FARADAYIC[SM] Development of Electrically Mediated Electrophoretic Deposition for Thermal Barrier Coatings

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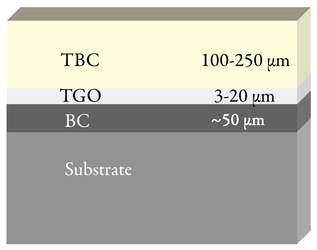
Background

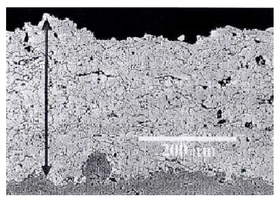
- There is a need for an affordable, non-line-of-sight method of coating complex-shaped turbine engine components with thermal barrier coatings (TBCs) that have controllable thickness distributions and a microstructure that is sufficiently strain-tolerant and will survive in the turbine environment.
- 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)

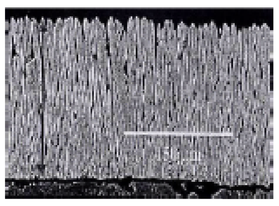
Technology Comparison

Plasma Spray TBC Microstructure



- Laminar microstructure with disc-like pores
- Low thermal conductivity but weakened fracture toughness

Electron Beam-PVD TBC Microstructure



- Columnar microstructure
- Improved spallation and erosion resistance but higher thermal conductivities

Methodology

Electrophoretic Deposition

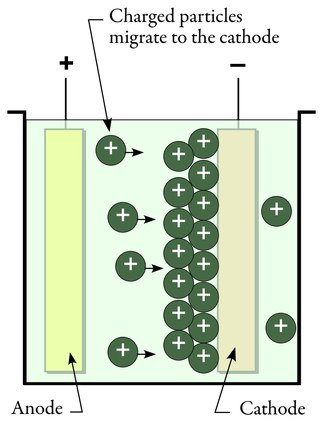
Three fundamental steps:

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

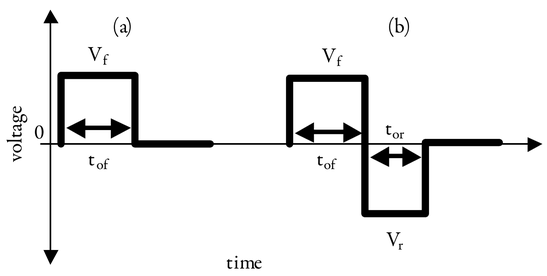
(2) Electric field-induced migration of the particles toward an oppositely charged substrate (cathode in the case right)

(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.



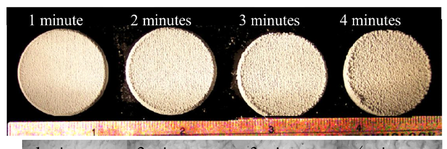
Pulse/Pulse Reverse Waveforms



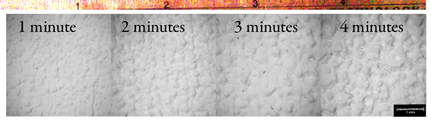
Basic waveforms for (a) FARADAYIC[SM] pulse reverse EPD experiments

DC EPD (Early) Work

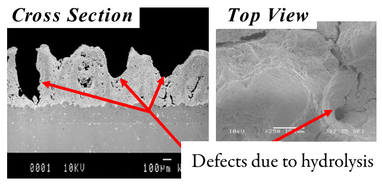
Comparison of 4 samples deposited using DC EPD

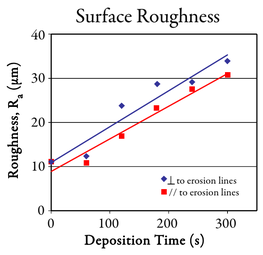


Optical micrograph images of the surface of the same 4 samples deposited using DC EPD

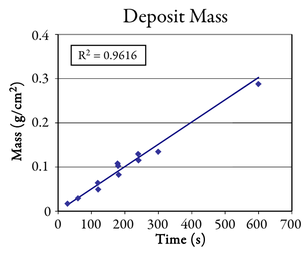


Cross-section (left) and top view (right) images of hydrolysis defects seen in samples process by DC EPD



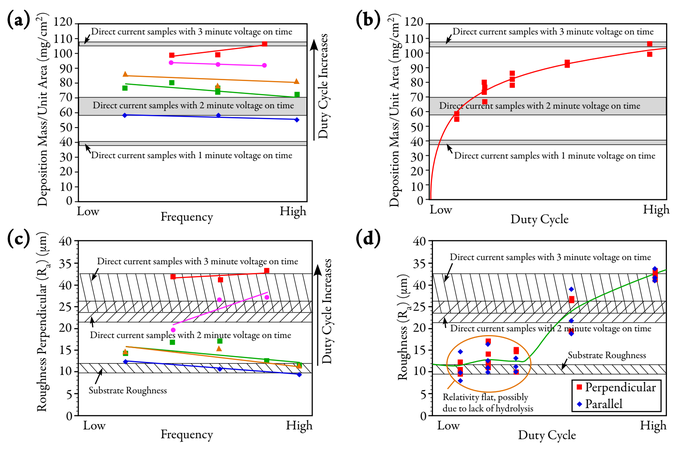


(Left) Surface roughness of samples processed by DC EPD. As the samples are ran for a greater time, they become rougher due to more severe hydrolysis effects on the surface.

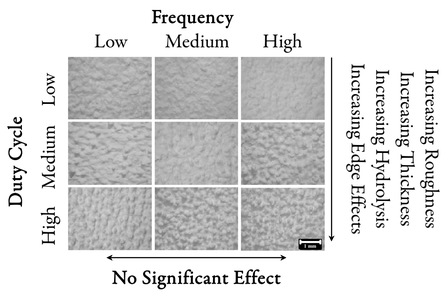


(Right) Mass of coating deposited during DC EPD showing the linear relationship between deposition mass and deposition time.

FARADAYIC[SM] EPD Process Parameters

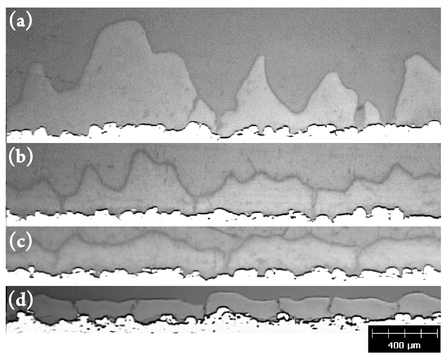


The effects of pulsed current parameters on deposition mass per unit area (a, b) and average surface roughness (c, d). Frequency effects are on the left and duty cycle effects are on the right. Guides for the eyes have been added to aid in identifying the general trend of the data

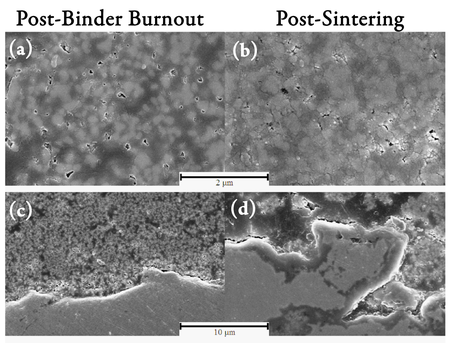


Surface of samples prepared using the FARADAYIC[SM] EPD process under varying deposition parameters

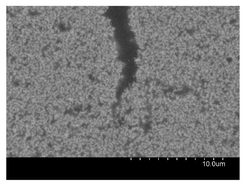
Microstructue



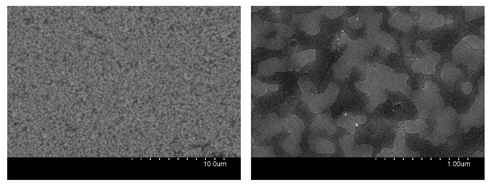
Cross-section micrographs of (a) DC-EPD sample (295 µm) compared with FARADAYIC[SM] EPD samples with (notation as duty cycle (γ)/frequency (f)) (b) high g/high f (185 µm), (c) medium γ/high f (190 µm), and (d) low γ/high f (102 µm). Notice a drastic decrease in peaks and valleys, leading to an overall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



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.

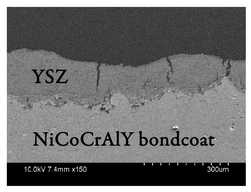


(Left) Image of drying induced mud crack tips in sintered films deposited at by EPD. This mud cracking forms immediately upon drying at 80-90 °C and is more prevalent in films deposited at higher duty cycle (γ). Frequency (f) does not appear to have a significant effect on cracking



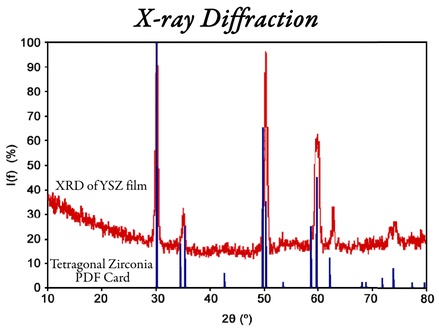
(Right) Images of the bulk of the film in a sample deposited at low γ/high f magnified at (left) 5 kx and (right) 50 kx. Deposit particle size is ~100-300 µm. Samples were sintered at 1092°C for 4 hours. Significant necking of the particles has occurred, however a high degree of porosity remains.

(Right) Image of a typical film processed at 20% γf. Vertical cracks are mud-cracking effects due to drying.



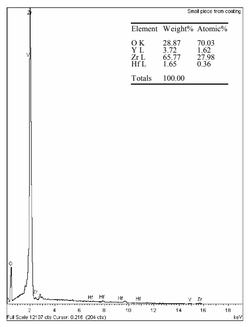
Elemental and Phase Analysis

X-ray Diffraction



X-ray diffraction (XRD) of TBC material (8% YSZ) deposited by pulsed FARADAYIC[SM] 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



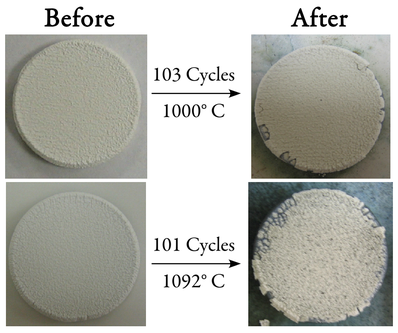
X-ray Fluorescence (XRF) of TBC material (8% YSZ) deposited by pulsed FARADAYIC[SM] EPD and sintered at 1092 ° C. No carbon contamination could be detected in the film after post processing.

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.

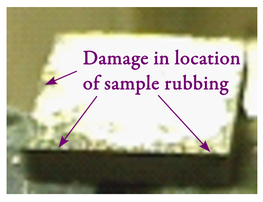
Very little spallation (4.9%) has occurred and is concentrated at the edges of the sample where the bond coat is not as uniform, the TBC is somewhat thicker, and sharp corner radii are found. The bulk of the film has seen little to no damage from the thermal cycling experiment.



Haynes 230 Substrate, NiCoCrAlY BC

One full cooling cycle during the long term thermal cycling test

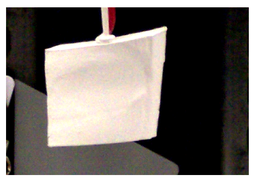
After 300+ thermal cycles



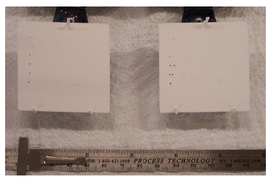
Long Term Testing:

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

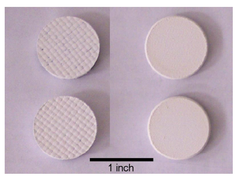
Selected Activities



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[SM] parameters
- Samples prepared using pulsed FARADAYIC[SM] EPD showed improvement over those prepared using conventional EPD by exhibiting:
  - decreased roughness
  - decreased hydrolysis
  - decreased edge effects
  - enhanced uniformity
- FARADAYIC[SM] 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[SM] 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.)
- Testing of samples within a burner rig
- Develop the ability to generate films with high density and films with controlled variable porosity