed various surface treatment strategies to minimize the deposition of CMAS, one of which is laser glazing (i.e., remelting the top layer of the TBCs). However, the experiments were limited to static CMAS testing of the laser-glazed TBCs. In this study, the laser-glazing parameters were

optimized to obtain a thin glazed layer at the surface of the TBCs. In an attempt to mimic real-world conditions, a commercially available CMAS powder was sprayed onto the laser-glazed 8YSZ coatings using an atmospheric plasma spraying process. Furthermore, the dynamic CMAS behavior was compared between the laser-glazed and as-sprayed TBCs. SEM/EDS and XRD analyses were performed to identify and quantify the elements and phases of the CMAS on the TBCs.

Development of Multicomponent Stabilized Zirconia as Ultrahigh Temperature Thermal Barrier Materials

Mr. Sairam Ramachandran and Prof. Ashutosh S. Gandhi, Institute of Technology Bombay, Mumbai, India

Tetragonal zirconia with 8 mol.% YO_{1.5} as a stabilizer (8YSZ) has been the conventionally used thermal barrier coating (TBC) material. It undergoes phase transformations during service which limits its service temperature to less than ~ 1200 $^{\circ}\text{C}$. Cubic zirconia ceramics are phase-stable across the relevant temperature range, and possess lower thermal conductivity than tetragonal YSZ: In the present work, we have designed and synthesized new cubic zirconia compositions stabilized by 5 to 10 rare earth oxides. Powders were synthesized by the solution combustion synthesis method. X-ray diffraction and Raman spectroscopy were used for structural analysis to confirm the cubic phase formation. X-ray photoelectron spectroscopy was done on the samples to determine the oxygen vacancy and stoichiometry of the multicomponent systems. Sintering studies were carried out from 1200 to 1700 $^{\circ}\text{C}$ by conventional as well as spark plasma sintering. Microstructural and compositional investigations were carried out by scanning and transmission electron microscopy. Thermal conductivity values ($\kappa \sim 0.9$ W/m.K) at 1000 $^{\circ}\text{C}$ lower than conventional tetragonal YSZ were obtained. Coefficients of thermal expansion were measured and evaluated for their suitability for ultrahigh temperature application. The results pave the way towards developing TBCs with ultrahigh temperature capability.

Session: Thermal and Environmental Barrier Coatings for Gas Turbines VIII

Developing Oxidation-Resistant ZrC-Based Coating via Plasma Spraying for Advanced Thermal Protection Systems

Dr. Niroj Maharjan^{1,2}, Mr. Michael Boschen², Dr. Duy Quang Pham², Dr. Sam Meure¹, and Prof. Andrew Ang^{1,2}; ¹Swinburne University of Technology, Hawthorn, Victoria, Australia; ²Australian Research Council, Industrial Transformation Training Centre in Surface Engineering for Advanced Materials, Swinburne University of Technology, Hawthorn, Victoria, Australia

Ultrahigh temperature ceramic borides, such as ZrB₂ and HfB₂, have been widely investigated as a thermal protection system (TPS) in extreme environments including hypersonic flight, nuclear reactor and advanced energy systems, due to their high thermal conductivity and melting point. However, they exhibit poor oxidation resistance and limited fracture toughness for extended applications beyond ~ 1600 $^{\circ}\text{C}$. Zirconium carbide (ZrC), with its ultrahigh melting point (3540 $^{\circ}\text{C}$) and excellent thermal shock resistance, has recently emerged as a promising material for such applications. By combining ZrC with transition metal carbides and silicon carbide, a stable protective oxide layer can form even at temperatures exceeding 2000 $^{\circ}\text{C}$. This talk will present findings from exploration to develop oxidation resistant ZrC-based coating using plasma spraying process with a focus on high temperature stability. The influence of a processing condition on oxide inclusions and coating structure will be elaborated and its impact on the performance assessed using isothermal oxidation and high-temperature oxyfuel flame test will be discussed. The underlying mechanisms driving these results will be examined, offering valuable insights for further development of TPS for extreme environments.

Boride and Carbide Coating by Plasma Spraying: Manufacturing and Assessment at Temperatures High than 2000 K

Dr. Arthur Charrue¹, Dr. Aurélie Quet¹, Dr. Charlotte Gregis², Mr. Vincent Génissel¹, and Dr. Marianne Balat-Pichelin³; ¹CEA Le Ripault, Monts, France; ²ArianeGroup SAS, Le Haillan, France; ³PROMES-CNRS, Font-Romeu-Odeillo, France

Space applications involving atmospheric re-entry impose high challenges to materials. Due to high velocity, materials will see temperatures higher than 2000 K, during several minutes in an oxidant atmosphere. Thermostructural composites such as carbon/carbon composites are good candidates to answer to this application. Nevertheless, these thermostructural materials meet oxidation problems at high levels of temperature and need a protective layer. Ultrahigh temperature ceramic coatings applied by plasma spraying are a solution to protect composites from oxidation.

This study deals with the manufacturing of boride and carbide coatings by inert atmosphere plasma spraying on carbon/carbon composite and the assessment of their behavior at temperatures higher than 2000 K. Coatings were evaluated in low-pressure atmosphere under an oxidizing plasma jet with Vulcain set-up. Different oxidation mechanisms will be discussed based on SEM, XRD, EDS and SXES analyses.

Cold Spray Additive Manufacturing of Satellite Propellant Tanks Using Ti-6Al-4V Alloy

Dr. Philip McNutt and Dr. Dibakor Boruah, TWI Limited, Cambridge, United Kingdom

Satellite propellant tanks require advanced materials and manufacturing techniques to endure harsh space environments while maintaining structural integrity and mass efficiency. Ti-6Al-4V, a titanium alloy renowned for its high strength-to-weight ratio, excellent corrosion resistance, and fatigue strength, is an ideal choice for aerospace applications, including satellite tanks. This study investigates the potential of cold spray additive manufacturing (CSAM) to fabricate these tanks, presenting an innovative alternative to traditional methods like welding or subtractive machining.

Cold spray is a solid-state deposition process that preserves the material's original properties, avoiding issues such as oxidation, phase transformation, and thermal distortion common in conventional high-temperature processes. Using Ti-6Al-4V powder, CSAM enables the production of near-net-shape components with minimal post-processing, enhancing material utilization and reducing production time and costs.

The research focuses on the mechanical properties, microstructure, and dimensional accuracy of cold-sprayed Ti-6Al-4V components. The results show that the deposited layers exhibit high density, excellent adhesion, and strength comparable to wrought materials. Moreover, the cold spray process provides significant flexibility in designing complex geometries, making it particularly well-suited for customized or mission-specific satellite tanks.

Study on the Type II Hot Corrosion of MCrAlY

Mr. Zhaoran Zheng, BGRIMM Technology Group, Beijing, China

This study conducted a hot salt corrosion test at 700 °C on five MCrAlY materials. Through the analysis of the material surface, corrosion products, corrosion cross-section, corrosion weight loss and other properties, the effect of basic elements of MCrAlY such as Co, Cr, and Al on sulfur-containing materials at 700 °C was studied. The results show that at 700°C, the corrosion products are mainly chromium oxide and aluminum oxide, accompanied by a small amount of spinel. Corrosion spreads to depth in the form of a reticular aluminum oxide, and the vicinity of the reticular aluminum oxide is often accompanied by the formation of chromium sulfide. Co and Cr are beneficial elements for resisting hot corrosion. Among them, resistance of Cr to hot corrosion at 700 °C is higher than that of Co.

Session: Surface Preparation, Load Bearing, Tribology, Corrosion, Abradable and Repair III

Automating Metal Component Refurbishment: How Can the Power of Digital Tools Boost Quality, Productivity and Safety?

Dr. Alejandro Vargas Uscategui, Mr. Hans Lohr, and Dr. Peter C. King, CSIRO Manufacturing, Clayton, Victoria, Australia

As industries like aerospace and defense seek efficient, reliable solutions for manufacturing and repairs, advanced deposition and coating technologies have become increasingly valuable for creating durable coatings, building 3D structures, and restoring worn or corroded parts. Among these, solid-state processes like cold spray stand out, capable of processing diverse materials such as aluminum and titanium while minimizing thermal stress, distortion, and oxidation, thus preserving original component properties and extending service life. However, many of these processes rely heavily on manual application, posing challenges such as inconsistent quality, dependency on operator skill, limited parameter control, and safety risks. This presentation introduces Continuous3D, a digital manufacturing tool that automates advanced repair and coating processes, delivering high-precision, consistent, and high-quality results while boosting productivity and enhancing operator safety. Practical examples will demonstrate the impact of Continuous3D, showcasing its potential to transform manufacturing and repair practices, address labor shortages, and bridge the workforce skills gap.

Coatings for Fluid Erosion Protection

Dr. Juan Manuel Mendez¹, Mr. Steve Guetre¹, Mr. Marcio Duffles², Dr. Stefan Tzanev¹, Mr. Michael Patterson¹, Ms. Marissa MacLean, P. Eng¹, and Mr. Jason Lee¹; ¹MDS Coating Technologies Corporation, Saint Laurent, Quebec, Canada; ²America's Phenix, Washington, DC, USA

Gas turbine engine fan blades experience leading edge erosion caused by water ingestion due to aircraft taking off and landing on wet runways. The eroded leading edge exhibits irregular pitting and tends to flatten after extensive operations; hence, changing the optimal aerodynamic shape of the edge. This results in turbulent flow over the fan blade which leads to decreased fan efficiency and increased engine fuel consumption. MDS Coating Technologies previously developed a coating optimized to protect the leading edge of fan blades and demonstrated the coating's capability to increase durability and aerodynamic performance via rig testing and flight demonstrations.

An initiative to further improve the durability of blades with an advanced coating was launched. New ceramic coatings were deposited by physical vapor deposition in an industrial machine. Several coatings of varying compositions and architectures were applied to specialized coupons, which were first assessed using cavitation tests based on ASTM G32 standard. A selection from the most promising candidates were deposited on segments of leading edges from several fan blades from different jet engines. These coupons were tested under very aggressive water droplet impingement: applying up to 100 passes of 2 mm diameter droplets accelerated to Mach 2 speeds. When compared to uncoated fan blade leading edge fragments from the same jet engines, the coatings delayed the onset for surface damage (i.e. increased the incubation period), reduced the area affected by material loss and diminished the depth of the largest pit.

Revolutionizing Manufacturing: The Role of Laser Cleaning in Thermal Barrier Coatings Deposition and Removal.

Dr. Dmitri Novikov, IPG Photonics, Marlborough, Massachusetts, USA

This presentation delves into cutting-edge advancements in laser cleaning and ablation technologies, underscoring their transformative impact on mass manufacturing, with a special focus on the aerospace industry. Traditional cleaning methods such as abrasive grit blasting, water jets, and chemical baths are being rapidly supplanted by laser cleaning due to its superior speed, precision, energy efficiency, and environmental advantages. The study provides an in-depth exploration of the physics behind laser-material interactions, highlighting the ability to control parameters such as wavelength and energy density to selectively remove contaminants without damaging the underlying substrate.

Laser cleaning offers several key benefits, including noncontact operation, minimal waste generation, and enhanced precision, making it highly suitable for diverse materials and complex geometries. Additionally, the economic and operational benefits are significant, with notable reductions in consumable costs and the growing affordability of high-power fiber lasers. The integration of laser cleaning into industrial processes is poised to improve productivity, repeatability, and environmental sustainability, heralding a major shift towards more efficient and responsible manufacturing practices.

Session: Thermal and Environmental Barrier Coatings for Gas Turbines IX

Suspension Plasma Spray versus Electron-Beam Physical Vapor Deposition Yttria-Stabilized Zirconia Thermal Barrier Coatings: Durability under Thermal Cycle in Thermal Gradient Environment

Dr. Rogerio S. Lima and Dr. Bruno Guerreiro, National Research Council of Canada, Boucherville, Quebec, Canada

One important question lasting in the thermal spray community is if the knowledge of suspension plasma spray (SPS) ZrO₂-8wt%Y₂O₃ (YSZ) thermal barrier coatings (TBCs) can reach the performance levels of their electron-beam physical vapour deposition (EB-PVD) counterparts, and to eventually replace them as the state-of-the-art TBC for aviation gas turbine engine blades. This work aims to bring some important clarifications on this subject. The SPS YSZ TBCs were engineered using industry-produced ethanol-based suspensions (from 25 to 75 wt%) provided by Innovnano, Saint-Gobain and Treibacher. The Mettech Axial III plasma spray torch and the Polycontrols M40 suspension feeder were employed to manufacture the SPS YSZ TBCs. The benchmark EB-PVD YSZ TBCs (including the Pt/Al bond coat) were manufactured by a private industrial contractor. All TBCs were deposited on single-crystal Rene N515 substrates. The bond coat material for the SPS YSZ TBCs was the NiCoCrAlY+HfSi; produced via air plasma spray (APS). The performance comparison amongst all these TBCs in thermal gradient cycling (5 min hot and 2 min cool cycles) was undertaken via a thermal gradient laser-rig testing system. These are released results from the Surftec Thermal Spray Industrial R&D Group of the National Research Council of Canada.

Axial Plasma Spraying of Solution Precursors: Adding a New Dimension to Future Thermal Barrier Coatings Development?

Thomas Hervy¹, Nicholas Curry², Mr. Stefan Björklund³, Dr. Frantisek Lukac⁴, Dr. Rahul Jude Alroy³ and **Prof. Shrikant Joshi**¹; ¹University of Limoges, Limoges, France; ²Thermal Spray Innovations, Zell am See, Austria; ³University West, Trollhättan, Sweden; ⁴Czech Academy of Sciences, Prague, Czech Republic

Thermal barrier coatings (TBCs) are an essential part of modern gas turbines for aviation and power generation. As such, there is an incessant demand for improved TBC performance and longevity. Among the possible coating microstructures, the columnar structure first produced by electron beam physical vapor deposition was found to be the most durable. The subsequently developed suspension plasma spray coatings are seen as an alternative method for producing columnar TBC's but require flammable solvents to achieve such structures. Aqueous solution precursors have also been utilized as a feedstock to deposit TBCs; however, columnar structures have proven elusive, with deposition conditions and throughputs with radial feed spray torches also being industrially unattractive. The first columnar coatings from an aqueous solution precursor using an axial feed capable plasma torch will be presented. Coatings have been shown to be columnar structured over a robust operating window, fully tetragonal in phase constitution and capable of being deposited at rates that can be commercially interesting. The evolution of the columnar structure has also been experimentally visualized. These initial results lay a good foundation for further TBC development utilizing an aqueous, powder-free, feedstock.

Isothermal Oxidation Performance of High-Entropy Zirconate as an Advanced Topcoat for Thermal Barrier Coatings

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High-entropy zirconates are a novel class of advanced materials that have been introduced recently as promising materials for top coat applications in thermal barrier coatings (TBCs). High-entropy zirconates have the potential to exhibit superior properties when compared to conventional yttria-stabilized zirconia (8YSZ) top coats, which have a limited working temperature range of 1200–1300 °C. In this work, the isothermal oxidation behavior of high-entropy zirconate top coats with a chemical composition of (Y_{0.2}Nd_{0.2}Gd_{0.2}Sm_{0.2}Dy_{0.2})₂Zr₂O₇ has been studied. High-entropy top coats were thermally sprayed by suspension plasma spraying (SPS) on an HVOF-sprayed MCrAlY bond coat. By using the Mettech Axial III torch, the top coats were produced with two distinct microstructures: columnar and dense vertically cracked (DVC). Oxidation tests were conducted at 5, 25, 50, and 100 hours at 1150 °C to assess the performance of both microstructures in comparison to conventional 8YSZ top coats. The development and growth of the thermally grown oxide (TGO) layer were studied to evaluate oxidation resistance and potential applications in high-temperature environments, such as gas turbine vanes, blades, and combustors.

Keywords: Thermal Spray, Suspension Plasma Spray, Thermal Barrier Coating, High-Entropy Zirconate, Oxidation

Data-Driven Design and Rapid Evaluation of Novel Thermal Barrier Coatings

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Thermal barrier coatings have been an important component of aero and gas turbine engines since the 1980's. The fundamental purpose is to enable higher operating temperatures to improve the efficiency, durability, and power output of the engine. It is desirable that thermal barrier coatings have low thermal conductivity, high toughness, high thermal cyclability, and high resistance to the many chemistries of sand (i.e., calcium-magnesium-alumino-silicates). Two of the most used materials, yttria-stabilized zirconia and Gd₂Zr₂O₇, were developed in the 1980's and early 2000's; respectively. While many other classes of materials have been evaluated as potential thermal barrier coatings, few have been adopted commercially. With the recent development of the high entropy oxide field, the number of possible compositions has increased exponentially such that this multi-objective problem is intractable for human intuition alone. In this presentation, it will be demonstrated that the conventional wisdom of thermal barrier coating composition design can be enhanced by employing materials informatics. This is accomplished using a combination of thermodynamic modeling, artificial intelligence, and high-throughput experimental validation for refining the models.

The Performance Comparison of APS and PS-PVD Environmental Barrier Coatings

Prof. Xiaofeng Zhang, Prof. Min Liu, Dr. Ziqian Deng, Prof. Chunming Deng, and Prof. Changguang Deng; Guangdong Academy of Science, Guangzhou, China

With the increase of turbine inlet temperature for aero-engine, superalloy cannot meet the work requirements. Ceramic matrix composites (CMC) with SiC/SiC as a typical material can increase the temperature by 150–200 °C, and the density is 1/3, compared with superalloys. Therefore, CMC is an important direction for next generation aero-engine. However, the CMC can be oxidized at high temperatures and reacts with water vapor. Therefore, high-performance environmental barrier coating (EBC) protection is required. In the past 10 years, APS and PS-PVD EBC coatings were carried out. Besides, the Al surface modification technology is also proposed. The deposition mechanism of APS and PS-PVD EBC was studied. And the corrosion resistance and high-temperature oxidation of EBC coating were studied.

AEROMAT | 2025

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**2025 ABSTRACT
PROCEEDINGS**

Session: Additive Manufacturing I

Direct Energy Deposition and Selected Laser Melting Processing Applications at MT Aerospace

Mr. Michael Windisch, MT Aerospace, Augsburg, Germany

Direct energy deposition (DED) and selected laser melting (SLM) have been successfully applied at MT Aerospace. Within an ESA FLPP study, DED was optimized for propellant half-shell manufacturing. Demonstrators were manufactured verifying geometry, defect, and material requirements. A feasibility study performed on several aluminum alloys with DED identified limitations to several new alloys and feasible application to one AlCu alloy.

Selected laser melting is in operation at MT for both commercial and aerospace hardware including aluminum, titanium, and steel alloys. Engine applications included firing test qualification. ECSS requirements qualification and certification are in progress and partly implemented. Production of fracture-critical hardware is ongoing.

Modeling Microstructure of Additive Manufactured Metal Parts

R Sambathkumar, X Gao, R Avil, O Stryzhyboroda, C Huang, and
J Jakumeit; Access e.V., Aachen, Germany

Additive manufacturing of metals allows one-step, near-net shape fabrication of complex and intricate components that are difficult to be economically produced by other means. Stainless steels, aluminum, titanium, and nickel alloys are commonly printed using powder-bed fusion or directed energy deposition techniques. In laser-based powder-bed fusion (LPBF), metal powder is melted and solidified into the component being built. The microstructure of the built component evolves during the process and the final solidification microstructure varies depending on the chosen process parameters, resulting in different mechanical properties of the manufactured component. Using numerical modeling and simulation, it is possible to predict the solidification microstructure evolution, enabling the optimization of the final microstructure to obtain the desired mechanical properties.

In this contribution, we use a finite volume code tailored specifically for melt pool modeling and grain growth prediction using a cellular automata technique. The target of this study is to simulate the LPBF process for Ti6Al4V alloy considering the enthalpy-based, thermal-solidification model with phase transformation. The single-track thermal model based on different process parameters is simulated. Thermal conditions from the single track will serve as a basis for the microstructure evolution prediction where LGK dendritic growth model is incorporated. A sensitivity analysis is performed considering different hatch spacing, nucleation density, power and speed, and their results are compared. The melt pool simulations are validated against the microstructure from metallography. Similarly, the as-deposited grain growth simulations will be validated against the experiments. The results demonstrate the potential of the finite volume and cellular automata (FV-CA) model to make accurate predictions of the final microstructure.

Keywords: Additive manufacturing, LPBF, microstructure evolution, process design, process optimization

Developing Additively Manufactured Engine Parts for Small Launch Vehicles and Reusable Launch Vehicles

Dr. Keum-Oh Lee¹, Dr. Hyeonjun Kim¹, Mr. Jaesung Shin¹, Mr. Byoungjik Lim¹, and Dr. Yong-Oh Noh²; ¹ Aerospace Research Institute, Daejeon, Korea, Republic of (South), ² Vitzro Nextech, Ansan, Korea, Republic of (South)

In recent years, new space companies have been using additive manufacturing to develop and produce engine components. This study shows the results of using additive manufacturing to produce methane engine components for the development of small launch vehicles and reusable launch vehicles in South Korea. The 1-, 3-, and 35-ton thrust engine combustors were fabricated using powder-bed fusion, and the design had to be modified to create fine regenerative cooling channels because the powder sometimes clogged the channels and was difficult to remove. Combustion tests confirmed that both nickel-base and copper-base alloys can be used as combustion chambers.

Developing Aerospace High-Strength Aluminum Additive Friction Stir Deposition Process for Critical Defense Parts

Mr. Jacob Swanson, Mr. Noah Barnhill, Mr. Mitchell Keeler, and Mr. Joey Wheeler, ASTRO America, Moline, Illinois, USA

Additive friction stir deposition (AFSD) is a method of additive manufacturing in which metal rod inputs are spun at high speeds and plastically deformed into uniform layers. By depositing subsequent layers over the initial deposition this technology allows for the printing of 3D structures and large geometries that manufacturers have historically produced through either a casting, rolling, or forging process. By increasing the TRL/MRL of this technology, industry partners will be able to put critical aviation parts into production via additive manufacturing on a larger scale reducing lead times and aircraft-on-ground penalties across multiple programs.

To achieve this ambitious plan ASTRO America, under contract with Army DEVCOM Ground Vehicle Systems Center (GVSC), and in conjunction with the Joint Manufacturing Technology Center (JMTC) at Rock Island Arsenal, has partnered with a large team of university researchers, industry research labs, Army partner organizations, and industry technology specialists to further qualification and the adoption of AFSD. The combination of all our partner organizations puts this project in a unique position to address a range of problems spanning from design to production, nondestructive testing, quality, and standardization, enabling rapid advancement into a low-rate production phase within two to three years.

The next stage of development will be a comprehensive look at 7xxx series high-strength aluminum alloys including the development and qualification of materials, machines, and parts to achieve production-ready capability for critical DoD components. In addition to continuing the refinement of AFSD process variables, process monitoring, and graphite-free tools, this stage of experiments will delve into the product and process metallurgy and thermal process development necessary to arrive at finished builds that reliably meet the relevant industry standards and certification-ready quality systems.

Session: Light Alloy Technology I

Scandium Additions in High-Performance Aluminum Alloys for Aerospace Applications

Dr. Timothy A. Langan¹, Henk Vander Laan¹, and Mr. Frank Palm²;

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Scandium is a very potent alloying element in aluminum. Early work at Alcoa in the U.S. and at aerospace laboratories in the former Soviet Union in the late 1960s and early 1970s showed that scandium additions increase performance when added to wrought commercial alloys. Subsequent work has shown that the most dramatic increases in performance are observed in high-strength Al-Mg 5xxx series-type alloys. The widespread adoption of Sc-containing aluminum alloys has been limited by commercial and supply issues. In this presentation, we will review previous aerospace applications for scandium-containing alloys and discuss the potential for future applications. In addition, we will update the current state of the scandium supply chain.

The Fatigue Properties of Anodized Aluminum Alloys

Ms. Ashley Kobylinski¹, Prof. Omar S. Es-Said¹, Dr. Michael Hahn², Mr. Michael Niedzinski³, Mr. Xiaodong Sun¹, Kade Cochran¹, Joey Slaybaugh¹, Sarah Leka¹, and Dr. Ricky Whelchel⁴; ¹Loyola Marymount University, Los Angeles, California, USA; ²Northrop Grumman Corporation, Torrance, California, USA; ³Constellium LLC, Muscle Shoals, Alabama, USA; ⁴Constellium Aerospace and Transportation, Ravenswood, West Virginia, USA

Anodizing is applied on aluminum alloy surfaces to improve wear and corrosion resistance- specifically in aerospace applications. Despite these benefits, the anodized coating adversely affects the fatigue properties of the aluminum alloy. The fatigue life is dependent on the alloy and type of chromic or nonchromic anodizing.

The fatigue knockdown factors (KDF) of 7050-T7451, 2195-T8, and 2050-T8 prepared by as-received (no anodizing, control), chromic, boric-sulfuric, or

tartaric-sulfuric anodizing are evaluated. The fatigue life of each alloy and anodize condition are compared to the corresponding alloy and as-received condition. The fatigue testing was conducted with a rotating-beam R.R. Moore machine at 30 and 50 ksi. Results show that chromic anodizing improved fatigue life for Al-Li alloys. The chromic anodized specimens showed fatigue life improvement for 2195-T8 at 30 ksi (KDF=2.16/1.04) and 2050-T84 at 50 ksi (KDF=1.06), and better lives overall compared to boric-sulfuric and tartaric-sulfuric with KDFs of 0.37-0.80. Comparing experimental data and SEM images, decreased anodized layer thickness resulted in improved fatigue life. Chromic anodizing consistently had the thinnest layer with an average thickness of 1.19 μm . The high applied stress (50 ksi) had lower cycles to fracture, and fractured surfaces showed crack initiation and one origin. In contrast, the low applied stress (30 ksi) had greater cycles to fracture, greater variability in the number of cycles, and fractured surfaces showed crack nucleation with multiple origins.

The Utilization of Extrusions for Aerospace Applications

Steven Babaniaris¹ and Dr. Justin Lamb²; ¹Universal Alloy Corporation, Dumbravita, Romania, ²Universal Alloy Corporation, Canton, Georgia, USA

Metallic extrusions are used by the aerospace industry for structural applications in both aluminum- and titanium-alloy systems. The utilization of extrusions can lead not only to better buy-to-fly ratios, but additionally increased performance over other product forms in certain applications when properly leveraged. Due to their higher flow stresses and more complex metallurgical processing routes, the technologies used in the manufacturing of structural aerospace grade extrusions differ from those of automotive or architectural products. This presentation will cover the fundamentals of aluminum and titanium extrusions, discussing the differences in extrusion technologies depending on the alloy and application, the various paths to making hollow extrusions, the complexities of thick gauge "heavy" aluminum extrusions and the developments in complex titanium extrusions. Additionally, advances in aluminum alloy technology will be presented.

2074 Aluminum Sheet: Next Generation Low Density AIRWARE[®] Sheet for Fuselage Applications

Mr. Scott Buchwald¹, Dr. Hélène Godin², Mr. K. Paul Smith¹, and Mr. Peter Bittner³; ¹Constellium Aerospace and Transportation, Ravenswood, West Virginia, USA; ²Constellium C-TEC, Voreppe, France; ³Constellium, Hoffman Estates, Illinois, USA

For many years, 2024 clad T3 aluminum sheets have been the standard material used for external fuselage skin sheets. In the 1990's, 2524 clad T3 was developed, delivering improved toughness and crack growth rate, allowing lighter-weight designs, and allowing longer inspection intervals. Recently developed aircraft programs have adopted AIRWARE[®] 2198 skins, capturing the benefits of increased performance combined with low density. AIRWARE[®] 2074 builds on the success of 2198, raising the bar on performance and manufacturability, enabling structural weight reductions, facilitating sustainability targets, and supporting the use of both legacy and advanced fabrication techniques. The performance-weight balance of AIRWARE[®] 2074 also supports utilization by the Advanced Air Mobility market for cabin structures. The advantages and properties of AIRWARE[®] 2074 compared to incumbent solutions will be presented, along with an update on its standardization path. An update on several other Constellium solutions will also be shared.

Development of a Stretch Forming Process for 2055 Aluminum Lithium Fuselage Frames

Mr. Jonathan Beckman¹ and Mr. Aaron Lam²; ¹Gulfstream Aerospace, Savannah, Georgia, USA; ²Arconic Corporation, Lafayette, Indiana, USA

The use of formed and machined extrusions for integral aircraft fuselage frames allows for reduced part count, improved assembly, and weight savings when compared to legacy sheet metal designs. To determine the viability of using new aluminum alloys for fuselage frames, Gulfstream Aerospace has researched several high-strength extrusion alloys, including aluminum lithium alloys. Early efforts with aluminum lithium alloys led to inconsistent properties, severe recrystallization, and extensive orange peel. Gulfstream and Arconic were able to overcome these obstacles using a newly developed temper for 2055 aluminum extrusions. This presentation will step through the different trials performed and discuss the results throughout each stage of the trials.

Revolutionizing Aluminum Alloys: AMAG's Path to Unrestricted Innovation with AMAG CrossAlloy[®]

Mrs. Christine Manatt¹, Dr. Ramona Tosone², Dr. Florian Schmid², and Dr. Lukas Stemper²; ¹AMAG Rolling, Winona Lake, Indiana, USA; ²AMAG Rolling GmbH, Braunau am Inn, Austria

Since the beginning of their industrial use, aluminum alloys have been divided into eight alloy classes based on their main alloying element. Although great efforts have been made to maximize the potential of existing alloys, the possibilities to increase performance within these standardized alloy classes are limited. Ever increasing requirements with respect to mechanical and technical properties become even more challenging with increasing requirements for sustainability, scrap input rates and necessary reductions in CO₂ footprints.

AMAG's CrossAlloy[®] family offers a promising and novel answer to this increasingly pressing problem. This new class of aluminum alloys aims to combine desired material properties through innovative alloy design that is detached from classical, normative restrictions. In this way, not only can new alloys with improved properties be developed, but also unique blends of alloy classes can be utilized more effectively.

Creating a beneficial mix of high strength and good ductility in a single alloy has always been a challenge. To combine these seemingly contradictory material properties, AMAG CrossAlloy[®].57 was developed as the first member of the AMAG CrossAlloy[®] family. In short, it represents an optimized blend of a 5xxx and 7xxx alloy and, therefore, results in an alloy with a balanced combination of properties. In this regard, AMAG CrossAlloy[®].57 stands out as a high-strength alloy that incorporates many beneficial material properties known from 5xxx series alloys, such as corrosion resistance and weldability.

Use of High-Performance Materials by Smart Assembly and Forming Techniques

Mr. David Chartier¹ and Dr. Frank Eberl²; ¹Airbus Atlantic, Toulouse, France; ²Constellium Aerospace & Transportation, Issoire, France

Targeting a continuous decrease of environmental footprint, future aircraft generations should provide a high-performance level with a low level of CO₂ emission and good recyclability. For airframes, this translates into significant mass savings, easier maintenance with longer inspection intervals, and decreased sensitivity to corrosion. Such an improvement can be achieved by enhanced materials and the integration of smart forming and assembly techniques.

Friction stir welding has been studied extensively by major players in the aeronautics industry. This robust welding process can improve airframe performance by building up thick gauge structures using thinner gauge, higher-performance materials. Weight savings are possible due to the "T-joint" welded configuration and the good mechanical behavior of the welded joint. Cost savings can be achieved by reducing the machining time and developing dedicated materials.

As for friction stir welded structures, nearer net shape billets reduce the buy-to-fly ratio and increase the performance thanks to thinner gauge; roll forming for plates is an interesting enabler to increase the cost-performance balance of monolithic structures.

Thin gauge fuselage skin panels, particularly the aircraft nose fuselage, contain complex spherical shapes. They also require excellent forming capabilities to allow one-step stretch forming without any intermediate solutionizing treatments. For sheet material, the friction stir welding process is applied to further increase performance by decreasing the number of rivets.

Constellium, and Airbus Atlantic have been collaborating for many years to increase the maturity level of the technologies mentioned. Examples of various structural parts and 1:1 demonstrators formed and assembled with appropriate material choices of advanced alloys will be shown. The measurement of the carbon footprint by using life cycle analysis tools will complete the overview, confirming the excellent environmental performance of the metal technologies selected.

Session: Sustainability and Recycling I

Aluminum Solutions to Improve Sustainability in the Aerospace Industry

Dr. Sabine Spangel, Philipp Rumpf, Dr. Andreas Bach, Christian Tussing, Sasi Chinnasamy and Dr. Achim Bürger; Novelis Koblenz GmbH, Koblenz, Rheinland-Pfalz, Germany

In the past years the focus for the development of new materials for the aerospace industry moved from property improvements and cost-effective manufacturing methods towards sustainable solutions. Aluminum alloys can contribute in many ways to a sustainable aviation industry.

Opportunities for aluminum to be the material of choice in the future for aircraft applications are in new products and alloys, such as:

- Allowing a high recycling content with similar performance.
- For hydrogen storage to support new environmentally friendly propulsion concepts.
- Produced via new energy-efficient manufacturing routes.
- Supporting new manufacturing concepts at the aircraft manufacturers allowing for weight and fuel savings.

This paper describes new developments at Novelis for aerospace plate and sheet products to demonstrate how these topics are being addressed.

Digital Material Passports: Key Enabling Elements to Improve Quality, Sustainability and Circular Economy

Dr. Achim Hofmann, Advanced-Materials-Concepts GmbH, Bavaria, Germany

Digital material passports (DMPs) have emerged as a transformative tool that facilitates material data and tracking, quality assurance, sustainability, and end-of-life resource recovery along the supply chains. This paper discusses the role of DMPs as a foundational element in advancing transparency and traceability. DMPs have been identified as a key enabling element in the Aerospace-X consortium, which is funded by the German Federal Ministry of Economics and Climate Protection (BMWK) under the funding code ID 13MX004A as part of the Manufacturing-X funding program. The objectives of the consortium are building the digital ecosystem for the aerospace industry, ensuring digital continuity and common standards between aerospace product manufacturers, OEMs, and the (multitier) supply chain, and enabling a new form of collaborative, data-based value creation.

Our study explores the design and implementation of DMPs across aerospace as well as various industries, highlighting how digitalization of material information not only enhances product quality but also aligns with sustainability objectives. We address the technical and regulatory challenges in developing standardized digital material passports and present a framework for their integration into existing digital ecosystems. Using case studies, we demonstrate the potential of DMPs to increase quality, avoid falsification of material certificates respectively the use of nonqualified materials and components, increase transparency with respect to sustainability along the supply chains, support resource-efficient manufacturing, and enable compliance with evolving environmental regulations and OEM requirements.

The findings underscore that DMPs are not merely informational tools but essential enablers of sustainable supply chains. They influence design decisions, material and supplier choices, and recycling processes. As industries and policy-makers increasingly prioritize sustainable practices, DMPs offer a scalable solution to manage resources responsibly and foster a more circular economy.

Data and Decision Science-Driven Assessment of Sustainable Materials for Thermal Protection in Aerospace

Dr. Tanjore Jayaraman, United States Air Force Academy, Colorado Springs, Colorado, USA

Significant progress has been made in researching materials for thermal protection in aerospace vehicle technologies. The rapid development of aerospace technology has introduced new requirements for high-performance thermal protection systems, including but not limited to high-temperature resistance, lightweight characteristics, high transmission capabilities, and so on. Materials Informatics-enabled materials discovery and selection, popularly termed Materials 4.0, is enabled on the existing big data of synthesis, processing, modeling,

characterization, and properties of diverse materials for thermal protection in aerospace. A novel methodology that combines multiple-attribute, decision-making (MADM) methods, principal-component analysis (PCA), and hierarchical-cluster analysis (HCA) is applied. Weights of the properties (or attributes) were evaluated by objective (Shannon's entropy method) and subjective methods. The rank assigned by several MADM, viz., Technique of order preference by similarity to ideal solution (TOPSIS), Grey Relational Analysis (GRA), Multicriteria Q Analysis (MCQA), Operational competitive ratio (OCRA), and so forth, were consistent. PCA and HCA consolidated the MADM ranks and grouped similar alloys. The investigation highlights similarities across several materials for thermal protection, suggests potential replacement or substitute for existing materials for thermal protection, and provides directions for improvement and/or development of sustainable materials for thermal protection.

Adhesive Bonding in Cryogenic Conditions

Dr. Antonio Pagliuca, 3M Aerospace, Bracknell, United Kingdom

The increasing rates of global warming and decreasing levels of natural resources have contributed to significant levels of environmental change, with aerospace and transportation sectors accounting for 17% of global man-made CO₂ emissions. To face the climate challenge, the aerospace community is actively pursuing alternative greener energy sources such as green hydrogen. Significant technical challenges exist in storing liquid hydrogen in airframe structures where any structural discontinuities in storage tanks can create significant issues. In this scenario, structural adhesive bonding could be an effective solution. This paper will highlight testing of adhesives in bonding to both metallic and composite substrates. This will include mechanical performance of bonded joints at cryogenic temperatures, fatigue analysis and some insights into potential modelling techniques to provide a basis for adhesive selection criteria.

Materials Challenges for Sustainability in Reusable Space Launch Systems

Mr. Thomas N. Ackerson, Enterprise Engineering, Blue Origin, Merritt Island, Florida, USA

The Apollo and Space Shuttle programs are two examples where technical barriers were broken and significant materials and processing advances were made in a relatively short period of time. Today, we undergo another boost in materials and processing technology with the private sector becoming very involved in launch vehicles, space transport, space stations, and lunar landers. In order to drive the cost of space travel down significantly, the launch systems must be reusable and efficient. They must also be as lightweight as practical, and withstand the mechanical rigors of multiple launches, the thermal stresses of re-entry, and corrosion issues related to oceanic recovery. Corrosion protection is an area where significant progress is being made in replacing hexavalent chromium surface treatments with more environmentally-friendly conversion coatings. This talk will focus on these challenges, and some of the steps being taken to overcome them.

The Future of Aerospace Manufacturing and the Role of Advanced Materials

Mr. Tim Gaur, Airbus, Herndon, Virginia, USA

The ongoing fight against climate change coupled with an increasing demand for global air travel is accelerating the need for sustainable solutions in the aviation industry. Tackling this challenge takes many forms, but nearly all of them come back to the materials and related manufacturing processes that are needed to design and build future aircraft. This presentation will discuss how successes in advanced materials have unlocked today's most fuel-efficient aircraft. The discussion will also highlight some of the challenges facing aircraft manufacturers today, such as the need to replace older models with more efficient aircraft, as the industry seeks to meet its goal of net zero emissions by 2050. The presentation will then delve into the essential role advanced materials play in addressing these challenges, from the manufacturing stage, to in-service considerations, and finally the dismantling and disposal of aircraft. The presentation will touch on a variety of material and related processing technologies the industry is seeking for the future, the barriers that must be overcome to achieve success, and highlight how these new technologies will benefit the future of aviation.

Effect of Sustainable Aviation Fuel on the Volume Variation of Nitrile Elastomers

Ms. Erika Kano de Oliveira and Ms. Suelen Salih Teixeira Navarro, Embraer SA, São José dos Campos, São Paulo, Brazil

Sustainable aviation fuels (SAF) are being tested as a 100% replacement for petroleum fuel by the aviation industry as a commitment to reducing carbon emissions. Embraer successfully completed experimental flights with commercial and executive jets using 100% SAF. The literature indicates that the lack of aromatic compounds in SAF impacts the adequate sealing of nitrile elastomers and, if they have been previously exposed to conventional aviation fuel, recommends replacing them with new ones before refueling with 100% SAF. This study evaluated the volume variation in nitrile rubber O-rings when immersed in fuel, alternating between HEFA-SPK and Jet A.

Session: University of British Columbia and The German Aerospace Center Biogenic Structural and Functional Materials

Biomass Derived Antimicrobial Cellulose Aerogels as an Alternative to Fossil-Based Plastic Materials and Theoretical Studies of Gel Structure Formation

Prof. Barbara Milow¹, Mrs. Nina Borzecka¹, Mr. Bruno Goncalves¹, Mrs. Sam Yeo², Prof. Ameya Rege¹, Dr. Kathirvel Ganesan¹, and Prof. Sepideh Pakpour²; ¹The German Aerospace Center, Cologne, Germany; ²The University of British Columbia, Kelowna, British Columbia, Canada

Cellulose aerogels are biopolymer-based nanostructured porous solids gaining special interest due to their potential to be used as a sustainable thermal insulation and filter material. The fact that cellulose is the most abundant biopolymer on earth gives great potential to generate sustainable materials with exceptional physical properties. To benefit from the advantages of cellulose aerogels, the University of British Columbia (UBC) and the German Aerospace Center (DLR), alongside other partners, decided to cooperate in two different projects – GelSus and PISA.

The aim of these projects is the exploitation of agricultural lignocellulosic residues to develop cellulose aerogels for several applications as an alternative to current fossil-based plastic materials. GelSus focuses on the production of cellulose aerogels with antimicrobial properties for sustainable food packaging, filters, and thermal insulation. Whereas, PISA focuses on the pilot-scale production of cellulose aerogels to be used as a sustainable thermal insulation in buildings. The role of the DLR is the extraction of cellulose from the lignocellulosic biomass with an alkali-based process and the synthesis of cellulose aerogels, using the sodium hydroxide-urea approach to generate the cellulose solution. Additionally, multi-scale models are developed to describe a digital twin of the aerogel at a material level as well as the product level. Establishing successful correlations between the model parameters and those from synthesis, the models are to be further used to reverse engineer cellulose aerogels towards any targeted application. UBC enhances aerogels by incorporating antimicrobial agents, making them resistant to bacterial colonization and degradation, resulting in a longer service life and improved biocompatibility.

The obtained results demonstrate the significant potential of cellulose aerogels as a novel and sustainable thermal insulator with good antimicrobial properties. Good agreement of experimental and numerical observations was proven, indicating clear potential of the developed numerical approach for virtual representation of the chosen biopolymer-based aerogel system.

Development of Organic Aerogels Containing Chitosan Biopolymer from European Green Crab Shells

Dr. Lukas Bichler¹, **Mr. Mitchell Barrett**¹, Dr. Marina Schwan², Prof. Barbara Milow², Dr. Adam Dzierbinski², Dr. Martin Sgraja², Ms. Crysta Stubbs³, and Mr. Ryan Chamberland³; ¹The University of British Columbia, Kelowna, British Columbia, Canada; ²German Aerospace Center, Cologne, Germany; ³Coastal Restoration Society, Port Alberni, British Columbia, Canada

The European green crab (EGC) is recognized as one of the world's most destructive aquatic invasive species and has had a profound detrimental impact on the ecosystem of the Pacific coastline for over 20 years. The Coastal Restoration Society and the T'Sou-ke First Nations in British Columbia, Canada, have developed a large-scale trapping and control plan for EGC. This research is a part of the DLR@UBC collaboration, and focused on extracting chitin, a biopolymer naturally present in the EGC shells, and converting it to chitosan for use in organic aerogels. The carbonization and activation, along with the potential use of the organic aerogels for gas filtration applications are discussed.

Impact of Weak Organic Acids as Coagulants on Tailoring the Properties of Cellulose Aerogel Beads

Prof. Barbara Milow, Mr. Diogo Costa and Dr. Kathirvel Ganesan, The German Aerospace Center, Cologne, Germany

Cellulose is the most abundant polysaccharide on Earth and is well known for its renewability, biodegradability, and chemical stability.^{1,2} We have been investigating the use of weak organic acids to tailor the properties of cellulose aerogel beads.³ The cellulose solution was prepared by using commercial cellulose in a mixture of NaOH, urea, and water as a solvent.⁴ Three weak acids, acetic acid, lactic acid, and citric acid, and a strong acid, hydrochloric acid, were chosen as regeneration baths. The production of aerogel beads by conventional dropping technique was studied and optimized for each acid. The produced cellulose aerogels were characterized by nitrogen adsorption-desorption isotherm, BJH pore data analyses, density analyses, IR spectroscopy, scanning electron microscopy, and x-ray powder diffractometry, and their properties were compared. In common, all the aerogel beads showed interconnected nanofibrillar network. The pore size distribution was highly influenced by the acids employed for regeneration. High concentration of weak acids contributed to low shrinkage, high specific surface area and high pore volume. In conclusion, this study showed an alternate path way to tailor the properties of cellulose aerogel beads. Furthermore, cellulose from biomass waste can be used for such products too. Thus, hemp and flax from Canadian suppliers were used as starting material. Within the presentation an overview on the production of cellulose aerogels from various raw materials working under different conditions will be presented.

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Porous Carbon Materials for Electrochemical Applications

Dr. Marina Schwan¹, Ms. Jessica Kröner¹, Prof. Barbara Milow¹, Mr. Mitchell Barrett² and Dr. Lukas Bichler³; ¹The German Aerospace Center, Cologne, Germany; ²University of British Columbia – Okanagan Campus, Kelowna, British Columbia, Canada; ³University of Guelph, Guelph, Ontario, Canada

The increasing demand for energy storage leads to a high interest in battery technologies. Batteries with high specific performance, sufficient cycle stability, wide operating temperature range, light weight, high safety, and low cost are currently the subject of global research activities. The German Aerospace Center (DLR) and the University of British Columbia (UBC) collaboration benefits from high expertise of both partners and is working on advancing the development of next-generation batteries based on aerogel materials with carbon additives.

The electrical conductivity of powdered carbon materials is one of the key factors for electrochemical applications. The study presents synthesis, characterization, and the correlation between structural, physical, mechanical and electrical properties of pure carbon aerogels, as well as aerogel composites. The influence of

carbon feedstock activation on the properties of carbon aerogels, in particular on electrical conductivity, is shown. Additionally, the impact of adjusting the electrical conductivity of several aerogel-composites and their suitability as conductive additives in Li-ion batteries is explored.

Session: Additive Manufacturing II

Exploring Gradient Aerospace Alloys: Modeling, Manufacturing, and Evaluation

Mr. Matt Dolde, Mr. Thomas Ales and **Dr. Peter Collins**;
Iowa State University, Ames, Iowa USA

Functionally graded materials hold promise due to the ability to potentially control the location-specific microstructure, properties, and performance of larger unitized structures. While many researchers have explored controlling composition through additive manufacturing processes, technical risks present barriers to establishing the necessary confidence to implement such materials in practice. The risks are associated with the level of precision associated with compositional control, the integration of variations in unknown spatially-changing thermophysical properties into sensors, and the difficulties associated with nondestructive evaluation methods when composition changes spatially. This talk will discuss progress made in understanding gradient materials, their modeling, manufacturing, and evaluation using destructive and nondestructive methods.

Metal Additive Manufacturing for Critical Aerospace and Defense Components

Dr. Prabir K. Chaudhury, Education and Consulting LLC, Phoenix, Arizona, USA

Additive manufacturing (AM), known as 3D printing or direct manufacturing, has become the leading edge manufacturing technology. Today, metal additive manufacturing (MAM) is a reality, not only for prototype fabrication, also for functional parts in various industries. As the industry progresses towards implementing AM in more critical parts, new material and process innovation are imperative. Besides material development, there are opportunities for manufacturing critical, in particular fracture and fatigue, parts taking advantage of the ultrafine microstructure that is common in all metal AM processes. This presentation will show the results of such an effort in which the ultrafine grain microstructure is retained while breaking down the micro-inhomogeneity arising from elemental partitioning during solidification in all fusion-based metal AM processes. Current investigation shows how a forging preform can be designed with tailored stain distribution to recrystallize fine grains and impart grain flow during the forging resulting in high strength, fracture toughness, and fatigue properties that are essential in fracture and fatigue critical parts in aerospace and defense applications. The presentation will show the minimum strain required in AM 316 stainless steel and Ni alloy 718 to recrystallize strain-free fine grain and chemically homogenous microstructure during forging. The presentation will also show the forging preform design based on this minimum strain in the center and maximum strain required to generate grain flow on the outer envelope of the forging. The results of this investigation will include both PBF-LB and DED (WAMM) based forging preform design and forging performance to illustrate the path for manufacturing AM-based fracture and fatigue critical for the aerospace and defense industry.

Performance of Rolled Threads on 3D Printed Inconel 718 and 17-4PH Stainless-Steel Hex Head Fasteners

Dr. Noel P. Greis^{1,2}, **Dr. David Willens**³, Mr. Alex Deneault², and
Mr. Daniel Barmakian²; ¹University of North Carolina Charlotte, Charlotte,
North Carolina, USA; ²Kinefac Corporation, Worcester, Massachusetts, USA

The convergence of additive manufacturing (AM), innovation in materials, and advances in software tools has led to significant improvements in airframe and engine manufacture and performance due to superior strength-to-weight characteristics, as well as exceptional mechanical strength for load-bearing applications. Fasteners, due to requirements of high strength and resistance against dynamic loading, are manufactured from traditional wrought alloys rather than printed materials. Fastener threads are typically rolled, rather than cut, for the benefits of cold forming strength and fatigue resistance, material savings, and production

efficiency. This study evaluates the potential tensile and fatigue performance benefits of rolled threads on 3D printed Inconel 718 and 17-4 PH stainless steel hex head fastener blanks for aerospace applications using the cylindrical die thread rolling process.

Rolled threads can be up to 30% or stronger and more fatigueresistant than cut threads in a given material due to the compressive residual stresses, uninterrupted grain flow, and smooth surface finish resulting from the cold work operation. Threads can be rolled before or after heat treatment of the blank, but many critical applications, such as with aerospace, require thread rolling after heat treatment for maximum strength. Experiments were designed to evaluate the tensile strength and fatigue performance of 0.3750-24 UNJF-3A rolled threads and cut threads in Inconel 718 and 17-4PH stainless steel 3D printed hex bolt blanks produced by the powder-bed fusion direct metal laser sintering process. The shanks of the 3D printed blanks were turned after printing to the correct pre-roll diameter and were then thread rolled using the infeed rolling process on a two-die cylindrical die thread rolling machine. The tensile strength and fatigue performance are also compared to standard wrought 0.3750-24 UNJF-3A Inconel 718 and 17-4PH rolled thread fasteners for aerospace applications.

Session: Advances in Coatings and Surface Modification I

A Novel Approach for Applying 2K Coatings to Improve Outcomes and Reduce Cost

Mr. Michael R. Bonner, Saint Clair Systems, Inc., Washington, Michigan, USA

2K coatings are widely used in aerospace applications as an innovative means to increase the move towards 100% solids materials and reduce the need for thermal curing, thus reducing the energy required for the coating process. While the benefits are indisputable, there are issues associated with these technologies that can make them difficult to process in the manufacturing environment. All of these must be dealt with as part of the application process and, if not properly handled, can result in production delays that reduce throughput, reduce quality, and increase costs. Obviously, this runs counter to the objectives of these advanced technologies.

In this presentation, we will:

- Define induction time and pot life and the relationship between them.
- Discuss the implications these pose to the modern manufacturing process.
- Identify novel methods to leverage these properties, turning them from adversaries to allies in the application process.
- Identify opportunities to minimize waste, reduce rework, increase throughput, and improve the quality of the coating process.

Evaluation of Mechanical Properties of Thermal Spray Coatings Using Micropillar Compression Test

Mr. Yeon Woo Yoo¹, Prof. Sung-Gyu Kang², Mr. Yong-Jin Kang¹, Mr. Youngjin Park¹,
and Dr. Sunghun Lee¹; ¹Korea Institute of Materials Science, Changwon,
Korea, Republic of (South), ²Gyeongsang National University,
Jinju, Korea, Republic of (South)

Evaluating the mechanical properties of thermal spray coatings has traditionally relied on methods such as Vickers hardness and nanoindentation tests. However, these methods offer limited insight into the effect of internal defects in coatings on mechanical performance. To address this gap, we applied micropillar compression test to assess the mechanical properties of thermal spray coatings, considering the influence of coating microstructures and defects. Various thermal spray coatings with different microstructures were produced and fabricated into micropillar for mechanical testing. The results provided valuable insights into the correlation between coating microstructure and mechanical properties, allowing a more comprehensive understanding of how microstructural variations impact coating strength and resilience.

Antimicrobial and Advance Coatings for the Aerospace Industry

Dr. Alfred Mitchell, Luminore CopperTouch, Houston, Texas, USA

The aerospace industry demands advanced solutions to address microbial contamination in environments where cleanliness, durability, and efficiency are critical. Luminore Copper Touch, an EPA-registered antimicrobial coating for aerospace applications utilizes copper's natural properties to eliminate pathogens, offering a state-of-the-art approach to infection control. This study investigates the application of Luminore CopperTouch coatings within aerospace systems, focusing on its ability to reduce microbial transmission and biofilm buildup on high-contact surfaces.

Designed to integrate seamlessly with aerospace materials, including lightweight alloys and thermally stable composites, Luminore CopperTouch coatings form a durable antimicrobial layer that remains effective under extreme conditions, such as microgravity, high radiation, and temperature fluctuations. By preventing bacterial and viral growth, the coating ensures sterility on surfaces like cockpit controls, seat armrests, cabin walls, and storage compartments, mitigating risks associated with cross-contamination during long-duration space missions.

Laboratory testing and simulations under aerospace conditions demonstrate the coating's ability to reduce microbial loads by up to 99.9%. Its lightweight and corrosion-resistant properties align with aerospace industry standards, ensuring no compromise in weight or structural integrity. These features make Luminore CopperTouch an ideal solution for maintaining cleanliness and safety in spacecraft and aviation environments.

The versatility of this EPA-registered antimicrobial technology extends beyond aerospace applications to contamination-sensitive sectors such as healthcare, cleanrooms, and public transit systems. As aerospace missions increase in duration and complexity, adopting antimicrobial technologies like Luminore CopperTouch coatings will help ensure cleaner, safer environments for crew and passengers.

Future research will focus on optimizing the coating's durability, expanding its antimicrobial spectrum, and adapting it for advanced aerospace systems, including lunar habitats and deep-space vehicles. This positions Luminore CopperTouch antimicrobial coatings as a transformative, scalable solution for managing microbial risks in critical environments.

Session: Light Alloy Technology II

Aluminum Alloys for High-Temperature Application

Dr. H el ene Godin¹, Mr. K. Paul Smith², and Bernard Demestral¹;

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Airware solutions are considered for various applications besides the typical aircraft structural components, for example for engine parts, because of their low density, excellent corrosion resistance, and a good combination of strength and toughness. These applications often require high-temperature resistance.

The behavior at high temperature of the two baseline aluminum alloys 2219 and 2618 are compared to new Constellium alloys. Airware alloys and new conventional alloys are tested in this study. Tensile tests are done at room and high temperature (150, 200, 250, and 300 °C). Alloys are also tested after long-time exposure at high temperatures (100, 1000, and 3000 hours at 150, 200, 250, and 300 °C). After exposure at temperature without any load, samples were tested at room and exposed temperature. Results show that the drop of tensile properties after exposure at temperature is independent of the product form; plate or extrusion; or the testing direction. Constellium has developed a model capable of predicting the static behavior of those alloys after exposure at high temperature, tested at the exposed temperature, or at room temperature. Creep tests are also performed between 110 and 200 °C and show that AlCuLi products under certain conditions have better creep resistance than conventional alloys.

Terran R Relativity's Space Heavy Lift Space Launch Vehicle

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Terran R is a medium-to-heavy lift reusable rocket currently in development by Relativity Space. Designed to carry 23,500 kilograms to low earth orbit (LEO), the rocket is strategically sized for LEO constellations, large satellites, rideshare missions, and more. The two-stage rocket uses liquid natural gas (LNG) and liquid oxygen (LOX) as propellants, a combination often referred to as Methalox. Each Aeon R engine on the first stage is designed to produce a sea level thrust of 268,000 lbf, for a combined vehicle liftoff thrust of 3,484,000 lbf.

Terran R's design is an evolution of best-in-class architecture solutions, with strategic design choices to prioritize efficiency, cost-savings, and time to market. Relativity Space is leveraging additive manufacturing alongside friction stir welding and the most advanced aluminum alloys to ensure a highly optimized structure. Several Constellium advanced alloys such as 2195, 2196, 2050, 2297, 7140, and 7160 were selected for a trade study. Final selection minimizes buy-to-fly ratio and assures a vehicle with a high safety margin for orbital missions. The paper will provide examples of innovative solutions and material selection methodology.

Session: University of British Columbia and The German Aerospace Center

Accelerated Sustainable Materials Design I

Transforming Mechanical Test Labs into Autonomous Knowledge Discovery Hubs

Dr. Eric Breitbarth, Mr. Florian Paysan, Mr. Eric Dietrich, Dr. David Melching, Mr. Manuel K uch, Ms. Vanessa Sch one, Mr. Ferdinand D omling, and Prof. Guillermo Requena; The German Aerospace Center, Cologne, Germany

The integration of machine learning, large language models, intelligent robotics, quantum computing, and advanced data acquisition is transforming traditional mechanical test labs into autonomous hubs for knowledge discovery. As we face pressing challenges like climate change and resource scarcity, leveraging these technologies in laboratory settings becomes essential for faster and more insightful scientific progress.

This talk will explore an automated, data-driven approach to knowledge discovery through fatigue crack growth experiments. In this setup, intelligent robotic systems continuously track the crack tip of a fatigue crack, capturing high-resolution digital image correlation (DIC) data. A machine learning model then processes these datasets to automatically detect and assess crack tip positions and associated crack tip loadings. Feature extraction is enhanced by a combination of classical algorithms and artificial intelligence, creating a rich dataset of analyzed results like the evolution of the plastic zone or the fracture surface characteristics.

To ensure the coherence and interoperability of diverse data sources, graph databases embedded with ontologies, semantics, and provenance data are employed. This structured approach enables the automated recognition of cause-and-effect relationships, consolidating knowledge within a unified knowledge graph. By streamlining data capture, analysis, and integration, autonomous labs hold the potential to significantly shorten development cycles, accelerating the path to market for new materials and products.

This paradigm shift from manual testing to autonomous knowledge discovery not only advances the scientific method and strengthens our capacity to address complex, global challenges with speed and precision.

High-Throughput Computational Screening of Aluminum Alloys from Scraps

Katrin Bugelnig, KB¹; Silvana Tumminello¹, Dr. Tobias Strohmann¹, Maike Becker¹, Nuria Navarrete¹, Florian Kargl¹, M. Kolbe¹, Janis Ganzenmüller¹, Julie Villanova², and Prof. Guillermo Requena²; ¹The German Aerospace Center, Cologne, Germany; ²European Synchrotron Radiation Facility, Grenoble, France

To meet societal goals like climate neutrality by 2050 and a circular economy, material discovery must be faster and more flexible, especially as raw material costs and supply chain issues increase. Advanced technologies like computational screening, 3D/4D characterization, and machine learning enable rapid responses to these challenges.

A new Al-based alloy suitable for additive manufacturing (AM) derived from scrap metal mixtures was developed using high-throughput alloy screening paired with experimental validation. The new alloy is intended for aerospace applications and must meet requirements such as low sensitivity to hot-cracking, appropriate strength and elongation and corrosion resistance.

In high-throughput computational screening, up to 10 k alloy compositions were generated by mixing the scrap alloys at different ratios. The CALPHAD method was used for equilibrium and nonequilibrium simulations to assess key parameters, including phases, solidification intervals, and mechanical properties like yield strength and hot-cracking sensitivity. A random forest model predicted properties from simulations and literature, while a multi-objective evolutionary algorithm filtered alloys with target characteristics. Uncertainty calculations addressed compositional variations in scrap, ensuring robust designs.

Experimental methods, including SEM/EDX, laser flash analysis, DSC, synchrotron techniques, and laser track experiments, validated the simulations. These tests helped narrow down one to two optimal scrap mixtures for powder production and laser powder bed fusion (LPBF) processing.

Rapid Assessment of the Recyclability of Aluminum Alloys as a Function of Iron Content

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Aluminum is an attractive sustainable material due to its use in several key sectors and can be continuously recycled while retaining its properties, making it an excellent candidate to meet the carbon neutrality and circular economy requirements of the European Green Deal. Recycling is often associated with introduction of impurities, such as increased Fe content affecting material performance. To decrease time, cost and energy, it is imperative to investigate the effect of increasing Fe content in Al-Mg-Si alloys and ways to manage the increase without the need to remove the impurities.

This study focuses on extruded AA6082 Al alloys (Al-0.7Mg-1.0Si-0.5Mn-xFe wt.%). The influence of variations in Fe content on alloy properties was investigated by simulation and experiment. As a first step, high-throughput computational screening was performed on hundreds of chemical compositions generated as a function of Fe content. The CALPHAD method was used for equilibrium and nonequilibrium simulations to evaluate key parameters including phases, solidification intervals, thermophysical parameters, and mechanical properties such as yield strength. Subsequent sensitivity and uncertainty analysis allowed the effects of varying Fe content on microstructural, thermophysical, and mechanical properties to be addressed, as well as identifying Fe tolerance ranges for alloy properties with low sensitivity to Fe variations.

The second step involved experimental investigation on two AA6082 alloys with Fe content of 0.18 and 0.35 wt%. The mechanical properties, especially fracture response, were studied by uniaxial tensile testing and VDA testing. SEM and micro-CT were conducted to characterize the size, number density, and spatial distribution of the constituent particles, which potentially affect fracture behavior. Quantitative analysis for the constituent particles was accelerated by the automation for segmentation using machine learning. The fracture response was then related to the degree of clustering of the constituent particles.

Session: Additive Manufacturing III

Printable, High Strength, Burn-Resistant Nickel Superalloy Designed Using ICMD Software

Mr. Kerem Taskin, QuesTek Innovations LLC, Evanston, Illinois, USA

High-performance rocket engines use high-pressure liquid oxygen fuel which can create a combustion reaction when exposed to common high-strength nickel alloys. In these high-pressure combustion environments, there is a need for nickel-base superalloys that exhibit burn resistance, or oxygen compatibility, as well as high strength, two competing properties. Such an alloy also enables minimizing weight and maximizing thrust of rockets, which is particularly important for reusable rockets where the degradation of materials must be minimized to reduce the need to replace components between launches.

With the recent progress toward industrialization of space travel, there are more rocket manufacturers than ever, and there is a need for flexible, fast, and supply chain resilient manufacturing paths such as additive manufacturing. With known tradeoffs between high-pressure oxygen burn resistance, high strength, and printability for nickel-base superalloys due to a propensity for strain age cracking, achieving these three properties presents a complex alloy design scenario. Using the ICMD[®] platform, QuesTek has developed alloy concepts by co-optimizing these three key properties with physics-based ICME modeling. These alloys have been prototyped and tested, including advanced characterization of nanoscale microstructure to fine-tune ICME model calibration to iterate on the alloy design.

Improving Manufacturing Readiness of Additive Friction Stir Deposition for Ferrous and Nickel-Base Materials

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Mr. Russell Steel³, and Dr. Yuri Hovanski¹; ¹Brigham Young University,

Provo, Utah USA; ²MELD Manufacturing Corporation, Christiansburg, Virginia, USA;

³Mazak Megastir, Provo, Utah

Additive friction stir deposition (AFSD) is a near net shape, solid-state additive process capable of printing numerous metals at high-deposition rates. While AFSD has seen increasing success at printing titanium and aluminum alloys of varying alloys, printing of ferrous and nickel-base products has lagged in the development due to complexities associated with tooling. Traditionally, these materials would use super-abrasive tools like polycrystalline cubic boron nitride (PCBN); however, the heat and stress associated with the process has significantly limited tool life in previous studies. Using a modified liquid-cooled tool holder often deployed for high temperature friction stir welding, improvements were made in cooling systems of a MELD L-3, 3-axis, discrete feed AFSD machine. Measurements of the cooling changes were quantified to understand the magnitude of the changes on cooling the tool, spindle and the print deck. Furthermore, the addition of the liquid-cooled tool holder enabled the cooling system to undergo additional changes that allowed greater flow of cooling water, which further enabled long-term printing of these high melting temperature materials, both from a tool life and machine perspective. A detailed layout of the tool-holder integration, novel PCBN tooling, and printing of 316L stainless steel is presented as a means of quantifying and demonstrating the value of the machine and tool updates.

Alloy Prototyping in Additive Manufacturing Using the Flexibility of Ultrasonic Atomization

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Advances in additive manufacturing (AM) have highlighted the growing need for a wider range of metal alloys in powder form. Traditional atomization techniques, such as gas, plasma, and centrifugal methods, though capable of producing high-purity spherical powders, are limited by high material input requirements, expensive equipment, and compatibility with a narrow range of materials. This creates a bottleneck in material diversity, particularly when small quantities are required for prototyping, research, or unit manufacturing.

Ultrasonic atomization offers a compelling solution by addressing these limitations, enabling the production of tailored powders with minimal material input. Unlike large-scale methods, ultrasonic atomization is particularly suitable for labo-

ratory-scale production, allowing for rapid validation of novel alloy compositions, phase structures, and mechanical properties. A plasma processing module with a crucible-free process minimizes contamination risks, making it ideal for handling materials such as titanium, nickel, and refractory materials commonly used in aerospace applications. An induction melting module for Mg and Al can be used to precisely control the temperature when processing low melting point materials to minimize the risk of evaporation.

This presentation will explore ultrasonic atomization in a series of case studies with custom Mg, Al, Ti, and HEA alloys as a versatile and cost-effective alternative, showcasing its capability to produce small batches of reactive and exotic materials for 3D printing, and other advanced manufacturing techniques. By overcoming the material and cost limitations of conventional methods, ultrasonic atomization enables researchers and manufacturers to expedite alloy development and explore new material possibilities in a more accessible, scalable manner.

Break Through in Metallic Properties by Additive Manufacturing

Dr. Youping Gao, Castheon Inc, Thousand Oaks, California, USA

Contrast to traditional bulk metal manufacturing process, laser powder bed fusion additive manufacturing (LPBF-AM) is different in many ways.

Although, principally, LPBF follows welding processes, which means epitaxial grain growth bypassing nucleation followed by competitive grain growth and elimination. However, boundary conditions of LPBF-AM are hugely different from typical welding, which created this micro-scale grain optimization. As a result, LPBF-AM can produce very unique and superior material properties by forming supersaturated solid solutions in the engineering final shapes without being quenched, and by introducing strengthening mechanisms without altering the alloy compositions that do not exist in the bulk metal manufacturing process. Alloys in two different categories: nickel-base superalloy and niobium-base refractory alloy, are being investigated in this work. Each exhibited significant superior properties that their wrought equivalents couldn't come close. For H230, a high tungsten (14%) solid solutions strengthened alloy, in LPBF-AM was enhanced by carbide dispersion strengthening where stable, nanoparticles of WC were dispersively produced. For Nb C103, nano-sized HfO was introduced dispersively. With these strengthening mechanisms in the AM structure, breakthrough materials properties were achieved.

Session: Composite Materials and Structures

Hydroxy Functional Co-Curable Polyurethane Films for Composite Surfacing

Mr. Ron Fattal, Films, AkzoNobel, Waukegan, California, USA

Most current surfacing films are based on epoxy-amine chemistry, which has known disadvantages including low UV resistance, limited shelf life requiring cold storage, and high hardness post-curing that requires aggressive sanding to achieve proper adhesion. The market has asked for a solution devoid of the above-mentioned disadvantages. The solution presented is a thermally curable multilayer film to be used as an in-mold composite surfacing film, wherein the surfacing film layer comprises an OH-functional polyurethane and a thermally activatable curing agent, which can react with the OH groups at a temperature higher than 120 °C. The surfacing film can further comprise optional layers such as an adjustable tack layer and a reinforcement layer to aid in the handling of the material and layup in composite tooling. This allows for customization of the solution to meet the needs of the production part and process, including for automated tape layup processing. The advantages of the composite surfacing film are the elimination of typical surface defects (e.g., pits, cracks, pinholes) that can occur in the composite molding process by providing uniform film thickness and consistent appearance direct from the tool. Functionally, it can also serve as an in-mold primer providing an integrated layer of outstanding UV protection for the underlying composite. In addition, as a urethane the cured film can also act as a co-cured assembly top coat, ready to receive a finished decorative top coat with minimal activation required. Manufacturing steps that can be eliminated using this type of film include surface filling, curing, sanding and priming. These eliminated steps can save many hours in labor and hangar time for large exterior composite surfaces. VOC and hazardous material waste streams can also be reduced or eliminated in the painting process.

Monitoring Damage Development in Laminated Composites Using Acoustic Emission During High Cyclic Shear Loading

Dr. Hamza Segnidi, University of Hassan II, Casablanca, Ben M'Sick, Morocco

Although research into composites with long fibers is progressing rapidly, specific studies are still needed before their industrial adoption for structural applications. The durability and damage tolerance of these materials, crucial to their fatigue life, depend on an understanding of fatigue damage mechanisms, particularly delamination. While Mode I delamination has been widely studied, little research exists on Mode II without artificial defects. In this study, acoustic emission (AE) was used to monitor damage in a glass fiber/epoxy laminate composite subjected to cyclic interlaminar shear loading at load ratios, $R = -1$ and 0.1 on virgin DCB specimens. EA parameters, such as count rates and event distribution, served as indicators for damage growth and quantification of accumulated damage levels. EA proved effective in predicting the stress corresponding to mode II delamination in real time. S-N curves constructed from EA signals show three distinct stages: damage initiation, damage growth and delamination. Optical and electronic microscopy analysis was used to interpret the mechanisms leading to mode II delamination.

Strength Prediction for Composite Parts Utilizing the Material Modeling Approach

Ms. Amanda N Baranowski, Mr. Seth A Yakel, Ms. Cosette A Geesey, Ms. Catherine M Parra, and Dr. Mahesh Chengalva; BCA Product Development, Boeing, Everett, Washington, USA

The aerospace industry is increasingly using composites for structural applications. The 787 aircraft, for example, makes extensive utilization of composite materials for the primary structure. This ever-increasing consumption of composite materials in aerospace has caused a corresponding increase in physical testing to ensure parts have sufficient strength. However, extensive physical testing can be very expensive and contribute significantly to the overall cost of a new airplane program.

The ability to predict strength of composite parts and structures provides a significant competitive advantage. Not only can expensive physical tests be minimized but the vast design space of potential composite configurations can be explored far beyond what physical testing can achieve.

To enable this predictive capability, composite simulation methods have been developed at the Boeing Company that employ the material modeling approach. In this approach, material properties that can be obtained from simple uniaxial tests are generalized for three-dimensional application using the principles of continuum mechanics. Algorithms for failure initiation and propagation are encapsulated into source code ("material subroutines") that can be interfaced with commercial finite element software such as ABAQUS. Once this is completed, stress analysts can then utilize the modeling capabilities of ABAQUS together with customized material subroutines to predict the strength of any type of composite structure in a highly generalized manner.

The presentation will include details of these methods as well as their applications to new composite material systems under development, with applications ranging from coupons to bolted joint assemblies.

Session: High Temperature and Gas Turbine Materials I

Novel Cr-Si Slurry Coatings for High-Temperature Materials

Mr. Michael Kerbstadt, Dr. Emma White, and Dr. Mathias Galetz; DECHEMA-Forschungsinstitut, Frankfurt am Main, Germany

TiAl- and Ni-base superalloys are commonly used in aerospace engines due to their outstanding high-temperature strength and creep properties. To also ensure sufficient oxidation and corrosion resistance, protective coatings are commonly applied.

Within the temperature range of 650–950 °C, where oxidation and Na₂SO₄-induced hot corrosion occurs, Cr-base coatings are advantageous. Cr-base diffusion coatings are applied by pack cementation, where the components are usually fully embedded into a powder mixture which is energy- and labor-intensive. Slurry-based coatings are significantly more economical and standard for aluminization. Recently, novel Cr-Si slurry coatings, applied by spray deposition, have been successfully developed and demonstrated at the industrial scale. Here, the TiAl alloy GE 48-8-7 and the Ni-base superalloy Rene 80 were coated. During the oxidation exposures carried out up to 900 °C, the Cr/Si-coatings showed a significantly increased oxidation resistance and correspondingly lower weight gains compared to uncoated and Cr-pack cementation coated material. This can be attributed to a highly protective multi-oxide scale consisting of an outer Cr₂O₃ and slow-growing SiO₂. Consequently, the oxygen partial pressure can be effectively reduced through the scales, and a dense Al₂O₃ subscale forms underneath the outer coating instead of detrimental internal oxidation of Al. Hot corrosion resistance was tested by the deposition of 4 mg/cm² Na₂SO₄ salt and following exposure at 700 °C and 900 °C for 300 hours in a gas mixture of synthetic air containing 0.1 % SO₂. Compared to the uncoated pack cemented references, the Cr-Si coatings showed higher corrosion resistance.

Besides their superior corrosion resistance and longer part lifetimes through improved hot corrosion resistance, this sustainable slurry process offers several advantages over the pack cementation process: reduced waste, local recoating for repairs, avoidance of hazardous substances such as halide activators.

Investigating the Influence of Calcium Chloride on the Nitridation Behavior of Silicon Powder

Mr. Ahsan Ali, National University of Sciences and Technology, Islamabad, Pakistan

High-quality α -Si₃N₄ has been produced by the direct gas nitridation process with the CaCl₂ salt additive in nitrogen at 1400 °C. Present work explores the effect of CaCl₂ as an additive to isolate the α -phase of Si₃N₄ and obtain high conversion ratios of Si to Si₃N₄ at a cost-effective method. The x-ray diffraction results show that the addition of CaCl₂ as an additive promotes the formation of α -phase Si₃N₄ and enhances the reaction kinetics for the formation of α -Si₃N₄ instead of β -Si₃N₄. SEM analysis shows that needle morphology associated with β -Si₃N₄ is reduced with the addition of CaCl₂ as an additive. These effects increase by increasing the CaCl₂ concentration. The optimal results were obtained by adding 7 weight percent CaCl₂ resulting in 96% α -phase formation for Si₃N₄. The dissociation of CaCl₂ and the enhancing effect of elemental Ca on the formation of α -Si₃N₄ and the overall reaction-enhancing effect of halogen salts are suggested to be the cause of this trend. This work offers a new approach, using CaCl₂ salt additive as a catalyst, to produce high-quality Si₃N₄ powders with improved sintering behavior at a lower cost.

Benefits of Multichamber Vacuum Heat Treatment with High-Pressure Gas and Oil Quenching

Mr. Thomas Hart, SECO/VACUUM, Meadville, Pennsylvania, USA

Traditional heat treatment in an atmosphere type furnace presents challenges for aerospace grade material processing due to the presence of oxygen in the furnace environment during heating and quenching. These process challenges are overcome by the use of vacuum heat treatment since oxygen is removed from the furnace with vacuum pumps before heating the material takes place. Traditional single-chamber vacuum furnaces are an excellent choice when selecting a furnace for sensitive aerospace grade material heat treatment; however, they have their limitations when referring to their quenching speed/power. Single-cham-

ber vacuum furnaces require not only the components and work holding to be quenched, they also require the internal hot zone to be cooled in addition to the product. Multichamber vacuum furnaces with separate quenching chambers do have the same restrictions as a single-chamber furnace regarding quenching. The dedicated quenching chamber allows a heated charge to be transferred from the heating chamber to the quenching chamber and quenched by itself while the heating chamber can remain at temperature. Providing a dedicated quenching chamber will allow for much faster quenching rates that are not achievable in a single-chamber design. An additional benefit to a multichamber vacuum furnace is that it can be equipped with an oil quenching chamber, a high-pressure gas quenching chamber, and in some cases can be equipped with both. Other benefits to multichamber vacuum furnaces include lower process costs, higher productivity, flexibility in its configuration, among many others. Processes that a multichamber vacuum furnace include low-pressure carburizing, through hardening, annealing, and brazing to name a few.

Influence of Hot Deformation Parameters on the Tensile Properties of VDM Alloy 780

Dr. Masood Hafez Haghghat¹, Dr. Bodo Gehrman¹, Dr. Helena Alves¹, and **Bill MacDonald**²; ¹VDM Metals International GmbH, Altena, Germany; ²VDM Metals USA, LLC, Florham Park, New Jersey, USA

Nickel-base superalloys are prominent candidates for aerospace applications to be employed under demanding conditions. Emerging new technologies to improve engine efficiency and reduce environmental footprints require alloys that can withstand severe conditions and higher temperatures. VDM Alloy 780 offers a diversity of properties, namely microstructure uniformity, high oxidation resistance, and good mechanical properties up to 700 °C as well as weldability and good hot workability, making it a suitable candidate for aerospace applications. Depending on the application, grain size following forging process should be controlled to meet the required mechanical properties and operational lifetime. Grain size and precipitation of γ and η/δ phases during and following hot deformation is the direct consequence of the recrystallization, grain growth and precipitation kinetics. In this work, the influence of forging temperature and heat treatment on the microstructure and tensile properties are studied. Two different forging temperatures (950 and 1050 °C) are used to generate microstructures in subsolvus and supersolvus domains, respectively, leading to full recrystallization and grain coarsening in supersolvus domain. The subsequent heat treatment helps to achieve a uniform distribution of γ precipitates, at which delta phases only appear to be present to a small extent. This determines the mechanical properties, particularly the tensile strength and elongation at rupture. Tuning the grain size and γ precipitations with a unique processing route could improve the mechanical properties of VDM Alloy 780, making it suitable for high-performance applications.

Session: Modeling and Simulation of Manufacturing Processes

Digital Twins for Accelerated Materials Innovation

Dr. Surya R. Kalidindi, Georgia Institute of Technology, Atlanta, Georgia, USA

This presentation will expound on the challenges involved in the generation of digital twins (DT) as valuable tools for supporting innovation and providing informed decision support for the optimization of material properties and/or performance of advanced heterogeneous material systems. This presentation will describe the foundational AI/ML (artificial intelligence/machine learning) concepts and frameworks needed to formulate and continuously update the DT of a selected material system. The central challenge comes from the need to establish reliable models for predicting the effective (macroscale) functional response of the heterogeneous material system, which is expected to exhibit highly complex, stochastic, nonlinear behavior. This task demands a rigorous statistical treatment (i.e., uncertainty reduction, quantification and propagation through a network of human-interpretable models) and fusion of insights extracted from inherently incomplete (i.e., limited available information), uncertain, and disparate (due to diverse sources of data gathered at different times and fidelities, such as physical experiments, nu-

merical simulations, and domain expertise) data used in calibrating the multiscale material model. This presentation will illustrate with examples how a suitably designed Bayesian framework combined with emergent AI/ML toolsets can uniquely address this challenge.

Accelerating Material Development with Computational Insights from FLOW-3D Additive Manufacturing

Mrs. Allyce Jackman and **Garrett Clyma**, Flow Science Inc.,
Santa Fe, New Mexico, USA

Finding process windows for new materials is costly and time consuming, especially for aerospace applications, where availability of material for testing is often limited by supply chains. Model-based qualification for material development can reduce waste and provide deeper insights into the process dynamics allowing for better control of the final material properties. Physics-based models of melt pool dynamics and solidification give critical information on defect formation, thermal gradients, and cooling rates which support experimental data and reduce trial runs.

FLOW-3D AM is a computational fluid dynamics (CFD) software developed by material scientists and computational engineers to accurately predict thermal-fluid behavior of metals during melting and solidification in laser-based processing. This presentation will detail how additive manufacturing simulations using **FLOW-3D AM** are supporting parameter development to bring new materials to market faster while saving on capital costs. Case studies will include examples of printing graded materials for enhanced performance as well as recycled material with impurities.

Digital Forgings: Application of ICME and Digital Twins for the Development of Aerospace Forgings

Mr. Thomas Witulski and Mrs. Angela Quadfasel, M&P Development,
Meinerzhagen, Germany

The size and geometric complexity of forgings for the aerospace industry require a great deal of effort in the design of the forging and the development of the optimum production route in order to meet the required property profile of the finished component. The use of integrated computational materials engineering (ICME) and the development of digital twins for these forgings makes it possible not only to reduce development times and costs, but also to design forging-optimized finished parts, which can then contribute to a reduction in weight and costs. Using the example of an integral die forging made of the aluminum alloy 7010 and an engine disk made of the superalloy U720Li, process chain simulations were carried out and compared with real results. The advantages of the combined use of ICME and digital twins for property prediction will be presented.

Advancing Precision Welding Through Computational Modeling with FLOW-3D Weld

Mrs. Allyce Jackman, Flow Science Inc., Santa Fe, New Mexico, USA

Producing high-strength, leak-proof welds is critical for aerospace manufacturing where flight safety is the first priority. Hermetic seals are often needed to protect sensitive components and require precise heat delivery and uniform fusion. Joining dissimilar materials such as Ti64 to IN718 for jet engine components is challenging due to different melting temperatures and thermal expansion. Simulation of laser welding that accounts for melt pool dynamics, vaporization, and solidification provides the information needed to understand how process parameters affect weld quality enabling process optimization.

FLOW-3D WELD is a computational fluid dynamics (CFD) software used to predict complex behavior during laser melting of metallic alloys. This presentation will discuss applications in which CFD simulations have been used to design weld schedules and eliminate defects in welded joints that use nickel, copper, titanium, and steel alloys.

Artificial Intelligence and Simulation-Based Optimization of Turbine Blade Manufacturing

J Jakumeit¹, Y Bami², T Bähr¹, G Zheng¹, R Laqua¹, S Chatterjee¹, C Nicolae¹ and J Schievenbusch¹; ¹Access e.V., Alabama, USA; ²Access e.V., Wisconsin, USA

Microporosity in investment castings is difficult to avoid and limits the mechanical properties and fatigue behavior of critical parts such as turbine blades. Its presence can lead to increased rejection rates, reduced component lifespans, and greater inspection requirements during operation. Therefore, a reduction in microporosity can have a significant impact on the environmental performance, safety, and durability of investment castings.

Traditional methods to optimize the casting process to minimize microporosity through experimental trials are both time-consuming and expensive. Numerical simulations are increasingly used to accelerate the development process. However, the prolonged simulation times – often spanning several hours – severely restrict the number of parameter configurations that can be affordably explored for microporosity assessment, thereby limiting their utility in optimization loops. To address these limitations, artificial intelligence (AI) offers a promising alternative through the introduction of well-trained machine learning (ML) models that can rapidly estimate the effects of changes in geometric or process parameters on microporosity. However, due to the high cost and time demand of casting trials, sufficient experimental data is rarely available to train ML models with the necessary predictive accuracy. In this contribution, we show that simulation-generated data can be used to effectively overcome this bottle neck by providing the datasets needed to train ML-models.

In the optimization of a complex setup involving 18 test bars, numerous rapid, small-scale simulations of critical component regions were used to generate training data. These simulations enabled the training of an ML model capable of quantifying microporosity in cast parts as a function of design and process parameters. The resulting ML model was employed to guide engineers in designing gating systems and selecting process parameters that minimize microporosity. The integration of this ML-driven approach into the casting development process significantly increased efficiency, enabling optimal configurations with minimal dependence on costly, time-intensive trials.

Keywords: microporosity prediction, process digitalization, process simulation, artificial intelligence, machine learning, process design, process optimization

Session: University of British Columbia and The German Aerospace Center Accelerated Sustainable Materials Design II

In-Situ Defect Detection in Electron Beam Powder-Bed Fusion via Surface Height Reconstruction from Backscattered Electron Signals

Mr. Meet Upadhyay, University of British Columbia, Vancouver,
British Columbia, Canada

In-situ defect detection during electron beam powder-bed fusion (EB-PBF) remains challenging, particularly with regard to surface height measurement. Traditional surface height measurement techniques are typically conducted post-process, limiting their potential for real-time quality control. Prior research has attempted to leverage backscattered electron (BSE) signals, which are less affected by environmental factors than signals to generate surface height maps in situ. Here, we present results applying this method to EB-PBF samples, examining measurement challenges and identifying sources of systematic error that stem from various process parameters. The goal is to establish a robust in-situ defect detection system for EB-PBF by developing a correlation between BSE signals and surface topography. This will advance the capability of the process to provide real-time feedback on surface quality, facilitating early detection and correction of defects.

Laser Powder Bed Fusion of Titanium Aluminide Ti48-2-2: Manufacturing and Testing of Highly Loaded Compressor Wheels

Dr. Jan Haubrich¹, Dr. Joachim Gussone¹, Prof. Guillermo Requena¹, Mr. Ralf Heber², Dr. Holger Gödecke², A. Stark³, and Dr. Norbert Schell³;
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The laser-based metal powder bed fusion process (PBF-LB/M) offers significant technological advantages in the aerospace sector for the production of complex and integrated parts, e.g., internally-cooled double-wall turbine blades, regeneratively-cooled rocket engines, or compressor wheels that are commonly difficult to manufacture. Especially for aeronautic gas turbine or compressor applications, high-temperature materials with high-specific strength such as titanium aluminides (TiAl) are of major interest.

During the last years we investigated the PBF-LB/M processing, heat treatments, and phase transformations of different titanium aluminides including the b-stabilized TNM-B1 (Ti-43.5Al-4Nb-1.0Mo-0.1B) and TNB-V4 (Ti-44.5Al-6.25Nb-0.8Mo-0.1B) γ -TiAl or the orthorhombic Ti-22Al-25Nb. Generally, PBF-LB/M of titanium aluminides requires high preheating temperatures of the build space in order to tackle the high brittle-to-ductile transition temperatures of these intermetallics. In this work, we developed a high-temperature laser powder bed fusion process for γ -TiAl Ti48-2-2 (Ti-48Al-2Cr-2Nb) and applied it to manufacturing and testing of light-weight compressor wheels in order to study the advantages and draw-backs of the high-temperature PBF-LB/M approach for such applications. Challenges related to the required high preheat temperatures, the microstructure formation, phase compositions, and phase conversions under different processing and postprocessing conditions were studied with a variety of methods, including synchrotron in-situ high energy x-ray diffraction with the desired material subsequently adjusted. Chemical problems such as minimizing Al evaporation as well as oxygen pick-up due to traces of residual gases or humidity were investigated and addressed. A manufacturing strategy for thin-walled structures and overhanging compressor blades without supports causing high post-processing efforts or deteriorating surface qualities was developed and put to use for manufacturing load- and weight-optimized compressor wheels. The build components were characterized using geometric inspection and computer-tomographic analysis. The achieved material properties and the part design were successfully validated in spin tests, highlighting the technical feasibility of using high-temperature PBF-LB/M for such demanding applications.

Incorporating Nonlinear Effects in Fast Semi-Analytical Thermal Modeling of Powder-Bed Fusion

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The usefulness of semi-analytical thermal models for predicting the connection between process, microstructure, and properties in powder-bed fusion has been well illustrated in recent years. Such an approach provides predictions that are orders of magnitude more computationally efficient than numerical approaches. However, the opportunity to make predictions that span several orders of magnitude in space and time comes at the cost of significant simplifications, limiting fully quantitative predictions without empirical calibration. This approach relies on the solution to a linear problem meaning that first order nonlinear effects induced by e.g., the temperature dependence of material properties and surface boundary conditions, are not incorporated. Here, we revisit these limitations and highlight ways that temperature varying material properties and radiative heat loss from the melt pool can be systematically accounted for without prior calibration. These corrections, made with an eye to minimizing additional computational overhead, bring the technique's predictive capability much closer to that of higher fidelity thermal simulations without a significant computational cost. Quantitative comparisons to experiments are used to illustrate the important impact of including such corrections.

Session: Additive Manufacturing IV

Utilizing Computational Materials Modeling and Big Data to Develop Printable High Gamma Prime Superalloys for Additive Manufacturing

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Metal-based additive manufacturing offers potential to disrupt the manufacturing process across multiple industries. However, the vast majority of modern alloys are incompatible with the complex thermal histories of additive manufacturing. For example, the high gamma-prime forming nickel-base superalloys are of considerable commercial interest owing to their properties; however, their gamma-prime content renders them nonweldable and prone to cracking during additive manufacturing. Computational materials modeling and big data analytics are becoming an increasingly valuable tool for developing new alloys for additive manufacturing. This work reports the use of such tools toward the design of a high gamma-prime superalloy with reduced cracking susceptibility while maintaining similar hardness to CM247. Experimental fabrication and characterization of the candidate alloys are performed. Results show the candidate alloys have improved printability, up to 41 times reduction in crack density (mm/mm²) compared with CM247, and good agreement with the modeled predictions.

Properties of AA7075 Produced with Additive Friction Stir Deposition: Graphite Free

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Recent improvements in additive friction stir deposition (AFSD) have enabled printing of 7xxx series aluminum alloys without the need for graphite lubrication. Modifications of tool geometries and materials in addition to updated processing parameters have improved deposition rates while printing materials that can achieve T7 properties of forgings. A discussion of the tooling, machine parameters and heat-treatments that enable these properties are presented. Characterization of the as-deposited and heat-treated materials are evaluated by means of static and dynamic mechanical testing. Additionally, macro and microscopic characterization of layers, interfaces, and fracture surfaces are presented to substantiate the results of mechanical testing. Comparisons between properties of builds made from discrete feed systems and continuous feed systems are presented as a means of demonstrating the robust nature of the process.

Novel True 3D Printing Method for Serial Production of Highly Performant Components up to 100,000 Pounds

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As the first true 3D metal additive manufacturing (MAM) technology available for metals, the MAM from MetalPrint3D-XXL offers outstanding speed, and consequently low cost. Printing holograms in over 6 ft by 3 ft in 1-inch layers at a time. It is a volumetric printing system as opposed to linear (1D) printing systems like DMLS or restricted surface (2D) printing systems like binder jetting, enabling printing speeds of tons per hour as opposed to the current pounds per hour. Currently, a precision of +/- 0.1% can be attained by matching or improving gravity casting, HPDC, or stamping. This technology is suitable for serial production up to 100,000 components/year. Since it does not require any kind of supporting structures, there is practically no restriction in the shape of internal features that can be attained. Currently, components up to 8 ft by 6 ft by 3 ft can be produced with a weight up to 100,000 lb in less than three full days at the cost level of gravity casting. With an order of magnitude, fewer energy required for Kg printed than DMLS, and a yield surpassing 96%, the sustainability is outstanding. In terms of performance, the technology presents exceptional control on interstitial levels and dislocation densities (as an example: %O and %N levels below 2ppm and dislocation levels even above 10¹⁵ 1/cm² can be attained in 4340 alloy). While printability of Li, Mg, Al, Ti, Fe, Cu, Ni, Co, Nb, Mo, W, ... alloys and even hard metal or CERMET (provided at least a 10% metal is present) has been demonstrated, optimization work has only been undertaken for Fe, Cu, Ni and Al alloys so far. Typical properties reached for 6061 aluminum are 340 MPa tensile strength with 270 MPa yield and 15% elongation. This MAM should help in the industrial uptake of Additive Manufacturing.

Increasing the Ductility of an Al-Cu-TiB₂ Composite by Additive Manufacturing

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To overcome the strength-ductility trade-off, Al2618 alloy that is reinforced with in-situ TiB₂ particles is processed by additive manufacturing (AM), specifically laser powder bed fusion (LPBF), with the assistance of 0.1%Sc. While a ductility of 7% is maintained, the yield strength and ultimate tensile strength are increased by 88 and 59% to 370 and 450 MPa, respectively. The improvement is achieved through an enhanced grain refinement of the aluminum matrix and the uniform dispersion of the TiB₂ reinforcing particles. The laser beam modifies the reinforcing particles and promotes the nucleation of aluminum grains in the melt pool under a high cooling rate that restricts the growth of the aluminum grains. Meanwhile, the comparable sizes of the matrix grains and the reinforcing particles block the motion of dislocations effectively, strengthening the AM products.

Additive Manufacturing Aluminum Alloy Matrix Composites without a Strength-Ductility Trade-Off

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Additive manufacturing (AM) offers an effective means of overcoming the strength-ductility trade-off of aluminum alloy matrix composites that are reinforced with in-situ TiB₂ and TiC particles. Powders of the composites are produced by gas atomization in the range of 16–65 μm for a good ability of printing. Laser powder bed fusion (LPBF) alters the reinforcing particles, and combined with a high cooling rate, promotes nucleation of aluminum grains in the melt pool, resulting in refined grains of both the matrix and the reinforcing particles. This process achieves a homogeneous dispersion of TiB₂ and TiC particles, increasing their ability in nucleating aluminum grains, which are refined to approximately 2 μm. As a result, the AM composites demonstrate superior toughness over their rolled matrices, respectively. Refining the particles and aluminum grains leads to 40% and 87% increases in ultimate tensile strength (UTS) and yield strength (YS), respectively, while maintaining the same elongation of 16% of AM Al-Mg products that are reinforced with TiC particles. Meanwhile, AM Al-Cu composites with TiB₂ particles also show significant increases, 59% and 88% increases in UTS and YS, respectively.

Flexural Behavior of Ti-6Al-4V Triply Periodic Minimal Surface Lattice Sandwich Structure Produced by Electron Beam Powder Bed Fusion

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Metallic sandwich structures are highly valued in the aerospace industry due to their high specific flexural strength and temperature resistance. However, traditional manufacturing processes for metallic joining of face sheets to a core structure (e.g., brazing) severely limit the final geometry that can be economically produced, and the structures are fraught with defects that limit the structural performance and durability. This presentation demonstrates the capability of electron beam powder bed fusion (EB-PBF) additive manufacturing to produce monolithic Ti-6Al-4V sandwich structures containing novel topology optimized core geometries. In this investigation, a triply periodic minimal surface (TPMS) Diamond lattice was applied to a sandwich core, and then the thickness was functionally graded using two different optimization strategies in order to satisfy a 4-point bend load case: 1) a compliance (density-based) minimization strategy, and 2) a Von Mises stress-based minimization strategy. The flexural behavior of the graded sandwich structures was compared with a uniform Diamond lattice topology in static 4-point bend experiments according to standard test method ASTM C393 for short beam core shear. Empirical data showed the density-graded core achieved a 19% load increase over the uniform core, while the stress-graded core further enhanced load capacity by 50% and exhibited a higher resistance to damage. Post-fracture analysis was performed by scanning electron microscopy and optical microstructural analysis where these revealed a superior monolithic sandwich structure, but with orthotropic properties relative to the build direction. This work is important to any materials and process engineer or designer to consider for future applications of additive metal sandwich structures.

Martensitic Stainless Steel with Precipitation Hardening and High Mechanical Strength for Additive Manufacturing.

Dr. Tiphaine Giroud¹, Dr. Solange Vivès², Mr. Loïc Michel¹, Ms. Alicia Nigon¹, and Dr. Laury-Hann Brassart¹; ¹Aubert & Duval, Les Ancizes-Comps, France; ²Aubert & Duval, Paris, France

The combination of additive manufacturing (AM) design freedom and a new generation of high-performance metal powders offers a great opportunity to achieve an industrial leap regarding performance, weight reduction, decarbonization, cost, etc. To support those challenges, Aubert & Duval is evaluating the AM powder version of MLX[®]19 grade that has originally been developed for forged mechanical parts.

The MLX[®]19 grade is a precipitation hardening stainless steel combining ultrahigh tensile strength and good corrosion resistance. This stainless steel has been designed for severe service conditions with targeted properties similar to 300M performance required for structural aerospace components: ultimate tensile strength range between 1800 and 1950 MPa, toughness (KIC) from 50 to 80 MPa.m^{1/2}. In this study, MLX[®]19 powder produced by gas atomization was processed by laser powder bed fusion (LPBF). AM processes result in specific nonequilibrium microstructures leading to original properties when compared to conventional processes such as forging. This work highlights the process-microstructure-performance parameters that have been optimized to improve mechanical properties. Thermal analysis, DRX measurement and SEM observations were performed to optimize heat treatments and understand their effect on hardening phases precipitation and mechanical properties. Based on the acquired knowledge, future work for the alloy development is discussed.

Session: Advances in Coatings and Surface Modification II

Characteristics of the Porous Anodic Oxide Film Formed on Aerospace Txxx Aluminum Alloy

Yudie Yuan, Y. Lin, J. Qin, F. Liang, J. Wu, Z. Wang, and G. Tian; Novelis Zhenjiang, Jiangsu, China

The Txxx series aluminum alloys are some of the most commonly used alloys for aerospace applications, they contain zinc, magnesium, and copper as the main alloying elements for the best specific mechanical properties, but also with the highest susceptibility to corrosion. Therefore, an effective corrosion protection system is required to fulfill structural integrity requirements for the product's entire lifetime at least three decades typically. Anodizing, i.e. the formation of an anodic oxide film with good barrier properties and a porous surface, has been widely adopted as the critical scheme in a typical multilayered aerospace corrosion protection system. In the present study, the properties of anodic oxide layers formed on 7055 T7951 plate at different gauges in chromic acid and tartaric-sulfuric acid were investigated, respectively. The effects of chemistry and crystallographic texture on optical appearance of the anodized 7055 plates were especially highlighted.

Composite Laser Ablation Surface Preparation to Replace Manual Processes in Aerospace Applications

Mr. Adam Hicks, Air Force Research Laboratory, Wright-Patterson Air Force Base, Ohio, USA

Throughout the past several years, the University of Dayton Research Institute (UDRI) and the U.S. Air Force have been developing and advancing the composite laser ablation for surface preparation (CLASP) process. CLASP is an athermal laser-based surface preparation method developed for high precision and rate. Over the past 18 months, UDRI has been working to transition the CLASP process into the world's only fully automated, industrial robot-driven femtosecond laser system.

UDRI has collected a body of mechanical, thermal, and laser quality data which will be covered. Thermal testing was performed to collect a robust data set of calibrated IR thermal camera measured surface temperatures during the process as a function of laser parameters. Mechanical testing data includes flatwise tension (ASTM D7291) and notched lap shear (ASTM D3165) for a variety of laser parame-

ters, and peel ply configurations. Data was collected to measure laser beam quality out of the robotically integrated system during motion to ensure process stability. The UDRI and Air Force team quantifies the optimal laser processing window for CLASP, the stability of the robotically integrated system within that window, and the mechanical properties that can be expected from the system.

Patterned Peening for Strength and Ductility Optimization

Dr. Mark Atwater, Liberty University, Lynchburg, Virginia, USA

Peening operations are vital to many applications and are continually diversifying. Each method has unique advantages and limitations, but one disadvantage common among traditional, impact-mediated peening operations is the randomized nature of impacts in terms of energy, trajectory, and position. Because of this randomness, these processes can only be controlled by setting global parameters, such as total surface coverage, air pressure, stand-off distance, shot size, and geometry, etc. This allows for practical application, but it limits the fundamental understanding and optimization of these peening processes. The work presented here extends the utility of a high-energy peening process known as surface mechanical attrition treatment (SMAT), which uses relatively large diameter shot (e.g., 3 mm spheres or larger) and produces a deeper residual stress profile and enhanced surface grain refinement in comparison to traditional shot peening. Recent reports on SMAT have indicated that incomplete surface coverage (much less than 100%) can still produce significant increases in strength while losing relatively little ductility. Unfortunately, because of the stochastic nature of these impacts, the distribution of impact energy can be highly nonuniform and results in localized weaknesses. To further study the potential for low-coverage peening, we have developed a position and energy-controlled SMAT process. This allows us to precisely place impacts and measure the energy of each impact. This removes the stochastic limitations in peening, and it allows us to quantitatively study impact effects and apply those principles more broadly. This has already resulted in unique outcomes in strengthening mechanisms, suppressing deformation-induced phase transformations, and outperforming randomized impacts. The processing methods, performance results (including fatigue), and the potential for commercial application will be discussed.

Session: High Temperature and Gas Turbine Materials II and Residual Stress for AeroSpace Components

Low-Cost Design Validation of Turbine Components Using High-Temperature Steel AISI 422 for Small Gas Turbine Engine

Mr. Nhat-Minh Hoang, Mr. Quoc-Huy Nghiem, Mr. Duy-Lanh Chu, and Mr. Phi-Minh Nguyen; Viettel Aerospace Institute, Hanoi, Vietnam

This study examines the application of stainless steel AISI 422, a high-temperature martensitic stainless steel, as a cost-effective alternative to conventional superalloys, such as Inconel, in gas turbine components. The selection of stainless steel AISI 422 is driven by its economic advantages, machinability, commendable corrosion resistance, and ability to retain high mechanical strength at temperatures up to 650 °C—attributes that are critical during the design validation phase. However, to successfully utilize AISI 422 under the extreme loading conditions typical for gas turbine engines, it is essential to maintain the turbine temperature strictly below 650 °C. Therefore, effective cooling and stress control of the turbine are paramount. This study emphasizes that comprehensive simulations are vital to evaluate the material's viability. The finite element method (FEM) and computational fluid dynamics (CFD) were employed to rigorously assess operating stresses and optimize the cooling system, ensuring that both thermal and mechanical stresses remained significantly below acceptable thresholds. By maintaining operational conditions at 80% of the design rotating speed and implementing an effective cooling strategy, the turbine rotor constructed from stainless steel AISI 422 successfully underwent ground testing at 80% of the design rotating speed, achieving a maximum operating temperature of 635 °C and validating the material's performance under these conditions. This approach not only demon-

strated substantial cost savings but also ensured compliance with stringent safety and performance standards, positioning stainless steel AISI 422 as a viable and economically advantageous option for specific gas turbine applications.

Keywords: high-temperature steel, gas turbine engine, turbine component, super alloy, stainless steel AISI 422

Influence of Long-Term Thermal Ageing on Mechanical Properties for In718 and In625

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For structural applications that may be exposed to medium to high temperatures during service, the use of superalloys such as In718 or In625 is a common material choice in aerospace. Justification to extend the aircraft's service-life and the possibility to encounter higher temperatures with future aircraft architectures might lead to particular metallurgical/mechanical evolution of the thermally exposed material. These are valuable reasons to review long-term thermal stability of In718 and In625. Both alloys, widely used over decades, have been extensively studied for jet engine applications (typically for temperatures above 650 °C exposed about 10,000 hours) focusing mainly on static, stress rupture or creep strain testing.

One could notice that intermediate temperature ranges (~600 to 650 °C) for much longer durations (>100,000 hours) have been less investigated, notably due to experimental constraints and lack of industrial emphasis. Next to this, fatigue, crack propagation or fracture toughness properties, which are valuable for structural design, have also been much less addressed. Based on this background, a project has been initiated to study this particular field of application by mechanically characterizing thermally aged materials (including some over three years) to monitor material performance evolution. Metallurgical characterizations have also been performed to try identifying some of the influencing factors impacting the mechanical properties while fractography investigation has been done to identify changes in the failure modes.

Finally, Hollomon & Jaffe (H&J) parameter has been used to attempt to predict the impact of various thermal aging on mechanical properties. Significant differences on the overall material behavior but also among the various mechanical properties have been observed after thermal aging. A parametric law has been proposed to model the evolutions of the studied mechanical properties versus H&J parameters. The accuracy of this law and its limitations will also be discussed.

Session: Tribology and Wear of Aerospace Materials: Low-Cost Manufacturing and Affordable Structures

Gear-Steel: Novel Material for Aircraft and Helicopter Drivetrain Parts

Dr. Gregory Vartanov, Advanced Materials Development Corp., Oakville, Ontario, Canada

Weight reduction of aircraft and helicopter drivetrain parts such as gears, shafts, etc., plays a crucial role in the overall weight reduction. This can be accomplished, among other methods, by utilizing the proposed Grade2 and Grade3 of gear-steel. Grade2 is a deep nitriding steel that is ideal for high precision aircraft and helicopter gears and shafts. The vacuum melted Grade2 is a high strength substitution of the commercial vacuum melted nitriding Nitralloy N VAC steel. After conventional gas-nitriding, Grade2 possesses a case hardness >HV 840, a core hardness >HRC 45, UTS>220 ksi, YS>210 ksi, El>12%, CVN>18 ft-lbs, and K_{IC} >70 ksiVin at r.t. More than 20% increase in UTS of Grade2 compared to Nitralloy N VAC allows to reduce weight by more than 10%, accomplished by reducing the cross-sections thickness of drivetrain parts.

Grade3 is a through hardening super-high-strength steel. After quenching and tempering, the vacuum melted Grade3 possesses a hardness HRC>56, UTS>305 ksi, YS>250 ksi, El>9%, CVN>18 ft-lbs, and K_{IC} >65 ksiVin at r.t. More than 65% increase in UTS of Grade3 compared to Nitralloy N VAC steel allows to reduce weight by more than 25%, accomplished by reducing the cross-sections thickness of drivetrain parts.

The following method of manufacturing of aircraft and helicopter drivetrain parts made from Grade3 is proposed:

- Rough machining of the parts.
- Hardening them by quenching and tempering.
- Finish machining the parts.

Utilizing Grade3 requires additional investment in redesigning drivetrain parts and upgrading the tools; however, the benefits of utilizing Grade3 significantly exceed the expenses of its implementation. Implementation of the Novel material is underway.

The Astonishing Diversity in the World of 2D Materials: Lessons Learned From MXenes and Transition Metal Carbo-Chalcogenides for Solid Lubrication

Prof. Carsten Gachot; Technische Universität Wien, Vienna, Austria

Tribology, the science of friction and wear, is becoming increasingly important as it gains more public attention as an efficient, reliable, and sustainable operation of machine elements. This is relevant for almost all industrial sectors since machines and mechanical systems with moving parts in relative motion are vital for most systems. According to Holmberg and Erdemir, 23% of the world's energy consumption originates from tribological contacts. Lubricants are commonly introduced between the rubbing surfaces, thus minimizing friction and wear. The most common lubricants are petroleum-based mineral oils in liquid form. However, diminishing oil resources, the need for ever-lower frictional losses, and higher demands on the lubricants in terms of resistance against extreme conditions such as high temperatures or low environmental pressures push liquid lubricants to their limits. It is expected that new lubricant technologies will contribute greatly to a reduction of friction and wear, such as the use of new 2D materials coatings in particular MXenes, transition metal carbo-chalcogenides (TMCCs), or black phosphorous (BP). In this talk, examples of new 2D materials coatings will be given and discussed in light of energy savings and sustainability, and their potential impact on aerospace applications.

Influence of WC12Co on the Microstructure and Tribological Performance of High-Velocity Air Fuel Sprayed AlCoCrFeNi High-Entropy Alloy Coating

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The remarkable mechanical and wear properties of thermally sprayed high-entropy alloy (HEA) coatings have opened exciting possibilities for aerospace applications under demanding environments. In this work, equiatomic AlCoCrFeNi HEA and WC12Co-reinforced AlCoCrFeNi HEA composite coatings were fabricated using the high velocity air fuel (HVOF) process. The addition of WC12Co to the HEA matrix significantly increased hardness and yield strength, enhancing the overall performance of the composite coatings. Ex-situ characterization was performed using XRD for phase analysis and SEM-EDS for cross-sectional microscopy. Both HVOF-sprayed coatings exhibited a typical lamellar structure, with phases including bcc + B2 and minor fcc phases. The WC12Co-AlCoCrFeNi composite additionally displayed metal carbide phases, along with variations in porosity and unmelted particles. The dry sliding wear behavior of the coatings was evaluated up to 450 °C using a ball-on-disc tribometer against alumina counter balls. The incorporation of WC12Co within the HEA matrix improved both mechanical and tribological properties, mainly through carbide reinforcement, bcc structure, and grain boundary strengthening. This strategic addition minimized plastic deformation and reduced the true contact area, leading to a lower coefficient of adhesion and enhanced wear resistance. These results emphasize the potential of reinforced HEA coatings as advanced tribological materials for high-temperature applications

Military Steel: Novel Material for Deep Penetrating Bombs

Dr. Gregory Vartanov, Advanced Materials Development Corp., Oakville, Ontario, Canada

Session: The University of British Columbia and The German Aerospace Center Safe and Competitive Composites Aerostructures I

Challenges in Predicting the Energy Absorption of Composite Materials under Axial Crush Loading

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The development of robust numerical approaches, which are capable of capturing the damage and failure mechanisms of materials and structures that are subjected to crash and impact loading, is crucial to support the design and certification of lightweight crash-worthy aircraft components. The significant increase in computational power over the last few years has enabled the use of numerical tools to investigate design optimizations for safety-critical structural applications. In particular, the prediction of the progressive damage and energy absorption of composite materials is a key issue for crash-worthiness of aircraft structures. In this study, we compare and investigate the limitations of three different material models that are based on the general framework of continuum damage mechanics theory, and implemented within the two commercial finite element software packages, ABAQUS and LS-DYNA. Starting with single-element simulations and moving up the structured building block approach for calibration and validation purposes, the material models are applied to the simulation of flat coupon and tube crush tests, which are representative configurations for the two major failure modes during axial crushing of fiber-reinforced polymer composites; namely, splaying and fragmentation. Fundamental modeling concepts such as mesh orientation and mesh size sensitivities as part of the simulation strategy are also considered in this study as they have an impact on the quality and reliability of the simulation results. Finally, modeling guidelines are provided for computationally robust and efficient simulation of axial crushing of composite structures.

Investigation of Crystallization Kinetics of Thermoplastic Composites

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Semicrystalline thermoplastics as a matrix material of fiber-reinforced composites have become increasingly common in the aerospace industry. The crystallization of the polymer matrix heavily influences part quality and performance and is also a common source of internal stress and warping when not accurately predicted. A detailed material model coupled with robust process simulations can help to alleviate uncertainties and produce high-quality parts. In order to understand the crystallization mechanics of the composite material, experimental techniques such as differential scanning calorimetry are used to develop digital material models and determine the influence of thermal gradients and different material parameters on the final degree of crystallization.

In a first study at the DLR, a simple method has been developed for adapting existing material models, developed by the UBC and Convergent Inc., to a new material. Recent works at the DLR, UBC and Convergent showed that the crystallization process is influenced both by the matrix material itself and by the fibers. The fiber volume content and fiber diameter, among other material properties, change the crystallization process and must be considered when creating material models. These influences on the crystallization temperature and rate increase with higher rates of cooling.

Future works will focus on understanding the influences on crystallization and in turn the influence of crystallinity on material parameters even further. Process simulations rely on detailed material models, and understanding all influencing parameters is crucial in predicting material behavior during processing and more firmly establishes processes like automated fiber placement.

Towards Model-Based Continuous Resistance Welding of Carbon Fiber Specimens

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Continuous resistance welding of thermoplastic composites (TPCs) enables the joining of high aspect ratio components, such as fuselage stiffeners. In this process, electrical current is applied locally by a moving end-effector through conductive connectors in contact with an implant at the weld interface. The resulting Joule heating melts the material at the interface, while pressure is applied simultaneously to form a weld. A key challenge in TPC welding is controlling the interface temperature, a critical parameter that cannot be directly measured without thermocouples. This study addresses this challenge by employing a physics-based finite element model to predict unmeasurable parameters like temperature and to determine process control variables, such as welding speed. To validate the approach, the welding end-effector is mounted on a robotic arm, and the model's ability to adapt to changing conditions during the process is tested. The quality of the welds is assessed using C-scan and microscopy techniques. This work demonstrates the potential of using simulation for controlling the continuous welding process and explores its scalability for industrial applications.

Session: Welding and Joining I

Evaluation of Polycrystalline Diamond Materials for Friction Stir Welding Tooling

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Recently, techniques have been developed to fabricate friction stir welding tools using polycrystalline diamond (PCD) as the base material. Methods used to fabricate PCD tools are proprietary to the supplier and are unique due to its high hardness (4500 Vickers). However, it is this high hardness that makes PCD a strong candidate for long-life friction-stir welding (FSW) tools. To achieve appropriate metal flow during FSW, the FSW tools can require fine features on both the tool shoulder and tool pin. With conventional FSW tool materials, e.g., H13 tool steel or MP159, a multiphase alloy, etc., fine features can wear via abrasion resulting in limited FSW tool life and contamination of the weld zone. Conversely, PCD tools offer exceptional abrasion resistance. To date, no quantitative study has been performed to evaluate the potential of PCD for long-life FSW tools. This study documents experimental results that evaluated PCD tool performance both for a large number (100) of initial plunges and for FSW in AA7075 up to 2400 feet.

Ultrahigh Speed Friction Stir Lap Welding of Aluminum Alloys

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Historically friction stir welding has been viewed as a welding process that improves quality at the cost of complicated setups and slower welding speeds. Friction stir lap welding (FSLW) has been shown in literature to be effective at linear speeds up to 1.5m/min, above which a hooking defect begins to deteriorate weld quality. While little investigation has been reported about increasing the linear speed of FSLW, numerous studies have demonstrated that traditional friction stir welding in butt configurations have been successful at speeds up to 6m/min. In order to increase the linear speeds of FSLW, a polycrystalline diamond tool using a multishoulder tool geometry was introduced to eliminate both the hooking defect reported at lower speeds and to enable higher rotational velocities of the tool. This novel approach enabled an order of magnitude increase in welding speed, which was defined as ultrahigh speed FSLW at speeds of 10m/min and higher. Using

Mazak's CNC platform with an integrated friction stir welding controller, an evaluation of welding was completed to demonstrate weld quality at these speeds. Characterization of the welds including both static and dynamic testing was completed to demonstrate that FSLW at 10m/min and faster can be used for assembly without any deleterious influence from this significant increase in productivity.

Multiprincipal Element Alloy Fillers for Brazing Gas Turbine Engine Components at Two Distinct Temperature Ranges

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Brazing is widely employed in the assembly and repair of gas turbine engine components, but existing brazing filler metals with boron and silicon as melting point depressants often fall short in providing adequate ductility, especially at wide gap widths, requiring expensive noble metal fillers based in gold and palladium to be used instead. Emerging multiprincipal element alloy (MPEA) brazing fillers without embrittling melting point depressants can provide excellent ductility at a fraction of the noble metal filler cost. For brazing of FCC base materials such as stainless steels and solid solution nickel alloys, MPEA fillers capable of producing a compatible single-phase fcc microstructure in the resultant joint metal after incorporating material from each substrate are identified. Additionally, in the design of these MPEA fillers, intentional melting temperature selection is critical to maximize compatibility with existing industrial brazing procedures and the thermal exposure limits of base materials.

This work investigates two distinct MPEA filler compositions selected for brazing in disparate temperature ranges: (1) approximately 990 – 1050 °C, and (2) approximately 1170 – 1200 °C. Brazing experiments employed composition (1) on 304 stainless steel and composition (2) on Haynes 214 and 233 alloys. For both compositions, the MPEAs demonstrated complete metallurgical compatibility with their substrate material(s), with accommodation of base material elements and no terminal intermetallic phases in the resultant joint metal regardless of the initial joint clearance. Consistent with this result, lap-shear testing of MPEA-brazed specimens demonstrated no increase in interfacial failure rates with increasing joint clearance up to at least 250 µm (0.010 in). For the Haynes alloy brazes, the influence of the MPEA filler and commercially available AMS 4782 on the distribution of byproduct gamma-prime formation during cooling at two different rates, and its implications on mechanical behavior, were also critically evaluated.

Compositionally Complex Alloy as Brazing Filler Metal for Joining Honeycomb Sealing Systems

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Honeycomb abradable sealing systems have a significant impact on the efficiency of gas turbines. The honeycomb seals are manufactured by brazing a corrugated hexagon metal sheet structure made from nickel-base superalloys onto a carrier plate. Using transient liquid phase bonding processes with filler materials containing boron or silicon as melt-point depressants can introduce brittle phases in the microstructure due to eutectic solidification after an insufficient isothermal hold, leading to limited ductility and potentially compromising the overall mechanical properties and longevity of the brazed components. To address this challenge, a novel MnFeCoNiCu compositionally complex alloy (CCA) filler was implemented, targeting a face-centered cubic phase with no embrittling microconstituents in the braze.

In this study, the reference braze filler alloy selected for comparison to the CCA is the nickel-chromium-silicon filler metal BNI-5 (AMS 4782) on Haynes 214 as the base material. The CCA braze filler metal used in this work has an approximate composition of Mn₃₅Fe₂₀Co₂₀Ni₂₀Cu₂₀ (in at.%). Considering the effects of high-temperature exposure on the microstructure of Haynes 214, the brazing parameters for the CCA filler on this substrate require independent optimization from those employed in prior work. To assist in this optimization, a novel in-situ contact angle measurement system was developed, allowing real-time analysis of the temperature and time-dependent contact angles at high temperatures and in various atmospheres. An analysis of the wetting kinetics of the CCA filler on Haynes 214 substrate was conducted to propose new brazing parameters that allow sufficient time to effectuate wetting while limiting the microstructural evolution of the Haynes 214 base material. Optimal results were achieved with brazing

temperatures between 1140 and 1200 °C, rapid cooling rates exceeding 30°C/min, and a maximum holding time at brazing temperature of 100 minutes, all of which contribute to enhancing the mechanical properties of the composite.

Enabling Friction Stir Process Improvements through Specifications

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As advancements in manufacturing processes develop, the codification of the requirements can potentially lead to delays in implementation for aerospace applications. The AWS D17J committee is adding details for both friction stir spot welding and additive friction stir deposition.

Session: Emerging Materials and Processes I

The Role of HOCUT® 4260 in Overcoming Aerospace Machining Challenges

Mr. Ron Weigel, Quaker Houghton, Shawnee, Kansas, USA

Machining in the aerospace industry presents a unique set of challenges, such as working with advanced alloys, maintaining strict tolerances, and managing significant heat buildup during the cutting process. These factors make precision and tool longevity crucial, while also posing considerable challenges related to surface integrity and productivity. Given these high demands, selecting the right coolant is essential, as it directly impacts machining efficiency, tool life, and part quality. HOCUT® 4260 is a premium semisynthetic coolant suitable for both machining and grinding. It provides extremely clean running emulsion, resulting in reduced drag-out, lower consumption, less waste, and a lower total cost of ownership. This coolant effectively addresses the challenges of machining by providing excellent lubricity, heat dissipation, and stability, even when working with complex aerospace-grade materials such as titanium and high-temperature alloys. Specifically engineered to meet the demanding conditions of aerospace machining, HOCUT® 4260 features a unique formulation that delivers superior cooling and lubrication properties. This helps reduce tool wear and improve overall machining performance. The coolant demonstrates remarkable stability, reducing operational costs and enhancing uptime. HOCUT® 4260 is compatible with all materials used in aerospace manufacturing, ensuring consistency and reliability in meeting stringent quality requirements.

Furthermore, as technology and Industry 4.0 advance, automating fluid management can significantly optimize aerospace machining processes. Automated systems can monitor and adjust coolant concentration, temperature, and flow in real-time, ensuring optimal fluid properties. This enhances machining performance, extends tool life, and reduces downtime associated with manual adjustments and coolant maintenance. When combined with HOCUT® 4260, automated fluid management such as QH FLUID INTELLIGENCE™ provides a seamless and efficient method for maintaining high production standards, reducing overall costs, and achieving the best machining outcomes for aerospace manufacturers.

Manufacturing of Radio Frequency Metasurfaces for Radar Applications

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The moving blades on windfarms cause clutter and, therefore, a reduction in detection capability on primary surveillance radar, and, due to the Doppler shifted returns from rotating turbine blades, can be confused with fast moving aircraft. The requirement for U.K. Security contiguous radar coverage around the U.K. can lead to over 90% of wind farm development proposals being rejected. This is an important issue given the U.K.'s ambition to increase offshore wind electricity generation by greater than 500% by 2030. This work demonstrated a potential solution by applying metasurfaces tuned to the appropriate RF frequency as part of the wind turbine blade manufacturing process, which can significantly reduce the blades RF scattering "footprint" thus lowering the disruption to radar rather than relying on modifications to signal generation hardware at the radar end and/or software filtering.

The two UK Dstl/DESNZ funded projects described here, embarked on the development of novel manufacturing methods for the creation of patterned conductive coatings applied to composite blade structures for radar cross section (RCS) reducing purposes. The techniques involve highly scalable, thermal spraying and laser micromachining processes with the potential to be implemented onto complex shaped composite structures, specifically in this case within the wind turbine blade manufacturing environment.

A section of wind turbine blade was spray coated with metal and laser etched to produce a predefined patterned metasurface, which demonstrated up to a 90% reduction in measured reflectivity, which could realize an RCS reduction of up to 10dB compared to an unpatterned coating across the frequency range of interest. The project demonstrated production of metasurfaces on blade sections, meters in scale, through the use of advanced metrology, offline programming, and simulation of metasurface manufacturing methods to create functional surfaces. Their mechanical performance, in representative service environments, such as salt spray corrosion and rain erosion, was also assessed.

Session: The University of British Columbia and The German Aerospace Center Safe and Competitive Composites Aerostructures II

Towards Tool-Less Thermoplastic Carbon-Fiber Reinforced Polymer Manufacturing Processes Using a Cooperating Robot System

Mr. Matthias Beyrle¹, Mr. Dominik Deden¹, **Dr. Michael Vistein**¹, Mr. Maximilian Janek¹, Dr. Lars Larsen¹, Mr. Julien-Mathieu Audet², Mr. Gabriel Côté², Mr. Yves Fortin², and Bruno Monsarrat²; ¹The German Aerospace Center, Augsburg, Bavaria, Germany; ²National Research Council Canada, Montréal, Quebec, Canada

Fiber-reinforced thermoplastics have gained popularity in the aerospace industry due to their light weight, formability, weldability, chemical resistance, and recyclability. In this paper, we present a production chain consisting of in-situ consolidated automated fiber placement (AFP) and a continuous ultrasonic welding process that enables component manufacturing without complex molds.

The AFP process is an additive manufacturing method for producing carbon-fiber reinforced polymer composites. We introduce a system that allows both AFP and ultrasonic welding to be performed without fixtures. A second robot serves as a counter-holder in both cases. For AFP, an end-effector with a roller was developed to move synchronously with the AFP head, enabling tape deposition for flat or curved free-form surfaces.

For ultrasonic welding, a solid end-effector was designed to act as an anvil. A steel strip is fed over a copper block, and the component is guided between the two end-effectors during the welding process. Our work demonstrates that both AFP and welding processes can be successfully carried out using a dual-robot process without fixtures.

An important technology enabler has been the development of a fast model-based elastic calibration method to characterize the structural behavior of the robots. The method conciliates requirements of minimal invasiveness, for seamless deployment in industrial settings, together with a high degree of coherence with the spectrum of action of the multirobot platform in production. Once calibrated, the kinetostatic models are exploited in a control scheme to correct the deviations of the force-cooperating robots in real-time. This enables the robots to follow their intended trajectories accurately in the case of both processes.

This approach demonstrates the possibility of cost-effective production of complex geometries. The results have successfully demonstrated the feasibility in principle. By eliminating molds, this method reduces production costs and increases flexibility, making it an attractive solution for fiber-reinforced thermoplastics.

Improving Quality Inspection in Automated Fiber Placement: A Data-Efficient, Unsupervised Anomaly Detection Framework

Assef Ghamisi, Todd Charter and Homayoun Najjaran, University of Victoria, Victoria, British Columbia, Canada

Automated fiber placement (AFP) plays a critical role in the production of high-performance composite structures, yet detecting defects in AFP remains a substantial challenge. Current defect detection methods primarily rely on manual inspection, a process that is time-consuming, labor-intensive, and susceptible to human error. Automated systems offer the potential for increased efficiency and consistency, but many existing approaches require large, labeled datasets of defective samples, which are costly and difficult to generate. Additionally, AFP defects vary in size, shape, and severity due to inconsistencies in tow placement, resin distribution, or environmental factors, further complicating automated detection.

To address these challenges, we present a comprehensive framework for automated defect detection that combines unsupervised deep learning with classical computer vision techniques. Our method eliminates the need for large datasets and predefined defect samples by leveraging the inherent symmetry in AFP processes to refine and subdivide the training data. Depth maps of composite parts, captured using optical coherence tomography (OCT), are converted into 2D representations and segmented into localized samples aligned with each composite tow. These samples are processed using a convolutional autoencoder, which is trained exclusively on nondefective data to detect anomalies based on reconstruction errors. These errors are then aggregated into anomaly maps, which are processed to identify and localize defects.

This approach reduces the reliance on extensive labeled datasets while offering a scalable and data-efficient solution for detecting various types of surface anomalies. The framework achieves comparable performance to existing methods, while overcoming the limitations of previous systems by detecting all types of anomalies without the need for a large number of defective samples. This advancement represents a significant step forward in automating quality assurance in AFP, improving both detection reliability and efficiency.

Keywords: Automated Fiber Placement, Optical Coherence Tomography, Quality Inspection

Vacuum Bag Leak Detection Using Machine Learning with Simulated Data from an Analogous Electric Circuit

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Vacuum-assisted composite manufacturing techniques, including resin transfer molding (VARTM) and prepreg methods, rely on atmospheric or autoclave pressure to consolidate fabric components. However, potential leakages on vacuum bags can cause air bubbles, voids, resin traps, uneven surface finishes, and weakened mechanical properties. Detecting and repairing leaks prior to the curing stage is essential to ensure high-quality manufacturing outcomes.

A common method for leak detection involves estimating their locations by monitoring the volumetric flow rates at multiple vacuum ports on the layup. However, traditional numerical approaches often fall short due to the extensive size of vacuum bags, complex geometries, and various vacuum port configurations. These challenges lead to inaccurate or unreliable predictions of leakage sites.

Machine learning (ML) offers a promising alternative, capable of predicting leakage locations using flow rate data. However, ML models require extensive datasets to accurately represent the flow characteristics of diverse layup configurations and leakage scenarios. Generating these datasets experimentally is resource-intensive, both in terms of time and labor. Conventional numerical solutions are also very time-consuming.

To address this challenge, we propose a novel analogy between vacuum bag assemblies and electrical circuits to simulate flow rate data efficiently. This approach has been experimentally validated across various geometries and leakage patterns, demonstrating high accuracy in mimicking real-world setups. Furthermore, the method accommodates a wide range of leakage sizes within sensor limits.

Using this framework, we generated synthetic datasets to train regression-based ML models. These models achieved high validation accuracy and were further tested on unseen experimental data, where they demonstrated strong predictive

performance. This integrated approach holds significant promise for improving leakage detection, enhancing manufacturing efficiency, and ensuring superior composite material quality.

Keywords: Vacuum bagging, composite manufacturing, machine learning, leak detection, leak localization

Session: Emerging Materials and Processes II

Material Properties of Precipitation Hardening Stainless Steel Ferrium® PH48S™

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Integrated computational materials engineering (ICME) technologies and the materials by design methodology, which implements a systems engineering design framework that considers the various interactions between chemistry, processing, and microstructure, are being widely applied for alloy development. This method provides the properties to achieve the desired material performance with lower development costs and a quicker transition to industry. Ferrium® PH48S™ is one of the computationally designed precipitation hardening stainless steels developed by QuesTek Innovations LLC, which has high strength, high toughness, and good corrosion resistance. Under collaboration with QuesTek, Daido Steel Co., Ltd. has revealed that Ferrium® PH48S™, which was manufactured at mass production scale and heat treated without the need for cryogenic treatment, has higher strength and toughness than conventional precipitation hardening stainless steels, combined with good corrosion resistance. It is expected that Ferrium® PH48S™ contributes to weight reduction and miniaturization due to good balance of strength and toughness, and elimination of coating for corrosion protection due to its high corrosion resistance compared with maraging steel and martensitic stainless steel.

Decision Science-Driven Assessment of Magnetocaloric Materials for Thermal Management Systems

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The two essential benefits of all-electric-aircraft (AEA) are reduced carbon emissions and maintenance. A critical challenge in AEAs is thermal management: batteries are difficult to cool because of the narrow and low optimal temperature range of high performance. A need for sustainable materials for thermal management systems is imminent. Magnetic cooling (MC) reveals the highest performance and energy conversion efficiency coefficient among various cooling technologies. MC utilizes magnetocaloric materials (MCMs) that heat up when exposed to a magnetic field and cool down when the field is removed—the cyclic exposure to, and shielding from a magnetic field creates a heat pump. The MCMs are a diverse class of materials, including but not limited to transition metal-based amorphous materials, rare-earth-based amorphous materials, rare-earth-containing crystalline materials (e.g., laves phases, etc.), and rare-earth-free crystalline materials (viz., Heusler alloys, etc.) synthesized/fabricated by a myriad of techniques. Materials informatics-enabled materials discovery and selection, popularly termed Materials 4.0, is enabled on the existing big data of synthesis, processing, modeling, characterization, and properties of diverse MCMs to identify novel MCMs for AEAs. A novel methodology that combines multiple-attribute decision-making (MADM) methods, principal component analysis (PCA), and hierarchical cluster analysis (HCA). Weights of the properties (or attributes) were evaluated by objective (Shannon's entropy method) and subjective methods. The rank is assigned by several MADMs, such as, technique of order preference by similarity to ideal solution (TOPSIS), grey relational analysis (GRA), operational competitive ratio (OCRA), and so forth, was consistent. PCA and HCA consolidated the MADM ranks and grouped similar alloys. The investigation highlights similarities across several MCMs, suggests potential replacement or substitute for existing MCMs, and provides directions for improvement and/or development of sustainable MCMs for thermal management systems.

Industrial Internet of Things, Industry 4.0, and AI: What Process Parameters Should I be Watching and Which Should I be Controlling?

Mr. Michael R. Bonner, Saint Clair Systems, Inc., Washington, Michigan, USA

Every manufacturer is hearing about the “Industrial Internet of Things” (IIoT) or Industry 4.0 and, of course, artificial intelligence (AI) – and their promise to revolutionize how we make products. So, if you ask any expert, “What parameters should I actually be controlling?” you’ll often get a quick “All of them!” answer. But that’s a cop-out. It’s easy to say, but it isn’t practical.

The fact is, despite the proliferation of sensing technologies that have endowed us with the ability to monitor virtually every aspect of our environment and process, implementing these comes with a cost. It’s not just about the sensors themselves. It’s also about the supporting network. And the processing. And the effort and energy costs. Unfortunately, these often get ignored during the upfront planning stages, and this can result in some significant surprises on the back end of the project.

Moreover, the hype and promise of AI has a powerful allure, which can only be realized if truly understood and carefully implemented – and when it comes to AI, data is king.

In short, it is essential to balance the cost and effort with the return. Nowhere is this more apparent than with the application of paints and coatings, which often involve the most expensive and energy-intensive processes in the manufacturing plant.

In this presentation we will:

- Define and contrast IIoT and Industry 4.0 and address their ramifications to modern manufacturers.
- Discuss the potential for AI implementation in manufacturing and the requirements to make it successful.
- Identify the properties that are essential to monitor at each point in the coating process.
- Identify the properties that are essential to control at each point in the coating process.
- Describe the best practice to implementing data collection and control to leverage the future of AI.

Intermetallic Matrix Alloys for Metal Cladding Application

Dr. C. Paul Qiao, L.E. Jones Company, Menominee, Michigan, USA

Alloy design with intermetallic phase matrix is an emerging trend for high temperature applications. Alloy J513 matrix is composed of multiple phases including intermetallic, martensitic and boride. Owing to its excellent wear resistance, J513 has been widely used for combustion engine valvetrain applications.

J513 is an iron rich alloy that possesses a good weldability with iron-based or nickel-based alloys. J513 can be readily atomized with gas, water and centrifugal spin approaches to obtain particulate materials for sintered powder metallurgy, 3D metal printing, and metal cladding applications.

J513 clad samples made with plasma arc welding and laser beam welding processes were examined. Good wear resistance of J513 clad samples was revealed by Plint wear test. The results obtained from this study can be useful for cladding ability investigation of other intermetallic matrix alloys such as Jonesite 19 and Jonesite 21.

Lost Core Nanomaterial Electroforming Process for the Low-Cost Manufacture of Complex High-Strength, Lightweight, High-Temperature Service Components

Dr. Jonathan McCrear, Mr. David Kim, and Dr. Gino Palumbo; Integran Technologies Inc, Mississauga, Ontario, Canada

Advancements in low-cost polymer additive manufacturing and electroforming of high-strength, thermally stable nanostructured metal alloys have enabled a novel, efficient, and cost-effective **lost core nanomaterial electroforming process (LCNE)**. This process is ideally suited for manufacturing complex, high-performance components designed for high-temperature applications across a wide range of industries, including aerospace, defense, and energy.

The LCNE process combines additive manufacturing of intricate polymer cores with electroforming of nanostructured alloys, allowing for the creation of lightweight, durable, and geometrically complex parts that can withstand high temperatures and harsh environments. This approach is especially beneficial for producing intricate components such as heat exchangers, turbine housings, mani-

folds, and other high-temperature ducting systems where conventional manufacturing techniques fall short.

This presentation will provide an overview of the key process steps, including core fabrication, electroforming, and core removal (if required), as well as a discussion of the unique properties of the nanostructured alloys used. The enhanced mechanical strength, thermal stability, and corrosion resistance of these materials make them ideal for demanding applications that require both performance and cost efficiency.

Scalium™: A New High-Strength Aluminum Alloy to be Used from Skis to Aerospace

Mr. Felix Lapointe; Ferreol Technologies, Québec, Canada

Ferreol Technologies mission is to reshape manufacturing industries internationally through the development of innovative materials. As a spin-off from Ferreol Skis—the second-largest alpine ski company in Canada—Ferreol Technologies draws on the expertise and creativity that fueled Ferreol pioneering ski designs. Over the last five years, Ferreol Skis has prioritized research and development to reduce the environmental impact of its skis while enhancing on-snow performance and user experience. This endeavor culminated in the creation of a novel aluminum alloy: Scalium™.

Scalium™ delivers exceptional mechanical properties, particularly a high yield strength, with values reaching up to 729 MPa, up to 45% stronger than typical 7000 series. Initially designed to meet the demanding performance requirements of alpine skis, this innovative material has attracted significant attention from major global ski manufacturers. Early tests integrating Scalium™ into their ski models have yielded highly promising results.

Recognizing its broader potential, Ferreol Technologies is now exploring applications of Scalium™ in industries where high strength, mass reduction, and carbon footprint minimization are critical, such as aerospace. Collaborations with aerospace OEMs are underway to fully characterize Scalium™ and quantify its benefits for aircraft and spacecraft components. These efforts aim to unlock significant mass savings and environmental benefits, positioning Scalium™ as a material of choice for the future.

With its commitment to innovation and sustainability, Ferreol Technologies is ready to reshape industries beyond skiing, driving progress in high-performance materials for global markets.

Predicting Material Properties and Its Validation Methodology

Mr. Marco Pelissero; Total Materia AG, Zurich, Zurich, Switzerland

Machine learning (ML) algorithms represent a valid methodology to provide material property prediction. ML can support better decision-making in material selection and performance assessments, when there is a data gap. The benefit to aerospace companies is that they can shorten the material selection process by reducing the need for expensive and time-consuming material characterization tests in materials laboratories.

The paper will present the different ML models used to perform data predictions, the way to train the algorithms with large curated properties data set and the methodology developed by Polytechnic of Turin to validate the algorithms by comparing the prediction with experimental data.

Corrosion Resistance Comparison of Two Maraging Stainless Steels for Aerospace Application

Dr. Laury-Hann Brassart¹, Mr. Jérémie Rougier¹, Dr. Charles Declairieux¹, and **Dr. Solange Vivès²**; ¹ Aubert & Duval, Les Ancizes, Puy-de-Dôme, France; ² Aubert & Duval, Paris, France

Martensitic stainless steels owe their high strength to ageing heat treatments, inducing hardening phases precipitation. The temperature of these treatments is around 450–550 °C and the nature of the precipitates varies according to the steel’s chemical composition.

This specific microstructure induces structural hardening and thus properties that meet the requirements of sometimes critical aeronautical structural parts. Thanks to a beneficial compromise between a mechanical strength (UTS) from 1500 to 1800 MPa and a fracture toughness (K_{Ic}) from 70 to 100 MPa√m, these steels are suitable for severe conditions in service.

In this context, Aubert & Duval produces MLX[®]465 (AMS5936) and MLX[®]17 (AMS5937) grades, which are high-strength steels with similar mechanical properties com-

pleted with good corrosion resistance thanks to a content of chromium (> 11 wt%) associated with molybdenum.

However, the higher amount of molybdenum for MLX[®]17 leads to a different corrosion behavior. This study focuses on the impact of this difference on the pitting corrosion resistance as well as stress-corrosion cracking sensibility.

The advantage of MLX[®]17 compared to MLX[®]465 lies in its better passive layer stability, as demonstrated with the pitting corrosion tests. Globally, the results showed that MLX[®]17 presents the best balance between mechanical properties and corrosion resistance.

Session: Materials Characterization and Failure Analysis

Small-Scale Alloy Development and Industrial Scale-Up Enabled by Complementary Characterization Methods Based on the Example of a PH-Steel

Dr. Manfred Stadler; voestalpine BÖHLER Edelstahl, Kapfenberg, Styria, Austria

Precipitation-hardening (PH) steels are corrosion-resistant materials that combine superior strength with sufficient toughness and ductility, making them highly suitable for safety-critical structural components in the aerospace industry. Their properties are determined by a complex microstructure consisting of a low-carbon martensitic matrix, from which both the toughness-enhancing austenite and strength-enhancing precipitations evolve during the aging heat treatment. The ratio of strength to toughness can mainly be adjusted by the aging conditions but also by marginal modifications of the chemical composition itself.

Since the use of these materials for aerospace applications demands high purity levels, they often undergo a complex melting and remelting process under vacuum leading to high manufacturing costs. This makes targeted alloy development challenging. Consequently, the evaluation of alloy concepts using material produced on a small scale, followed by upscaling to large-scale manufacturing, is a reasonable approach.

In this study, a PH grade (UNS46500) was investigated using complementary characterization methods such as light optical microscopy, scanning electron microscopy, electron-backscatter-diffraction, atom-probe-tomography and many more to gain a deeper understanding of how the existing phases determine the mechanical performance, as well as to assess its potential for the transfer to small-scale production.

In terms of microstructure and properties, the material which was melted on a small scale was sufficiently comparable with large-scale produced material to investigate individual, composition dependent phenomena. Nevertheless, production process related phenomena such as retained austenite formation were observed in certain areas of the bar, which needs to be considered to make a clean evaluation of the influence of specific alloying elements on the microstructure and properties. Finally, the transferability of promising alloying concepts to large-scale production was evaluated and implemented. Further comprehensive characterization of the manufactured material and mechanical testing concluded the product development process from a research and development perspective.

Profilometry-Based Indentation Plastometry: A Novel Method to Support Failure Analysis in Aerospace

Dr. Henry Begg¹, Dr. Oliver Morris¹, Dr. Zak Barrett², and Ms. Coral Smith²;

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Ascertaining the causes of failure of metallic aerospace components can require the determination or verification of mechanical properties. When small and/ or irregularly shaped parts are the only material available, these may not be well-suited for extracting a mechanical test coupon, or such destructive sectioning may limit further investigations. This may cause the investigator to make (micro) hardness tests but deriving mechanical data from these can introduce significant error. A more robust method is desirable.

This study reports an exploration and evaluation of profilometry-based indentation plastometry (PIP) as a novel, alternative technique to hardness or tensile testing for use in the aerospace industry. PIP combines an indentation-based

method with iterative finite element analysis (FEA) to obtain a stress-strain curve of the metallic sample being tested, and while conventional tensile testing requires standard coupon geometries and significant volumes of material, PIP can be performed on a variety of geometries, and on sample volumes as low as 3 by 3 by 1.5 mm; ideal for seminondestructive evaluations of stress-strain behavior from failed parts.

In this study, PIP measurements are performed on aerospace-grade 2xxx and 7xxx aluminum alloy samples and contrasted with results from comparative tensile testing. Distributions of standard mechanical properties (such as yield stress and ultimate tensile strength) are compared and discussed in the context of failure analysis, as well as wider applications in other areas where fine-scale mechanical testing proves challenging.

Microstructural Changes and Negative Creep of Inconel 783

Mr. Konstantin Mueller¹, Dr. Benedikt Albert², Dr. Rainer Völkl¹, and Prof. Uwe Glatzel¹; ¹University of Bayreuth, Bayreuth, Germany;

²MTU Aero Engines AG, Munich, Germany

Some materials used in structural components in aircraft turbines show a volume contraction in service. This phenomenon is often referred to as “negative creep.” However, the mechanisms behind negative creep are not yet well understood.

Inconel 783 is an oxidation-resistant, low-expansion nickel-cobalt-iron alloy; and, therefore, is considered for applications with tight clearance, such as rings, casings, shrouds, and seals in aircraft turbine engines. The objective here is to find correlations between microstructure evolution and negative creep in Inconel 783. Samples of this alloy are isothermally annealed without external load for a long time at various temperatures. To measure dimensional changes high resolution length measurement is used. The lattice parameters of different annealing states are determined by x-ray diffraction. The phase morphology and stability and their influence on the lattice parameters, as well as effects of oxidation, are considered. Equilibrium phase fractions and compositions of matrix, γ' and β phase are assessed by the calculation of phase diagram method (CALPHAD) is used.

Influence of Sample Preparation on Metallographic Examination of Thermal Spray Coatings

Ewa Bobala, GE Aerospace Poland, Warsaw, Poland

Metallographic examination of thermal spray coatings can be affected by improper sample preparation. Presence of features induced by sample preparation and smeared surface can obscure the actual coating microstructure, leading to misassessment by the metallurgist. The presentation describes how parameters of sample preparation processes can change the actual view of the coating microstructure, followed by examples of coatings commonly used in aircraft engines.

Imaging New Dimensionalities in Imaging of Elasticity

Mr. Thomas Ales and **Dr. Peter Collins**; Iowa State University, Ames, Iowa, USA

The possibility of using elastic properties to quantitatively image the microstructure and, concurrently, the properties of advanced materials is an exciting breakthrough for the materials scientist, enabling new fundamental research. This talk will explore three new types of research activities that may be enabled by imaging with elasticity.

First, we explore the possibility of using spatially resolved acoustic spectroscopy (SRAS) into a 3D characterization tool. We have successfully demonstrated the ability to integrate a SRAS system into a Robo-Met.3D serial sectioning instrument suited for the 3D serial sectioning of materials using precision mechanical polishing. The Robo-Met.3D typically uses an optical microscope to characterize the material. This 3D variant of SRAS makes it possible to study complex problems, such as microtexture in Ti-base alloys.

Second, we show our work on “functionally graded materials,” in which we use imaging techniques based upon elasticity, we have a possibility to not only study how microstructure and elastic behavior concurrently change across gradients of varying types (including both compositional and thermal gradients), but also a new potential route to use elasticity and microstructure to infer composition. These tools are vital to realize this promising new class of materials.

Lastly, we study problems across length scales, from the centimeter length scale to the angstrom length scale. There exists a variant of transmission electron microscopy (TEM) that enables the determination of crystal orientation with 1nm resolution. While PED studies often focus on grain orientation, we will introduce it

here with the possibility of using PED to interpret changes in the elastic properties and bonding at subnanometer resolution. In all three examples, we will focus on what may be possible using elasticity to characterize materials.

Buckling Strength Analysis and Effect of Local Welds in Isogrid Cylinder Structure

Dr. Joon Tae Yoo, Mr. Sanghoon Lee, Dr. Yeonhee Jung, Dr. Chunghee Park, Mr. Mincheol Shin, and Dr. Jong Hoon Yoon, Korea Aerospace Research Institute, Daejeon, Yuseong-gu, Korea, Republic of (South)

Large cylindrical structures made of metallic isogrid reinforcement are manufactured by the welding of plastically formed panels. Isogrid structures can be designed using an equivalent monocoque cylinder for compressive buckling mode. However, the welding joints between panels cause discontinuities that make different behavior with equivalent monocoque cylinder and cause reduced buckling strength. In this study, a buckling strength analysis is performed, considering the geometry of the weld joints, and the effect of the welding area on buckling strength is evaluated. Since welding joints generally have higher stiffness and relatively lower bending stiffness than isogrid reinforced areas, local reinforcement around the weld joints can minimize strength reduction. A nonlinear numerical analysis is conducted by varying the weld joint dimensions, considering the manufacturing process, to compare the trade-off between increased mass and strength. Finally, effective reinforcement methods to enhance buckling strength are studied.

Space Materials and Process Engineering, Selection, Validation and Application

Paresh R. Modi, Engineering Consulting Services, LLC, Fort Worth, Texas, USA

Selection of materials and processes, along with validation based on the application, are the foundation of structural integrity and mission success for spacecraft. The selected materials and processes are considered single-point failure items because any glitch in them could jeopardize the mission success of multimillion-dollar spacecraft.

Spacecrafts are launched into geostationary Earth, medium Earth, and low Earth orbits depending on the application. 9700 pound global positioning system GPSIII SV01 spacecraft of the Space Force was launched into MEO, 11,000 pound Geostationary Operational Environmental Satellite (GOES-R) of NASA was launched into GEO, and 24,500 pound Hubble Space Telescope of NASA was launched into LEO. The selected materials must be compatible with LEO, MEO, or GEO, depending on which orbit the spacecraft will operate in during its planned lifetime (~ 15 years). For example, the presence of ultraviolet radiation in LEO converts 96% of oxygen to atomic oxygen. Atomic oxygen is very reactive and energetic enough to break chemical bonds on the surface of many materials, reacting with them to form oxides.

A typical spacecraft comprises many systems such as, structure and mechanisms, propulsion, thermal, electrical and electronics, power, attitude control, payload, communication/command/data handling, etc. Each system requires precise selection of materials and processes to fabricate parts, components, subassemblies, and assemblies. The selection is based on the application and functionality of the system, and space environment including temperature extremes and radiation effects, compatibility of materials, lifespan of the spacecraft, etc.

Adequate knowledge and experience in material science and engineering, metallurgical engineering, process engineering, corrosion science, including galvanic and stress corrosion, fracture mechanics, and failure investigation and analysis are necessary for the selection of materials (metals and nonmetals) and processes. A detailed study of the aforementioned aspects will be discussed in the presentation for fabricating exemplary spacecraft considering selection of flawless materials and processes.

Session: The University of British Columbia and The German Aerospace Center Sensor Technology

Advanced Modeling Techniques for Next-Generation Polymer-Based Acoustic Nondestructive Testing Transducers

Dr. Martin Angerer, Mr. Jonas Welsch, Prof. Edmond Cretu, and Prof. Robert Rohling; The University of British Columbia, Vancouver, British Columbia, Canada

Nondestructive testing (NDT) plays a vital role in assuring the structural integrity of aircrafts. As the use of metal-alternative materials like carbon fiber laminates becomes more prevalent, continuous monitoring and in-situ testing capabilities become increasingly important. This requires lightweight, low-power, low-cost and potentially flexible ultrasound transducers. Polymer-based capacitive micro-machined ultrasonic transducer (polyCMUTs) can address these needs. PolyCMUTs are based on submillimeter sized drums with arbitrary arrangements, made from micromachined polymer layers. This offers a small form factor, rapid fabrication (~1 week), and highly customizable designs. To guarantee that the transducers meet the requirements, we employ extensive theoretical analysis and performance modeling. This work will present currently applied modeling and analysis techniques (analytic, numeric) of ultrasound transducers, with a focus on polyCMUTs. In more detail, we will introduce a modeling framework based on combining results from finite-element analysis (FEA) with much faster numerical methods. Validation with full-sized FEA and measurements showed less than 7% average deviations in terms of sensitivity, center frequency, and bandwidth, requiring less than 1% of the computation time. This enables the rapid exploration of the vast design space of micromachined ultrasonic transducers to tune the performance to application specific requirements. In addition, the modeling results provide a firm guidance for characterization and quality control to streamline development and design optimization. Hence, the presented approach provides a key tool in the rapid realization of next-generation ultrasound transducers for NDT.

Front-End Amplified polyCMUTs for Acoustic Emission Sensing of Carbon Fiber-Reinforced Polymer

Mr. Jinhao Lu, Dr. Martin Angerer, Mr. Jonas Welsch, Prof. Robert Rohling, and Prof. Edmond Cretu; The University of British Columbia, Vancouver, British Columbia, Canada

Nondestructive testing (NDT), particularly through acoustic emission (AE) sensing, plays a critical role in ensuring the structural health and integrity of various systems. However, traditional AE sensors based on piezoelectric materials are bulky, expensive, and limited in bandwidth, hindering their large-scale use in modern applications. In contrast, capacitive micromachined ultrasonic transducers (CMUTs) offer broader bandwidth, smaller form factors, and easier integration. The emerging technology of polymer-based capacitive micromachined transducers (polyCMUTs) allows for further cost reduction and rapid prototyping and fabrication times utilizing state-of-the-art microfabrication techniques. In this study, we designed, fabricated, and integrated polyCMUT AE sensors with pre-amplifier integration to improve sensitivity, signal transmission and noise levels over longer distances. The electronics, including a bias tee and a charge amplifier (1 pC/V gain), were optimized for low noise, achieving an input-referred noise density of 2.33 nV/ $\sqrt{\text{Hz}}$ using the OPA818 operational amplifier. Testing the passive polyCMUT sensors according to ISO 24543:2022(E) demonstrated a broad bandwidth (150 kHz to 1.7 MHz, with resonance at 1.3 MHz) and a tunable sensitivity, at levels comparable to commercial AE sensors. The pre-amplifier-integrated system achieved an off-resonance sensitivity of 3V/nm and an input-referred noise density of 2.8 nV/ $\sqrt{\text{Hz}}$ with an equivalent gain of 40 dB. Our polyCMUT sensors have a significantly lower acoustic impedance (3.5 MRayl) compared to traditional piezoelectric AE sensors (~30MRayl). Our lower impedance leads to much better acoustic coupling with carbon fiber reinforced polymer (CFRP), which has an impedance of about 4 MRayl. This, combined with the sensor's compact design (20 by 14 by 5 mm³), cost-effectiveness, and scalability, makes our pre-amplified polyCMUT AE sensors a promising solution for large-scale monitoring of CFRP, especially in aerospace applications such as unmanned aerial vehicles and aircrafts.

Implementation of polyCMUT-Based Ultrasonic Arrays in the Manufacturing Process of Lightweight Composite Structures

Mr. Dominik Görick¹, Mr. Jonas Welsch², Prof. Michael Kupke¹, Prof. Heinz Francois Voggenreiter³, Prof. Edmond Cretu², and Prof. Robert Rohling²;

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To meet the increasing demand for fuel-efficient and cost-effective aircraft designs, manufacturers are adopting improved materials, such as thermoplastic composites (TCs). A key advantage of TCs is their ability to be remelted, facilitating novel production processes like continuous ultrasonic welding (CUW). This fast and efficient technique eliminates the need for adhesives or complex joining methods. During CUW, a 20 kHz ultrasonic signal is applied to the welding zone, where friction causes the material to melt. A compaction unit applies pressure, forming a reliable joint between welded parts.

Ensuring process reliability and efficiency is crucial for establishing CUW in the industry. This requires real-time, nondestructive testing (NDT) to assess joint quality during welding. To achieve this, polymer-based capacitive micromachined ultrasonic transducers (polyCMUTs) were implemented. These sensors can transmit and receive ultrasonic signals in the low megahertz band, avoiding acoustic interference from the kilohertz frequency CUW process.

This selective frequency response is what enables the measurement and sets the polyCMUTs apart from piezoelectric transducers. The 20 kHz welding signal and its multiple higher harmonics were shown to oversaturate traditional NDT-transducers. For the system electronics a novel, open-source system named wearable ultralow power ultrasound probe or WULPUS was chosen, integrating an 8-channel pulser, an analog-to-digital converter, and wireless data transfer in a compact, power-efficient package. The polyCMUT transducer and the WULPUS system are mounted on a polyetheretherketone (PEEK) block to prevent damage and glycerin is used as the coupling medium. This setup minimizes space requirements and the system's impact on fabrication equipment. This presentation details the ongoing development and implementation of polyCMUT-based NDT, the performance of WULPUS, and the challenges faced in integrating this system for inline quality assurance in continuous ultrasonic welding.

Monitoring the Curing of Epoxy Resin Accelerated by Ultrasonication via Impedance Measurements

Mr. Daniel Csehngeri, Prof. Edmond Cretu, Prof. Anoush Poursartip, and Prof. Robert Rohling; The University of British Columbia, Vancouver, British Columbia, Canada

Carbon fiber-reinforced polymers (CFRP) play a vital role in various sectors, particularly aeronautics and automotive sectors, due to their exceptional properties, including high strength, stiffness, and corrosion resistance. These advantages, however, are counterbalanced by a complex manufacturing process with unique challenges, such as nonuniform curing that degrades performance. This work addresses two key aspects of curing: (a) the continuous monitoring of epoxy resin curing through nondestructive electrical impedance measurements, and (b) the potential benefit of additional ultrasound energy on the curing process to counteract nonuniform curing.

Electric impedance measurements offer a distinct advantage over conventional thermal analysis methods, allowing for continuous real-time monitoring throughout the entire curing duration. Sensor probes mounted on the surface track changes in their equivalent capacitance and resistance caused by the curing within the material. This approach can be an effective, nondestructive way to assess the local curing status of the resin.

Recent studies have indicated that high-intensity ultrasonic fields can significantly accelerate the curing of epoxy resins. However, there remains a critical need to differentiate between the thermal effects induced by ultrasound and the mechanical effects related to the added vibrational energy, and to develop a nondestructive, and continuous monitoring procedure that effectively separates these influences. Experiments were conducted using an ultrasonic bath to demonstrate the positive impact of mechanical vibrational energy on the curing process. Electrical impedance monitoring was used as a validation technique.

These promising results target: (a) improving the continuous monitoring of the local curing status, and (b) using the energy of guided ultrasonic waves to accelerate the curing time and to direct inhomogeneities, such as voids, away from critical structural regions with the aim of improving the overall quality of the cured material.

Quality Assurance of Vacuum Assisted Resin Infusion Manufacturing Processes via Acoustic Monitoring with polyCMUTs

Mr. Jonas Welsch¹, Dr. Martin Angerer¹, Mr. Jinhao Lu¹, Mr. Dominik Görick², Prof. Robert Rohling¹, and Prof. Edmond Cretu¹; ¹The University of British Columbia, Vancouver, British Columbia, Canada; ²The German Aerospace Center, Augsburg, Bavaria, Germany

The increasing complexity and use of composite structures demand robust quality assurance during manufacturing. Vacuum-assisted resin infusion (VARI) is a widely used process in which sheets of composite fibers are placed over forms, encased in vacuum bags, and infused with resin drawn by a vacuum. A critical challenge in VARI is controlling and monitoring the resin flow front to avoid voids or dry spots and overseeing the curing process to prevent warping and residual stress.

Current solutions, such as sensors that measure electrical resistance via embedded wires or capacitive sensors that detect changes in electric fields, are costly and require access to both sides of the part, limiting their practicality. We propose an alternative approach using a sensor network of active polymer-based capacitive micromachined ultrasonic transducers (polyCMUTs). These flexible, thin, and lightweight transducers are applied on top of the vacuum bag. They transmit and receive ultrasonic signals, allowing precise monitoring of resin flow and curing. Their small and flexible size, ease of application, and low cost enable the use of more sensors with minimal impact on the workpiece and more complex geometries, compared to traditional piezoelectric sensors.

By analyzing changes in ultrasonic signal parameters, such as time-of-flight and attenuation, we can accurately track the resin flow front and curing progress. This work presents results from initial prototyping and system development, demonstrating successful flow front and room temperature curing measurements on a small-scale (8 plies, 200 by 200 mm) demonstrator.

Session: Titanium Alloy Technology

ATI Titan 27[®]: Leveraging Slip to Improve Performance for Aerospace

Dr. Bhuvni Nirudhoddi¹, **Dr. Ming Li**¹, Dr. John Foltz², D.A. Shaner¹, Erik Rogoff², and Dr. Andrew J. Temple²; ¹ATI Specialty Rolled Products, Natrona Heights, Pennsylvania; ²ATI, Monroe, North Carolina

ATI Titan 27[®] is a lightweight α/β titanium alloy capable of a 15% increase in strength/weight ratio compared to the industry workhorse Ti 6Al-4V. Though the Ti-Al-Sn-V-Co alloy is similar in microstructure to legacy α/β titanium alloys, it has a higher propensity for activating nonclose packed c+a slip planes. This novel behavior enables high ductility in the alloy without sacrificing static properties and dynamic properties such as toughness and fatigue. The alloy's wide hot working range enables tunable properties through thermomechanical processing and heat treatment. Titan 27[®] has been successfully produced in multiple product forms such as plate, sheet, bar, and billet across at mill-scale level and is an ideal replacement for Ti 6Al-4V in a variety of ballistic, structural and dwell sensitive applications.

Development of Low-Cost Titanium Sheet via a Combination of Field Assisted Sintering Technology and Hot Rolling (FAST-roll)

Dr. Samuel Lister, Dr. William Pulfrey, and Prof. Martin Jackson; University of Sheffield, Sheffield, South Yorkshire, United Kingdom

The use of field assisted sintering technology (FAST) to consolidate metal powders and particulates is on the rise due to the short sintering cycles and flexibility the process permits. Through combining the process with low-cost feedstock and secondary thermomechanical processing operations, low-cost and sustainable titanium plate and sheet can be manufactured. Out-of-spec additive manufacturing (AM) powders and cleaned-graded machining swarf can be used independently, or together, as a truly low-cost feedstock, since FAST is agnostic to powder size and morphology.

This talk will give an overview of recent work developing the two-step FAST-roll hybrid processing route for various titanium alloys. Sections were taken at various reductions throughout the rolling process for characterization. These were analyzed via scanning electron microscopy and electron backscattered diffraction, allowing the microstructure and texture evolution of both powder and swarf-derived

FAST material to be understood and compared to conventional UD-rolled plate. Initial mechanical testing has been performed allowing comparison between the tensile properties of FAST-rolled plate and wrought material, demonstrating that FAST-*roll* has the potential to produce comparable properties and microstructures. These results demonstrate the potential for this method to be up scaled as a route to produce cost-effective and sustainable titanium sheet, with as little as two processing steps.

High-Temperature Titanium Alloy Development for Aerospace Applications: ATI Titan 171™ Alloy

Dr. David Brice, Mr. John V. Mantione, and Dr. Matias Garcia-Avila; ATI, Monroe, North Carolina

As aerospace and defense applications become increasingly demanding, the need for lightweight, strong, and temperature capable materials has become even more relevant. Modern jet engines rely on titanium alloys that exhibit relatively high elevated temperature strength, and emerging markets such as hypersonics have even more challenging requirements. ATI has undergone a focused effort to improve upon legacy titanium alloys to meet these needs, iterating off high-temperature capable alloys such as Ti-6Al-2Sn-4Zr-2Mo, Ti-5Al-2Sn-2Zr-4Mo-4Cr, and Ti-4Al-4Mo-2Sn. Specifically, a new beta-rich alloy, ATI Titan 171™ has demonstrated superior performance at temperatures up to 1000 °F. This presentation will focus on the research and development of ATI Titan 171™, from lab scale trials to production scale heats: including forging, rolling, and additive manufacturing; as well as an overview of material properties and microstructure.

Effect of High Temperature on Ti-6Al-4V Annealed Material Tensile Properties Between 900 and 1800 °F

Ms. Magdalena Michalowska and Mr. Jonathan Beckman;
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MMPDS contains data showing the effects of temperature on tensile ultimate strength (Ftu) and yield strength (Fty) up to 1000 °F for titanium Ti-6Al-4V annealed material. Some Gulfstream aircraft families have engine mounts manufactured from forged Ti-6Al-4V annealed titanium per AMS4928. As part of a compliance effort for fire protection of these parts, it was decided to test the effect of temperature on Ti-6Al-4V tensile properties between 900 and 1800 °F. Since this testing is designed to substantiate fire protection, the heating profile and time at temperature was based on experimental data representative of an engine fire in lieu of ASTM E21 recommendations. An external lab conducted a unique set-up, execution of the heating profile, and testing of the specimens to replicate the expected temperature exposure. Test results from each lot were averaged and normalized to a percentage of room temperature for ultimate tensile strength and yield strength. Additionally, an elevated temperature curve from 900 to 1800 °F was generated. The test methodologies and the results of this testing will be discussed during this presentation.

High-Temperature Titanium Alloy Development for Aerospace Applications: ATI Titan 1200™ Alloy

Dr. David Brice and Mr. John V. Mantione; ATI, Monroe, North Carolina, USA

As aerospace and defense applications become increasingly demanding, the need for lightweight, strong, and temperature capable materials has become even more relevant. Modern jet engines rely on titanium alloys that exhibit relatively high elevated temperature strength, and emerging markets such as hypersonics have even more challenging requirements. ATI has undergone a focused effort to improve upon legacy titanium alloys to meet these needs, iterating off high-temperature capable alloys such as Ti-6Al-2Sn-4Zr-2Mo, Ti-5Al-2Sn-2Zr-4Mo-4Cr, and Ti-4Al-4Mo-2Sn. Specifically, a new oxidation and creep-resistant alpha-beta titanium alloy, ATI Titan 1200™ has demonstrated superior performance at temperatures up to 1200 °F. This presentation will focus on the research and development of ATI Titan 1200™, from lab scale trials to production scale heats, as well as an overview of material properties and microstructure.

Novel Stainless Steel Substitutes Aerospace Titanium Alloys

Dr. Gregory Vartanov, Advanced Materials Development Corp., Oakville, Ontario, Canada

Titanium is a critical production material for the aerospace and defense industries, and in recent years many aerospace companies have been suffering from titanium shortage in the world market.

To find a long-term solution for that problem, AMD Corp. proposes a new material – Novel stainless steel – as a low-cost substitution of the high-strength titanium alloys commonly used in the aerospace industry. The steel possesses the same or higher specific strength (a ratio of strength to density) compared to the specific strength of the commercial Ti-6Al-4V alloy at the same ductility, toughness. Corrosion resistance of Novel stainless steel approaches the corrosion resistance of 15-5PH grade. Novel stainless steel can be utilized for high-temperature (>500 °C) applications, while Ti-6Al-4V alloy is limited to <500 °C. Another advantage of HSCR steel is better workability and machinability compared to the Ti-6Al-4V alloy.

Utilizing the Novel stainless steel offers the following benefits:

- Reduces dependency of aerospace companies on the few available titanium suppliers in the world market
- Reduces demand and indirectly affects the cost of titanium in the world market
- Lowers production cost of aerospace components by reducing the cost of the raw material and lowering the cost of manufacturing.

Novel stainless steel has been in development over the past decade, and the following results have been achieved:

- Granted U.S. patents
- Manufactured and tested Novel material
- Global aerospace companies have expressed interest in the commercialized Novel material.

Samples of Novel stainless steel has been produced as forged bars, as well as powder for hot isostatic pressing, and additive manufacturing. Implementation of the Novel material is underway.

Session: Welding and Joining II

Improving Production Performance of Refill Friction Stir Spot Welding

Dr. Yuri Hovanski, Ms. Ruth Belnap, Mr. Damon Gale, and Ms. Taylor Smith; Brigham Young University, Provo, Utah, USA

Refill friction stir spot welding (RFSSW) is a solid-state, spot-joining technique that produces ostensibly flush surfaces. While historically weld properties have been reported to be superior to other spot-joining technologies, the process has been hampered by long cycle times and unquantified tool life. Weld cycle times for aluminum alloys have ranged between two and ten seconds depending on alloy and thickness. Recent collaborations within the Center for Friction Stir Processing at Brigham Young University have demonstrated cycle times as low as 250 ms, with both static and dynamic mechanical properties that exceed the performance of resistance spot welding. Tool life of both coated steel and tungsten carbide tooling was evaluated to determine the influence of material selection on both the frequency of tool changes and cleaning, as well as the overall cost-per-spot associated with the tooling. Various dissimilar and similar alloy combinations (6xxx, 7xxx and 2xxx series aluminums) were evaluated ranging in forms from medium grade precipitation hardened sheet to high-strength extrusions in two and three sheet stack-ups. Assembly of flat sections as well as extruded stringers and curved skins are presented to showcase the process flexibility, productivity, and manufacturing readiness.

How Much Can Grain Refining Reduce the Solidification-Cracking Susceptibility?

Prof. Sindo Kou, University of Wisconsin, Madison, Wisconsin, USA

Grain refining can reduce effectively the susceptibility of alloys to cracking during solidification in welding, casting, and additive manufacturing. The present study showed that the relationship between temperature T and the fraction of solid f_s of an alloy during solidification (which can be calculated easily from the alloy composition using commercial thermodynamic software and databases) can be used to estimate how the extent of grain refining affects the cracking susceptibility. It was shown that, when grain refining decreases the grain diameter by a factor of n , the ratio of the surface area to the volume of grains increases by a factor of n to allow more coalescence between grains to resist solidification cracking. For columnar grains, the grain diameter is proportional to $(f_s)^{1/2}$, and the cracking susceptibility index $|dT/df_s|^{1/2}$ decreases to $(1/n) |dT/df_s|^{1/2}$. For equiaxed grains, the grain diameter is proportional to $(f_s)^{1/3}$, and the index $|dT/df_s|^{1/3}$ decreases to $(1/n) |dT/df_s|^{1/3}$. The curve of T vs. $(f_s)^{1/2}$ or T vs. $(f_s)^{1/3}$ was calculated, and the maximum steepness $|dT/df_s|^{1/2}$ or $|dT/df_s|^{1/3}$ up to $f_s = 0.98$ was used as the index. A positive result between the index and cracking-susceptibility tests in welding and casting was shown.