FARADAYIC Development of Electrically Mediated Electrophoretic Deposition for Thermal Barrier Coatings

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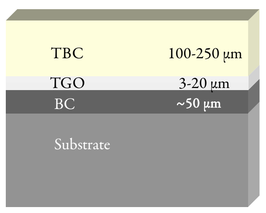
Background

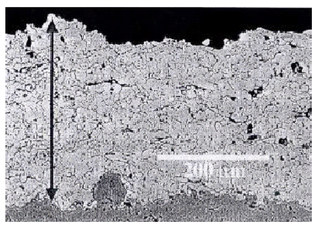
- There is a need for an affordable, non-line-of-sight method of coating complex-shaped turbine engine components with thermal barrier coatings (TBCs) that have controllable thickness distributions and a microstructure that is sufficiently strain-tolerant and will survive in the turbine environment.
- Typically plasma spray (PS) or electron beam physical vapor deposition (EB-PVD) are used to deposit TBCs
- Electrophoretic deposition (EPD) is a non-line-of-sight process that is easy to control and more cost effective when compared with the more conventional techniques.
- TBCs are one component of the thermal barrier system:
  - Substrate (Ni superalloy) supports structural load
  - Bond coat (BC – MCrAlY or Pt-Al) provides oxidation protection for substrate, alleviates CTE mismatch between TBC and substrate, enhances adhesion
  - Thermally Grown Oxide – prevents oxidation of bond coat
  - Thermal Barrier Coating (TBC) – thermal insulator



- Each mil of TBC can reduce surface temperature of underlying alloy by 17 – 33 °C
- Material candidates need to possess several important properties:
  - High melting point
  - Low thermal conductivity
  - CTE similar to the substrate or BC
  - Low sintering rate of microstructure
  - Chemical inertness
  - No phase transitions at operating temperature
- Most common TBC is yttrium stabilized zirconia (YSZ)

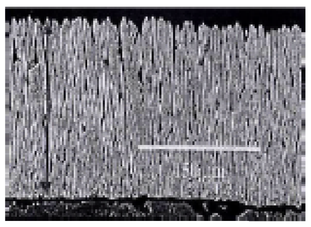
Technology Comparison

Plasma Spray TBC Microstructure



- Laminar microstructure, disc-like pores
- Relatively uniform distribution of microcracks parallel to the substrate surface
- Impedes heat flow, reduces the elastic modulus
- Low thermal conductivity, minimal stresses
- Suitable for abradable seals
- Pores and microcracks weaken the fracture toughness
- Not ideal for coating complex-shaped parts

Electron Beam-PVD TBC Microstructure



- Tapered columnar microstructure prevents the build-up of tensile stresses
- Reduce CTE mismatch stress between the TBC and the BC
- Strain tolerant coatings, improved spallation resistance and reduced erosion rates
- Higher thermal conductivities causing cracks at the TGO/BC interface
- Feature thickness increases with coating thickness

Methodology

Electrophoretic Deposition

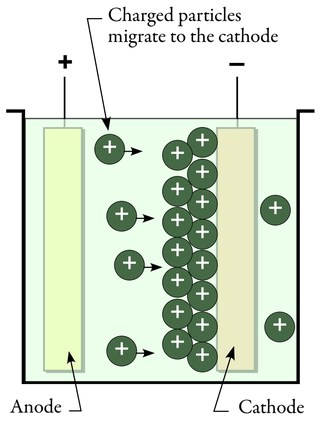
Three fundamental steps:

(1) Charging of the particles in suspension (can be either positive or negative)

(2) Electric field-induced migration of the particles toward an oppositely charged substrate (cathode in the case right)

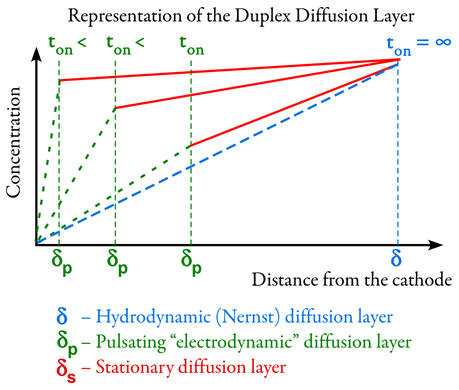
(3) Deposition and adherence of the particles onto the substrate.

Post treatment, such as sintering for ceramic coatings, is typically required to convert the coating into its final form.



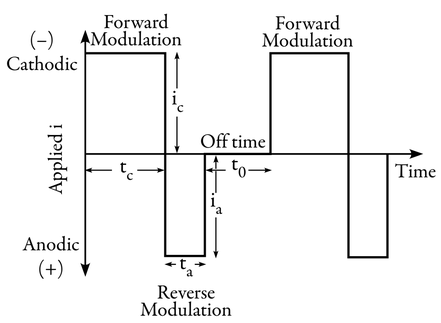
FARADAYIC Process

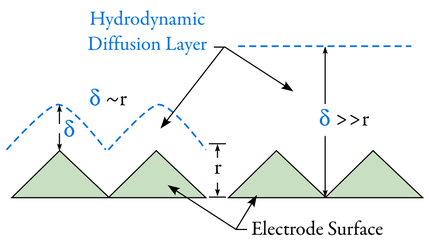
- Mass transport in pulse/pulse reverse processes is a combination of steady state and non-steady state diffusion processes.
- δ varies from 0 at the start of a pulse to a steady state value when the Nernst diffusion layer is established. If the current is interrupted before δ reaches steady state, the reacting ions diffuse back to the electrode and replenish the surface concentration before the next pulse. The reactant concentration at the surface pulses with the frequency of the modulation.
- The duplex diffusion layer consists of a pulsating layer, δ_p, and a stationary layer, δ_s. δ_p is proportional to the pulse on-time.



- Current distribution determines particle distribution. Controlled by geometric, kinetic and mass transport effects, which are influenced by cell design and waveform parameters.

Pulse/Pulse Reverse (FARADAYIC) Electric Field





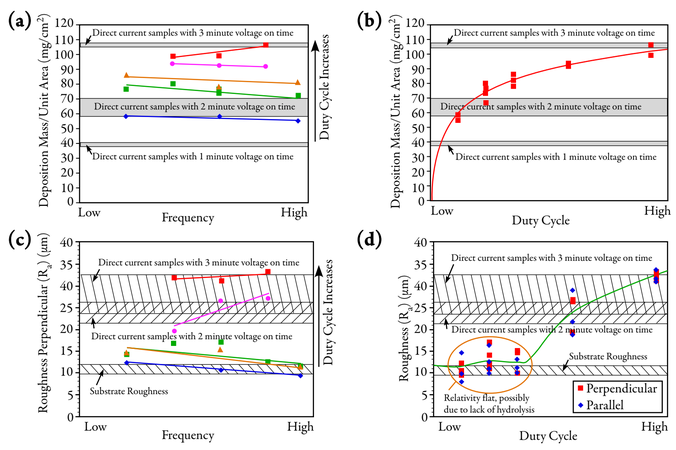
left - Macroprofile; right - Microprofile

Macroprofile: Diffusion layer tends to follow the surface contour. Mass transport control results in a uniform current distribution or a conformal deposit during deposition.

Microprofile: Diffusion layer thickness surface roughness. Mass transport control results in a non-uniform current distribution.

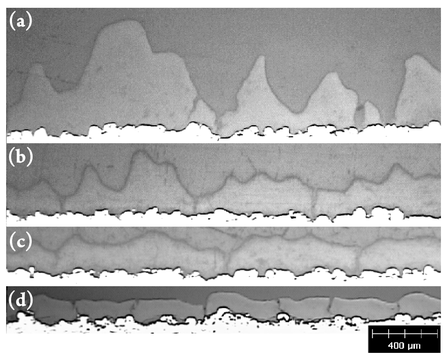
The appropriate waveform can alter the thickness of the pulsating diffusion layer and effectively focus or defocus the current distribution to create non-uniform or uniform deposition respectively.

FARADAYIC EPD Process Parameters



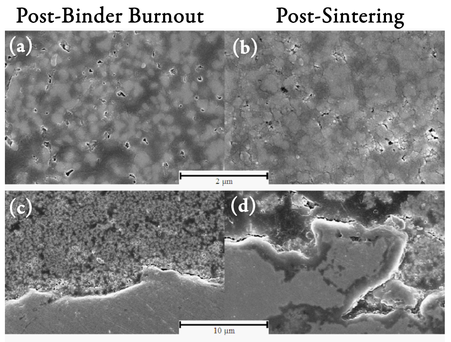
The effects of pulsed current parameters on deposition mass per unit area (a, b) and average surface roughness (c, d). Frequency effects are on the left and duty cycle effects are on the right. Guides for the eyes have been added to aid in identifying the general trend of the data

Microstructue

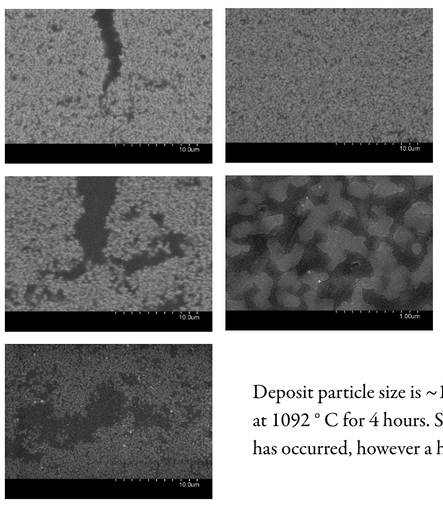


Cross-section micrographs of (a) DC-EPD sample (295 µm) compared with FARADAYIC EPD samples with (notation as duty cycle (g)/frequency (f)) (b) high g/high f (185 µm), (c) medium g/high f (190 µm), and (d) low g/high f (102 µm). Notice a drastic decrease in peaks and valleys, leading to an overall better film quality.

Post-Binder Burnout Post-Sintering



SEM micrograph comparison of various features seen in samples that have undergone a binder burnout process (left) and a sintering process (right). The pictures a & b show the particles that make up the film. Samples c & d show the bond coat-film interface and the effects of sintering on the bond coat.



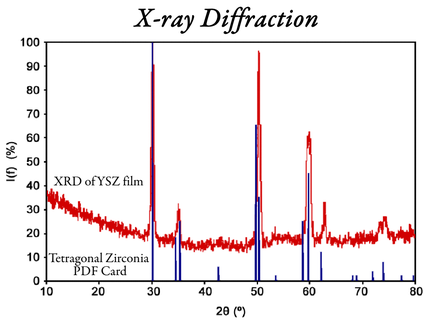
(Left Column) Images of drying induced mud crack tips in sintered films deposited at high frequency (f) and (top) low duty cycle (g), (middle) medium g, and (high) high g films. This mud cracking forms immediately upon drying at 80-90 ° C and is more prevalent in films deposited at higher g.

(Right Column) Images of the bulk of the film in a sample deposited at low g/high f magnified at (top) 5 kx and (bottom) 50 kx.

Deposit particle size is ~100-300 µm. Samples were sintered at 1092 ° C for 4 hours. Significant necking of the particles has occurred, however a high degree of porosity remains.

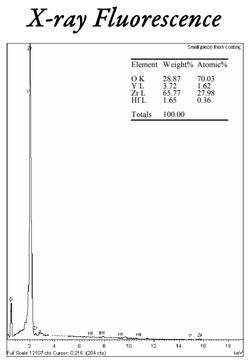
Elemental and Phase Analysis

X-ray Diffraction



X-ray diffraction (XRD) of TBC material (8% YSZ) deposited by pulsed FARADAYIC EPD and sintered at 1092 ° C. The data strongly correlates to the tetragonal phase of YSZ. Characteristic monoclinic peaks (2q = 28.174° and 31.467°) are absent from the scan.

X-ray Fluorescence



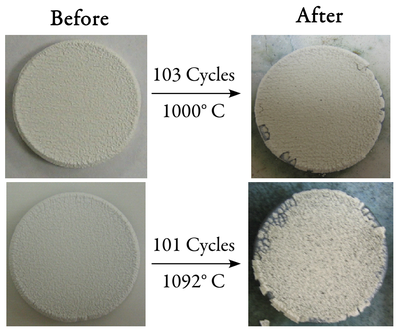
X-ray Fluorescence (XRF) of TBC material (8% YSZ) deposited by pulsed FARADAYIC EPD and sintered at 1092 ° C. No carbon contamination could be detected in the film after post processing.

Thermal Cycling

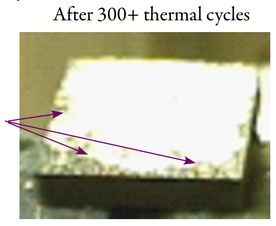
Thermal cycling parameters:

- Heat to 1092 ° C in air by placing the sample into a pre-heated furnace
- Hold for 1 hour
- Cool to RT by removing the sample from the furnace.

Very little spallation (4.9%) has occurred and is concentrated at the edges of the sample where the bond coat is not as uniform, the TBC is somewhat thicker, and sharp corner radii are found. The bulk of the film has seen little to no damage from the thermal cycling experiment.



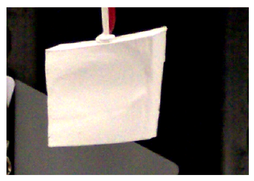
Haynes 230 Substrate, NiCoCrAlY BC
After 300+ thermal cycles



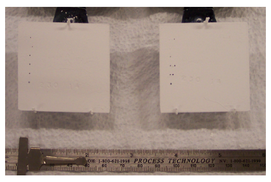
Long Term Testing:

- Samples placed into preheated furnace at 1100 °C (air) for 60 min.
- Removed from furnace with 15 minutes forced air cooling
- Repeat

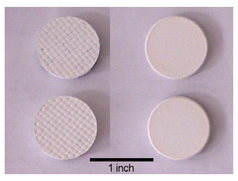
Selected Activities



2D and 3D complex shape depositions



Through hole depositions, no clogging of 396 µm holes



Depositions on CMC substrates

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Summary and Conclusions

- YSZ was deposited by EPD onto MCrAlY coated nickel-based superalloys using pulsed FARADAYIC parameters
- Samples prepared using pulsed FARADAYIC EPD showed improvement over those prepared using conventional EPD by exhibiting:
  - decreased roughness
  - decreased hydrolysis
  - decreased edge effects
  - enhanced uniformity
- FARADAYIC EPD did show longer deposition times than conventional EPD to get an equivalent mass of coating
- XRD confirmed that the YSZ is still in the tetragonal phase
- Thermal cycling tests are showing that the films are at least moderately resistant to cyclic stresses
- Conventionally processed films may be most beneficial in regions where high porosity is advantageous

Future Work

- Further investigation of the effect of FARADAYIC Parameters, especially pulse-reverse fields and how they relate to 3-D shapes.
- Investigate alternate post-processing techniques and the microstructures that result
  - Alternate atmosphere (vacuum, inert gas, oxygen, etc.)
  - Higher temperatures
  - Microwave sintering
  - Oxy-acetylene torch
  - IR Lamp
- Confirm thermal conductivity value of ~0.10-0.12 W/m/K
- Continue tests important to the end use environment (thermal stability, thermal cycling, etc.)
- Begin testing of samples within an interturbine burner rig
- Begin experiments on controlled porosity depositions