

ELEVATED TEMPERATURE COATINGS: SCIENCE AND TECHNOLOGY IV

Edited by:

Narendra B. Dahotre

Janet M. Hampikian

John E. Morral

ELEVATED TEMPERATURE COATINGS: SCIENCE AND TECHNOLOGY IV

Proceedings of a Symposium sponsored by
the Surface Engineering Committee of
the Materials Processing & Manufacturing Division (MPMD) and
the Corrosion and Environmental Effects Committee (Jt. with ASM/MSCTS) of
the Structural Materials Division (SMD) of
TMS (The Minerals, Metals & Materials Society).

Held at the TMS 2001 Annual Meeting in
New Orleans, Louisiana, USA
February 11-15, 2001.

Edited by:
Narendra B. Dahotre
Janet M. Hampikian
John E. Morral

A Publication of

TMS

Partial funding for this publication was provided by the Seeley W. Mudd Fund

A Publication of The Minerals, Metals & Materials Society

184 Thorn Hill Road
Warrendale, Pennsylvania 15086-7528
(724) 776-9000

Visit the TMS web site at
<http://www.tms.org>

The Minerals, Metals & Materials Society is not responsible for statements or opinions and is absolved of liability due to misuse of information contained in this publication.

Printed in the United States of America
ISBN Number 0-87339-489-5
Library of Congress Number: 2002108587

Authorization to photocopy items for internal or personal use, or the internal or personal use of specific clients, is granted by The Minerals, Metals & Materials Society for users registered with the Copyright Clearance Center (CCC) Transactional Reporting Service, provided that the base fee of \$7.00 per copy is paid directly to Copyright Clearance Center, 27 Congress Street, Salem, Massachusetts 01970. For those organizations that have been granted a photocopy license by Copyright Clearance Center, a separate system of payment has been arranged.

TMS

© 2001

If you are interested in purchasing a copy of this book, or if you would like to receive the latest TMS publications catalog, please telephone 1-800-759-4867 (U.S. only) or 724-776-9000, EXT. 270.

TABLE OF CONTENTS

PREFACE.....	vii
--------------	-----

THERMAL BARRIER COATINGS

ACCELERATED DURABILITY TESTING OF COATINGS FOR GAS TURBINES.....	1
<i>M.J. Stiger, R. R. Handoko, J.L. Beuth, F.S. Pettit and G.H. Meier</i>	
SYNTHESIS OF ALPHA- Al_2O_3 TEMPLATE ON Ni SUPERALLOY SURFACE BY CHEMICAL VAPOR DEPOSITION	15
<i>Y.-F. Su, M. Torzilli, J.D. Meyer, W.Y. Lee, M.J. Lance, C.J. Rawn and S. Ruppi</i>	
CHARACTERIZATION OF COMMERCIAL EB-PVD TBC SYSTEMS WITH CVD (Ni,Pt)Al BOND COATINGS	29
<i>J.A. Haynes, M.J. Lance, B.A. Pint and I.G. Wright</i>	
INTERFACIAL MICROSTRUCTURE FOR As-DEPOSITED AND CYCLED-TO-FAILURE THERMAL BARRIER COATING	45
<i>Altaf H. Carim, Tabbeth A. Dobbins, Merrilea J. Mayo and Lucille A. Giannuzzi</i>	
ADVANCED THERMAL COATING SYSTEMS: RESEARCH AND DEVELOPMENT TRENDS	61
<i>C. Leyens, U. Schulz and M. Peters</i>	
EFFECT OF Hf ADDITIONS TO Pt ALUMINIDE BOND COATS ON EB-PVD TBC LIFE.....	77
<i>James Nesbitt, Ben Nagaraj and Jeffrey Williams</i>	
DAMAGE INDUCED BY THERMAL CYCLING OF THERMAL BARRIER COATINGS	93
<i>Vladimir K. Tolpygo and David R. Clarke</i>	
MODELING THERMAL STRESSES AND MEASURING THIN FILM CTE IN MoSi_2 AND MoSi_2+SiC COMPOSITE COATINGS ON MOLYBDENUM	109
<i>Earl C. Hixson, C. Suryanarayana, Graham G.W. Mustoe and John J. Moore</i>	

INTERDIFFUSION OF COATINGS

INTERDIFFUSION BEHAVIOR IN AN ALUMINIDE COATED NICKEL-BASE ALLOY AT 1150°C	119
<i>B. Gleeson, E. Basuki and A. Crosky</i>	
PREDICTING INTERDIFFUSION MICROSTRUCTURE USING THE PHASE FIELD APPROACH	133
<i>Kaisheng Wu, Yunzhi Wang and John E. Morral</i>	
SYNTHESIS OF Hf-DOPED CVD β -NiAl COATING BY CONTINUOUS DOPING PROCEDURE	143
<i>G.Y. Kim, J.D. Meyer, L.M. He, W.Y. Lee and J.A. Haynes</i>	
A NEW ANALYSIS FOR THE DETERMINATION OF TERNARY INTERDIFFUSION COEFFICIENTS FOR Ni-Cr-Al AND Fe-Ni-Al ALLOYS	159
<i>Y.H. Sohn and M.A. Dayananda</i>	
IN-SITU PROCESSING OF NICKEL ALUMINIDE COATINGS ON STEEL SUBSTRATES	171
<i>Rajesh Ranganathan, Olga Vayena, Teiichi Ando, Charalabos C. Doumanidis and Craig A. Blue</i>	

METALLIC/INTERMETALLIC COATINGS AND OXIDATION

DEVELOPMENT OF PROTECTIVE COATINGS FOR HIGH-TEMPERATURE METALLIC MATERIALS	181
<i>R. Keith Bird, Terryl A. Wallace and Sankara N. Sankaran</i>	
RARE EARTH OXIDE COATINGS FOR LIFE EXTENSION OF CHROMIA FORMING ALLOYS	197
<i>Stela M.C. Fernandes and Lalgudi V. Ramanathan</i>	
HIGH TEMPERATURE SURFACE OXIDATION CHEMISTRY OF IN-738LC	209
<i>Sudipta Seal, Leyda A. Bracho, Vimal Desai and Kirk Scammon</i>	
OXIDATION KINETICS AND MORPHOLOGY OF LASER SURFACE ENGINEERED HARD COATING ON ALUMINUM	219
<i>Narendra B. Dahotre and Lalitha R. Katipelli</i>	
THE INFLUENCE OF METALLIC COATINGS ON THE STRUCTURE, WETTING, AND MECHANICAL STRENGTH OF CERAMIC/METAL INTERFACES	233
<i>Natalia Sobczak and Rajiv Asthana</i>	

CERAMIC COATINGS

FUNCTIONALLY GRADED MATERIALS PRODUCED BY LASER CLADDING	247
<i>Jeff T. De Hosson and Yutao Pei</i>	
ELECTROPHORETIC AND ELECTROLYTIC DEPOSITION OF CERAMIC FILMS	263
<i>I. Zhitomirsky</i>	
YTTRIA STABILIZED ZIRCONIA/ALUMINA COATINGS DEPOSITED BY COMBUSTION CHEMICAL VAPOR DEPOSITION	277
<i>D.W. Stollberg, J.M. Hampikian, M. McIntosh and W.B. Carter</i>	
HIGH TEMPERATURE OXIDATION OF VC COATED H13 STEEL	291
<i>Swapnil Shah and Narendra B. Dahotre</i>	
NEAR NET SHAPE FORMING OF HAFNIUM-BASED CERAMIC COMPONENTS: SYNTHESIS AND CHARACTERIZATION	301
<i>Arvind Agarwal, Tim McKeechnie, Stuart Starett and Mark M. Opeka</i>	
PROTECTIVE CVD MULLITE COATINGS WITH CONTROLLED COMPOSITION AND MICROSTRUCTURE	317
<i>S.M. Zemskova, J.A. Haynes and K.M. Cooley</i>	
THE SPECTRAL EMITTANCE AND STABILITY OF COATINGS AND TEXTURED SURFACES FOR THERMOPHOTOVOLTAIC (TPV) RADIATOR APPLICATIONS	327
<i>B.V. Cockeram and J.L. Hollenbeck</i>	
TEXTURED DIAMOND FILMS ON Si AND Cu SUBSTRATES BY HFCVD TECHNIQUE	343
<i>Ashok. Kumar, A.K. Sikder, J. Mark Anthony and D.S. Misra</i>	
AUTHOR INDEX	357
SUBJECT INDEX	359

PREFACE

Elevated Temperature Coatings: Science and Technology IV is the fourth volume in a series of invited and contributed papers presented in the symposium: High Temperature Coatings IV. This symposium was organized by Narendra B. Dahotre, Janet M. Hampikian and John E. Morral and held in New Orleans, Louisiana, during the TMS annual meeting, February 11-15, 2001. This volume consists of invited and contributed papers from national and international researchers representing universities, federal laboratories and industries. Thus, it provides a rich diversity of material in the research area of High Temperature Coatings. The sponsorship of the TMS Surface Engineering Committee of Materials Design and Manufacturing Division, the Joint TMS/ASM Corrosion and Environmental Effects Committee of Structural Materials Division, and the Materials Science Critical Technology Sector of ASM is gratefully acknowledged.

The topic of High Temperature Coatings is one that is motivated by the increasing need for improved surface characteristics from a wide range of materials without compromising bulk characteristics such as mechanical performance. An example of this is the current thrust toward achieving higher operating temperature in industrial gas turbine engine components through use of thermal barrier coatings in high temperature gradient areas such as on turbine nozzles and blades. The specific materials topics covered in this symposium include: Thermal Barrier Coatings, Interdiffusion of Coatings, Metallic/Intermetallic Coatings, and Oxidation and Ceramic Coatings. Thus this time in addition to being concerned with the adherence of thermal barrier coatings and the oxidation resistance of metallic coatings, one group of papers was concerned with interdiffusion and microstructural changes that occur in metallic coatings during service.

We are grateful for the institutional support provided by the University of Tennessee Space Institute, the School of Materials Science and Engineering at the Georgia Institute of Technology, and the Institute of Materials Science and the School of Engineering at the University of Connecticut. Finally, we appreciate the continuing assistance from TMS for the Symposia on High Temperature Coatings.

Professor Narendra B. Dahotre

Department of Materials Science and Engineering
Laser Materials Processing Group
The University of Tennessee
Space Institute
10521 Research Drive, Suit 400
Knoxville, Tennessee 37932

Professor Janet M. Hampikian

School of Materials Science and Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0245

Professor John E. Morral

Department of Metallurgy and Materials Engineering
Institute of Materials Science
University of Connecticut
Storrs, CT 06268-3136

AUTHOR INDEX

A

Agarwal, A., 301
Ando, T., 171
Anthony, J.M., 343
Asthana, R., 233

B

Basuki, E., 119
Beuth, J.L., 1
Bird, R.K., 181
Blue, C.A., 171
Bracho, L.A., 209

C

Carim, A.H., 45
Carter, W.B., 277
Clarke, D.R., 93
Cockeram, B.V., 327
Cooley, K.M., 317
Crosky, A., 119

D

Dahotre, N.B., 219, 291
Dayananda, M.A., 159
De Hosson, J.T., 247
Desai, V., 209
Dobbins, T.A., 45
Doumanidis, C.C., 171

F

Fernandes, S.M.C., 197

G

Giannuzzi, L.A., 45
Gleeson, B., 119

H

Hampikian, J.M., 277
Handoko, R.R., 1
Haynes, J.A., 29, 143, 317
He, L.M., 143
Hixson, E.C., 109
Hollenbeck, J.L., 327

K

Katipelli, L.R., 219
Kim, G.Y., 143
Kumar, A., 343

L

Lance, M.J., 15, 29
Lee, W.Y., 15, 143
Leyens, C., 61

M

Mayo, M.J., 45
McIntosh, M., 277
McKeechnie, T., 301
Meier, G.H., 1
Meyer, J.D., 15, 143
Misra, D.S., 343
Moore, J.J., 109
Mustoe, G.G.W., 109

N

Nagaraj, B., 77
Nesbitt, J., 77

O

Opeka, M.M., 301

P

Pei, Y., 247
Peters, M., 61
Pettit, F.S., 1
Pint, B.A., 29

R

Ramanathan, L.V., 197
Ranganathan, R., 171
Rawn, C.J., 15
Ruppi, S., 15

S

Sankaran, S.N., 181
Scammon, K., 209
Schulz, U., 61
Seal, S., 209
Shah, S., 291
Sikder, A.K., 343
Sobczak, N., 233
Sohn, Y.H., 159
Starett, S., 301
Stiger, M.J., 1
Stollberg, D.W., 277
Su, Y.-F., 15
Suryanarayana, C., 109

T

Tolpygo, V.K., 93
Torzilli, M., 15

V

Vayena, O., 171

W

Wallace, T.A., 181
Wang, Y., 133
Williams, J., 77
Wright, I.G., 29
Wu, K., 133

Z

Zemskova, S.M., 317
Zhitomirsky, I., 263

SUBJECT INDEX

602CA Alloy

- Composition, 184
- Density, 184
- Ductility, 184
- Oxidation
 - Static, 188-192
- Yield strength, 184

A

- AISI H13 Steel, 292-295
- Al/Alumina Couple, 233
- Al/Graphite Couples, 233
- Alpha- Al_2O_3 , 15
- Aluminide, 120
- Alumina, 30-44
 - Electrolytic deposition, 268, 273
 - Electrophoretic deposition, 268, 270
 - Fibers, 270
- Aluminum Alloys, 248
 - Al-50 w/o Si, 248
- Analysis of Diffusion Couple, 160
- As-Sprayed Structure
 - Microcracks, 310
 - Porosity, 309-310, 312
 - Splats, 310

B

- Bond Coat(s), 63, 64, 69-75, 94-106, 144
 - Aluminide, 63, 74, 75, 79
 - McrAlY-type, 63, 73, 74, 75
 - Pt-modified aluminide, 79
- Buckling, 74
 - Small scale buckling, 74
 - Large scale buckling, 74
- Buffer Layer, 346, 351

C

- Catalytic Efficiency
 - Coated Inconel 617, 194
 - Definition, 183
 - Test procedures, 187
- Cavities, 98-100

Characterization

- Focused ion beam (FIB), 50, 51
- Electron microscopy
 - Scanning (SEM), 49-52, 55, 56
 - Transmission (TEM), 49-57
- Energy-dispersive spectroscopy (EDS), 50, 54, 55

Chemical Vapor Deposition (CVD), 344

Chromia

- Forming alloys, 198

Ceramic Coating

- Alternative, 66, 67, 68
- Electrolytic deposition, 265, 267, 269, 270, 273
- Electrophoretic deposition, 265, 267, 269, 270
- PYSZ, 63, 65, 68, 69

Coating(s), 198, 328

- Oxidation effects, 188-194
- Procedures, 186
- Sol-gel, 184-185

Coefficient of Thermal Expansion (CTE)

- Measuring thin film CTE, 115-117
- of MoSi_2 , 112
- of SiC, 112

Combustion Chemical Vapor Deposition (CCVD), 278

Composite Coating, 292, 294, 298-300

Compressive Stress, 355

Computer Simulation, 134, 138

Contact Angles, 233

CVD, 15, 144

D

Deposition Rate

- Electrolytic deposition, 267
- Electrophoretic deposition, 267

Diamond

- Electrophoretic seeding, 270, 271
 - Charging mechanism, 271
- Fiber, 271
- Films, 344

Die-Casting, 292, 293, 300

- Dies, 292, 293, 300

Diffusion, 224

Diffusion coating, 120

Diffusion couple, 136-138

Diffusion path, 136-137

E

Electrode Reactions

Base generation, 265

Hydrolysis, 267

Electrodeposition

Electrolytic deposition, 265, 268, 269, 270,
273

Electrophoretic deposition, 265, 267, 269,
270

Electron Beam Physical Vapor Deposition, 64

Emissivity, 328

Emittance

Coated Inconel 617, 192-193

Test procedures, 187

Eutectic, 248, 252

Excimer Laser, 346

F

Fe-Ni-Al, 160

Finite Element Modeling

Boundary conditions, 111

Modeling optimization, 112-113

of Thermal stresses, 113-115

Fracture Toughness, 278

Functionally Graded Materials (FGMs), 248

G

Gamma TiAl

Composition, 184

Density, 184

Oxidation

Static, 182

Yield strength, 184

H

Hf-Doping, 144

HFCVD, 345, 346

High-Density Infrared (HDI)

Equipment, 173-174

Processing parameters, 174

Processing results, 176-179

High Temperature Coating, 134-135, 160

High Temperature Oxidation, 214

I

Inconel 617 Alloy

Catalytic efficiency, 194

Composition, 184

Density, 184

Ductility, 188

Emittance, 192-193

Oxidation

Dynamic, 193-194

Static, 188-192

Yield strength, 184

Interdiffusion

Coefficients, 160

Cross-term effect, 130

Diffusion paths, 126-128, 129-131

Fluxes, 160

Uphill diffusion, 123, 128-130

Interface

Separation, 101-105

Strength, 233

Structure, 233

L

Laser Cladding, 248

Laser Surface Engineering, 220, 221, 292-294, 300

M

Materials

Ni-Cr-Al-Y, 46-59

Yttria-stabilized zirconia, 46-59

MCrAlY Coating(s), 160

Microstructure

Coarsening, 136-137

Grain size, 57

Interdiffusional microstructures, 134

Interfaces, 46-59

Modeling, 134-135

Morphological Characterization, 198

Morphology, 220, 222

Moving Interface, 134, 136-138

Mullite, 319

Chemical vapor deposition (CVD), 319

Silicon nitride oxidation protection,
319

N

- Nanoindentation, 278
- Nanostructured Materials
 - Electrolytic deposition, 265, 273
 - Zirconia, 273
- Near Net Shape Forming
 - Vacuum plasma spray, 303, 305
- Ni Base Superalloy, 210
- Ni-Cr-Al, 160
- Ni-superalloy, 15
- Nickel Aluminide, 144

O

- Organoceramic Composites
 - Electrolytic deposition, 273
 - Polymer, 273
- Oxidation, 94-98, 198
 - and Interdiffusion, 160
 - Dynamic
 - Exposure procedures, 187
 - Weight change for Inconel 617, 193-194
 - Kinetics, 220, 221, 222, 225-231, 292, 293, 296-300
 - Mechanism, 198
 - Protection, 198
 - Static
 - Effects on ductility, 188
 - Exposure procedures, 186
 - Microstructural effects, 189-192
 - Weight change
 - For Gamma TiAl, 192
 - for Superalloys, 188-189

P

- Parabolic Growth, 211, 212
- Phase Field Approach, 134-135, 138
- Phase Transformation, 67, 68, 98
 - Beta recession, 131
 - Kinetics, 131
- Plasma Arc,
 - Processing parameters, 174
 - Processing results, 175
- PM 1000 Alloy
 - Composition, 184
 - Density, 184
 - Oxidation
 - Static, 188-192
 - Yield strength, 184
- Powder Morphology, 304, 309

Processing

- Air plasma spraying (APS), 46-59
- High-velocity oxyfuel (HVOF), 55-57
- Oxidation, 46-56
- Thermal cycling, 46-48

Push-Off Test, 233

Pyrolytic Carbon, 354

R

- Radiator, 328
- Raman Spectroscopy, 344, 346
- Rare Earth(s)
 - Oxides, 198
- Reactive Element(s), 144
 - Hf, 79, 80

S

- Sessile Drop Test, 233
- Small Angle Grain Boundaries, 248
- Sol Gel Process, 198
- Sulfur Segregation, 72
- Surface Rumpling, 101-103
- Surface Texturing, 328

T

- TBCs, 30, 31, 32, 34, 37, 39-44
- Temperature Gradient, 344, 346
- Tenary
 - Interdiffusion, 160
 - System, 134-135
- Texture, 344
- TGD, 15
- Thermal Barrier Coatings (TBC's), 15, 46-59, 62-76, 78, 94-106
 - Bond strength, 69, 70, 71, 72
 - Bond stress, 69-72
 - Cyclic furnace life, 80, 83
 - Durability, 69, 74
 - EB-PVD coatings, 78, 79, 80
 - Failure mechanism, 70-73, 94-106
 - Failure, 79, 80
 - Mode, 69, 70
- Thermal Conductivity, 65, 66
- Thermal Grown Oxide, 63, 68, 69, 70, 72
 - Alumina, 63, 72
 - Growth stresses, 73, 74
 - Residual Stresses, 74
- Thermal Stability, 328
- Thermally Grown Alumina (TGO), 79, 83, 86, 87
- Thermo Gravimetric Analysis, 222, 230, 293

Thermophotovoltaic, 328

Thin Films, 233

Titania

Electrolytic deposition, 268, 273

Electrophoretic deposition, 268

U

Ultrahigh Temperature Ceramics (UHTC)

Hafnium

Carbide, 303-304, 608, 310-312

Dibroride, 303-304, 308-310

Nitride, 303-304, 307-308, 312-313

V

Vandium Carbide, 292-295

Voids, 30-44

W

Wettability, 233

Wettability-Bonding Relationships, 233

X

X-Ray Photoelectron Spectroscopy, 211, 212, 213

Y

Yttria Stabilized Zirconia (YSZ), 278

YSZ/Alumina Composite, 278

Z

Zirconia

Electrolytic deposition, 273

Organoceramic composite, 272, 273

Electrophoretic deposition, 270

Fibers, 270