Manufacturing Science of Layered Multifunctional coatings

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Hot section coatings have been critical enablers in recent years.

Photo Courtesy – Dr. Ramesh Subramanian, Siemens

These are complex Dynamically Evolving Structures.
TBC Manufacturing Technologies

Plasma Sprayed TBCs

EBPVD TBCs

SPS TBCs

PSPVD TBCs
Thermal spray manufacturing variants

- Topcoat
  - EBPVD
  - APS
  - SPS
- Bondcoat
  - Ni/Pt-Al
  - APS
  - VPS
  - HVOF
- Superalloy

LPPS
APS
SPS
High Through-put APS

Liquid Fuel HVOF
Gas Fuel HVOF
VPS
Evolution of TBC Materials and Thermal Spray Manufacturing

Gas Turbine Engine

Evolution of TBC microstructures

Porous

DVC

Layer-1

Layer-2

Layer-3

1960-1990

1990 - present

2007 & 2014

2014

Overhaul & Repair expands

Pounds/year

Plasma spray process

GE’s DVC

DOE in manufacturing

Advanced Turbine System

Pratt & Whitney implements zirconate coatings

Pratt & Whitney

Siemens

Gadolinium

Zirconate

Vertically Cracked TBCs Invented

Zirconia

CaZr,MgZr 20%YSZ

1960

1970

1980

1990

2000

2010

Space Program

Zirconia

CaZr,MgZr 20%YSZ

Vertically Cracked TBCs Invented

Aero engine

7% YSZ

Transition duct
APS TBC fabrication involves numerous variables

- Composition
- Morphology
- Size Distribution

- Plume Orientation
- Plume Spread
- Particle State

- Feed rate
- Raster / Rotation Rate
- Angle of Deposition

- Defect (Cracks & Pores)
- Crystal (Phase & Composition)
- Layering (Splat Characteristics)
- Grain (Size)
  Anisotropy

Implications

Extreme variability – local and global
Infant mortality and poor reliability
Difficult to incorporate into life models

Multitude of applicators locations
Multitude of spray devices & parameters
Multitude of evaluation Criteria and variants
TBC Processing Reliability/Quality is becoming increasingly important

**Traditional Role of TBC ⇒ Life Extension**

Extra protection on substrates

**Future Role of TBC ⇒ Prime Reliant**

Must protect (super-alloy) substrates

Requires better control of quality variability

- Robust scientific understanding of manufacturing process
- Effective tool to **assess coating quality** and **process/coating reliability**

(both from development and manufacturing point of view)
Plasma spray is a highly complex deposition process: Materials Synthesized from Extreme Conditions

**NON-EQUILIBRIUM PROCESSING**
- Ultra rapid heating and phase change
- Rapid cooling and solidification
- Impact pressure induced transformations

**MULTI-SCALE STRUCTURE AND PROPERTIES**
- Nano-, micro-, meso- and macro-scales
- Defect-dominated attributes

**HIGHLY ANISOTROPIC BEHAVIOR**
- Process-induced residual stresses
- Anisotropic properties across length scales
- Non-linear elastic behavior

Need to develop interdisciplinary Processing/Manufacturing Science
Established as an NSF MRSEC in 1996
Integrated Interdisciplinary Research Aimed at Advancing Science, Technology and Outreach for Thermal Spray Technology

Linking Research to Practice
Industry has started to adopt these capabilities for manufacturing control, Enhanced new processes, novel designs, models and applications

Article in Integrating Materials and Manufacturing Innovation
PAINT: Partnership for Accelerated Insertion of New Technology:
Case Study for Thermal Spray

A large portfolio of scientific information has been developed manufacturing science of TBCs.
Demonstrated Industrial Benefits of Advanced Manufacturing Science through Joint Experiments: 32 Field Trips in the Last 7 Years

Post-docs and students facilitate effective knowledge transfer to industrial workforce through cooperative experimentation using advanced technologies and scientific methodologies developed in academia.

Simultaneously, they benefit from the industrial insight and priorities.

Stony Brook-Caterpillar Team

Companies involved in field trips

- CATERPILLAR
- VOLVO AERO
- PRAXAIR
- CHROMALLOY
- Alcoa Howmet
**Advanced science impacts both efficiency and reliability**

**Observation**
Observations of novel phenomena in thermal plasmas (injection sweet spot)

**Fundamental Science**
Observations and quantification of non-linear properties of ceramic coatings

**Proof of Concept Demo**
Successful testing of hypothesis in field: Tinker AF Base & Plasma Technology Inc.

**OUTCOME:**
Procedures for simultaneously enhancing process efficiencies and reliability
The Past and Future

Industrial perception of APS manufacturing as a constraint

- Lack of understanding of the scientific nuances
- Perception of poor Repeatability, Reproducibility and Reliability
- In effective control and metrology tools
- Lack of integrated understanding
- Disconnect between design, materials and processes

=> Implication: Manufacturing is a “burden”

With advanced science manufacturing can be an enabler

- Implemention of Segmented or Dense Vertically Cracked Coatings
  - (Directionally solidified, in-plane compliant coatings)
- Understanding the importance of toughness of metastable t” YSZ on durability
- Advanced process control through insitu sensor based feedback
- Predictive microstructures through maps, correlations and models
- Process-property guided layered engineering
Thermal spray as an additive and layered manufacturing technology

Bring Manufacturing Science and Novel Capabilities to Expand Design and Materials Options
E.g. Optimal Layer Design for Improved Durability

Critical microstructural parameters

- Intrinsic Material Toughness
- Manufactured Material Toughness
Toughness engineered multilayer TBCs

Conventional TBCs

- Superalloy Substrate
  - Overlay BC
    - Porous YSZ
      - Low K
      - Low E
    - Layer-1
    - Layer-2
    - High $K_{IC}$ TBC Layer

Enhanced Durability TBCs

- Superalloy Substrate
  - Overlay BC
    - Porous YSZ
      - Low K
      - Low E
    - Layer-1
    - Layer-2
    - High $K_{IC}$ TBC Layer

Bar chart showing TBC lifetime (hours):

- Single layer TBCs
  - Conventional TBCs
  - Bi-layer TBCs

Legend:

- Bi-layer TBCs
- Single layer TBCs
- Conventional
Simultaneous optimization of durability and functionality

- **bi-layer YSZ-TBCs with improved durability**
- **Single layer YSZ TBCs**
- **Inverse bi-layer TBC**
- **bi-layer TBC**
- **DVC**

TBC lifetime (hours) vs. RT Thermal conductivity (W/m-K)
Coatings experience multiple failure mechanisms

- Ceramic strength/toughness
- Coating density
- Ceramic coating compliance and ceramic chemistry
- Coating porosity/cracks
- Bond coat chemistry, Roughness
- Ceramic coating toughness
- Bond coat roughness
- Coating thickness
- Ceramic coating composition
- Pore architecture
- Coating thickness
Multilayered architecture to combat multifunctional requirements

Development/Evaluation Plan

Erosion Resistant Top Coat
- Produce dense YSZ and Gd₂Zr₂O₇ top coat layers
- Evaluate erosion resistance of dense materials
- Develop density-graded structure for top coat

Thermal Barrier Layers
- Determine Gd₂Zr₂O₇ properties (thermal/mechanical) under thermal gradients
- Assess IGCC environmental effects on degradation of zirconates

Bond Coat
- Evaluate processing (HVOF/LPPS + anneal) effects on microstructure and phase composition of MCrAlY (where M = Ni, Co, Si, Hf, and/or La)
- Determine IGCC environmental effects on long-term oxidation of bond coat materials

System Level
- Determine thermal gradient effects on overall multilayer TBC system
- Evaluate the impact of water vapor on degradation of multilayer TBC

Plasma spray is naturally suited for such layered manufacturing
Design consideration for YSZ- GDZ multilayer architectures

Multifunctional Multimaterial TBCs

- Erosion, CMAS Resistant
- Low $K$, $E$ GZO Layer

Possible Microstructural Variants

- Dense GDZ / DVC GDZ
- Porous YSZ / Porous GDZ
- DVC / Thin interfacial layer of dense YSZ
The multilayer TBC architecture

- 50+ coating conditions
- 40+ architectures
- 600+ FCT samples

- Adequate erosion resistance
- Significantly higher durability
- CMAS resistance
- Mechanisms and Methodology to incorporate any new composition

Validated through FCT testing both in house, ORNL and industry (Siemens, GE) during UTSR program
Successfully validated at industrial sites (GE, Siemens, Praxair)

FCT: 2000°F (1093°C), 45 mins cycling

![Bar chart showing TBC lifetime (cycles) for various bond coat configurations: Porous YSZ, Dense YSZ, Bi-layer YSZ, YSZ-GDZ. All failed at BC/TC interface.](image)

JETS test

![Image of JETS test setup with Dr. Li Li’s courtesy note.](image)

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6 x 2000 cycles: No Failure yet

Courtesy: Ben Nagaraj
Applying similar ideas to emergent TBCs, EBCs, T/EBCs

Current TBCs

Current bill of TBCs

Application challenges

Increasing Turbine operation Temperature

Y:1980

Conventional single layer TBC

Low-K YSZ

Ni based- Bond Coat

Superalloy

Phase-stability

CMAS

Y:2015

Multilayer Advanced TBC

Low K, CMAS Resistant GdZrO

Low E, K- YSZ

High Kc - YSZ

Ni based- Bond Coat

Superalloy

Phase-stability

CMAS

Substrate Temp Limit

Multilayer Advanced EBCs

Yb2SiO5

Low water volatalization

Si-bondcoat

CMCs

Mullite-oxygen barrier

SiO2(s) + 2H2O(g) = Si(OH)4(g)
MesoPlasma™ 3D-Printing Technology

- Provides **new process capabilities** not achieved with conventional plasma spray / cold spray

**Direct Write Technology**

- Precision, multi-layered metallic and ceramic dielectric patterns
- Printed thermocouples and high watt density heaters onto parts
- Stand-alone heat flux sensor and heater products
- Printed patterns onto temperature-sensitive polymer films