Topical Symposia
Room Royal Palm 4-6 - Session TS1
Thermal and Kinetic Spray Deposition

Moderators: Andrew Vackel, Sandia National Laboratories, USA, Charles Kay, ASB Industries, Inc., USA

8:00am **TS1-1 Latest Developments for Turbomachinery Coatings**, ***Kirsten Bobzin***, *L Zhao, F Linke, S Wiesner, B Yildirim, T Liang, M Welters,* Surface Engineering Institute - RWTH Aachen University, Germany **INVITED**

In accordance with the key objectives -higher efficiencies and lower emissions- components of modern turbomachinery systems, i.e. stationary and rotating blades, are subject to very high demands, which need to be fulfilled among others with innovative coating solutions. Protective coatings are, therefore, the state of art to ensure functionality of turbomachinery components with prolonged life times.

In this presentation, some of research work of Surface Engineering Institute of RWTH Aachen University on the above-mentioned coating solutions is introduced summarily. Firstly, an erosion resistant coating based on nanocomposite nitride (Ti,Al,Si)N applied by means of high speed physical vapor deposition (HS-PVD) for protection of gas turbine compressor blades and a thick erosion resistant Ni-based composite coating applied by deposition brazing for protection of steam turbine blades will be presented. Subsequently, EB-PVD thermal barrier coatings (TBC) based on different pyrochlore zirconates with multilayer coating architecture will be demonstrated. Furthermore, a highly porous, plasma sprayed TBC, based on Gd_2O_3- Yb_2O_3 co-doped ytrria-stabilized zirkonia (YSZ), will be introduced. Finally, two oxidation protective coatings for γ-TiAl substrates will be subjected. The first one is an amorphous (Al,Cr)ON coating deposited by means of HS-PVD. The second one is a plasma sprayed coating with a Ti-diffusion barrier interlayer. All of the coatings show promising results with respect to their intended functions.

8:40am **TS1-3 Repair of Nickel Base Superalloys by Cold Spray**, ***Robert Vaßen***, *R Singh, T Kalfhaus, G Mauer, O Guillon,* Forschungszentrum Jülich GmbH, Germany; *J Gibmeier,* Karlsruhe Institute of Technology (KIT), Germany **INVITED**

In the cold spray process, deposition of particles takes place through intensive plastic deformation upon impact in a solid state at temperatures well below their melting point. The high particle impact velocities and corresponding peening effects can lead to high compressive residual stresses in cold spray coatings. This can be advantageous with regard to mechanical properties as fatigue life and hence, cold spray seems to be an ideal process for repair applications. In this study, Inconel 718 powder particles were cold-sprayed on Inconel 718 substrates by using nitrogen gas for an application as a repair tool for aero engine components. First, velocities of the cold sprayed particles have been determined as a function of process conditions and particle size. Critical velocities have been determined considering the deposition efficiencies.

Furthermore, the magnitude of the residual stress and its distribution through the thickness of the cold-sprayed coatings were measured by using the hole-drilling and the bending methods. Mainly compressive residual stresses were observed in cold-sprayed Inconel 718 coatings. Accumulation of residual stresses in the coatings is highly affected by peening during deposition and it decreases with increase in thickness. It has been observed that the bond--strengths of cold-sprayed Inconel 718 coatings are highly influenced by coating thickness and residual stress states of the coating/substrate system. A detailed discussion will be given.

In addition, also further results on cold spraying different Ni base superalloys on CMSX 4 type substrates will be presented and discussed. Especially the influence of substrate temperature will be highlighted.

9:20am **TS1-5 Multi-layer Metallization of Polymer Materials via Thermal Spray**, ***Andrew Vackel***, *M Smith, A Miller,* Sandia National Laboratories, USA; *B Peter, B Post,* Oak Ridge National Laboratories, USA

With the emerging prevalence of 3D printed polymer materials for rapid prototyping, there is an increasing demand for a similar ease and quickness in producing metallic and multi-material components. One such approach is through the metallization of printed polymer parts using thermal spray, where thick deposits can be quickly and economically deposited. However, technical challenges include management of residual stress of the deposit, assessing the adhesion strength of sprayed metal onto polymers, and potential thermal degradation of polymer substrates from molten droplet impingement during spraying.

This presentation will discuss the methodologies used to accomplish successful metallization of polymer substrates (e.g., ABS, HDPE) including *in-situ* measurements of substrate deflection for calculation of residual stress, mechanisms and quantification of adhesion between polymers and sprayed metal, and optimization of spray processing and material layering.

9:40am **TS1-6 Dielectric Ceramic Thick Films produced via Aerosol Deposition**, ***EricA. Patterson***, ASEE Postdoc, US Naval Research Lab, USA; *S Johnson, E Gorzkowski,* U.S. Naval Research Laboratory, USA

The aerosol deposition (AD) method is a thick-film deposition process that uses ~500 nm particle size oxide powders to produce 95% dense films, up to several hundred micrometers thick with nanometer sized grains. The deposition can be performed on a variety of substrates because bonding and densification between the film/substrate interface are thought to be facilitated by local temperature rise, high pressure, particle fracture, and chemical bonding during deposition, which leads to the nano-grained microstructures created at room temperature. In this work, we present film characterization results of depositing dielectric and ferroelectric materials using aerosol deposition. Film properties will be compared when adjusting process parameters such as varying flow gas rate, gas type, and substrate material. Further characterization will be performed by changing annealing conditions, and electrode application.

10:00am **TS1-7 Tribological Properties of Cold Sprayed Metal Matrix Composite Coatings**, ***Richard Chromik***, McGill University, Canada **INVITED**

Metal matrix composites (MMCs) provide a significant advantage for their tribological properties compared to pure metals. There is a long history of metal-ceramic composites for enhancement of load carrying capacity and solid lubricating composites for friction reduction. Both type of composites will generate 'tribofilms' that help to reduce wear and control friction. One may also engineer MMCs with both hard phase and solid lubricants.

There are many methods of manufacture for MMCs in bulk form and a few options for manufacturing them as coatings. Cold spray is one such coating deposition technique that has received increased attention in recent years. Researchers have developed a wide range of MMC coatings by cold spray, typically basing materials selection on metal-ceramic or metal-solid lubricant MMCs made by traditional methods. Recent work from our group has included cold spray coatings of Al-Al_2O_3, Ti-TiC, Cu-MoS_2 and Ni-WC.

In this presentation, cold sprayed MMCs will be discussed in terms of their 'sprayability' and, for successful coating systems, their tribological properties. Coatings are tested in sliding wear and sometimes fretting wear test conditions. For both cases, post-characterization of cross-sectioned wear scars reveals microstructural evolution near surface leading to formation of tribofilms that provide wear resistance and friction control. Structure and properties of the tribofilms are determined with SEM, TEM, EDS, Raman spectroscopy and nanoindentation. Tribofilms are found to be mixtures of the two components in the MMC, but with finer microstructure and some level of oxidation that leads to higher hardness. The tribological performance of cold sprayed MMC coatings, similar to MMCs made by other methods of manufacture, depends significantly on the nature of the third bodies formed by the wear process. However, due to the cold-worked nature of cold sprayed metals and the lack of full metallurgical bonding in some coatings, some differences were observed and will be discussed.

10:40am **TS1-9 Assessment of Magnetic Orientation of Barium Hexaferrite Thick Films Deposited by Aerosol Deposition with *in situ* Magnetic Field**, ***ScooterD. Johnson***, Naval Research Laboratory, USA; *D Park,* Korean Institute of Material Science, Korea; *A Hauser, S Ranjit, K Law,* University of Alabama, USA; *H Newman, S Shin, S Qadri, E Gorzkowski,* Naval Research Laboratory, USA

Devices utilizing magnetic materials such as frequency selective limiters, circulators, inductors, and filters are critical components in many of today's electronics [1]. The need for ferromagnetic materials in these devices poses many difficulties for minimizing device size, weight, and cost. One issue that hampers integration of ferromagnetic materials is the high-melting temperature of the ferrite compared with the low-melting temperature component structure [2]. Furthermore, the need for low-loss and narrow bandwidth operation adds another significant barrier to the advancement of integration of ferromagnetic materials into these device structures.

The high-frequency operation regime and strong uniaxial anisotropy of barium hexaferrite ($BaFe_{12}O_{19}$, BaM) makes this material particularly interesting to utilize as an oriented film for microwave components. In this study, we characterize BaM films deposited onto sapphire substrates by a room-temperature thick-film growth technique called aerosol deposition.

We perfomed alternating gradient magnetometry depth studies on a series of as-deposited films that show a variation in magnetization with depth. Cross-sectional SEM images indicate laterally uniform film density. Electron dispersive spectroscopy of the interfacial region suggest significant Al_2O_3 mixing into the film volume. Fe XPS spectra indicate a change in peak weighting as a function of thickness, possibly indicative of modified structure or oxygen incorporation due to Al incorporation.

To explore the possibility of magnetically orienting the films we deposited additional films in the presence of a 4 kOe static magnetic field. We report VSM, FMR, and XRD results of these films as-deposited and after post-deposition sintering at temperatures from 700C to 1000C.

The films deposited in the field show an increased saturation magnetization and remanence compared to the films deposited with no applied field. XRD results of all of the films in this study suggest good crystallinity. Rietveld refinement of the data also suggests that the films deposited in the field presence have a smaller unit cell volume compared to films deposited without the applied field. Post-growth sintering increases the crystallite size from about 10 nm to 25 nm. Annealing improves the overall properties of the films further increasing the magentic orientation and saturation.

[1] Adams, J., Davis, L., Dionne, G., Schloemann, E., and Stitzer, S., IEEE Transactions on Microwave Theory and Technology, **50** (2002), No. 3, pp.721.

[2] Johnson, S., Newman, H., Glaser, E., Cheng, S.-F., Tadjer, M., Kub, F., and Eddy, C., IEEE Trans. on Magnetics, **51**, (2015), No. 5, pp. 2200206.

11:00am **TS1-10 Development of Repair Methods for Nickel Based Super Alloys using Cold Gas Spray**, ***Tobias Kalfhaus****, R Vaßen,* Forschungszentrum Jülich GmbH, Germany

The hot section parts in aviation engines and stationary gas turbines are exposed to extreme environments, where high temperatures and eroding atmospheres lead to oxidation, corrosion and fatigue damage of the inserted parts. As the manufacture of the nickel based superalloys for those high temperature applications is expensive, the repair of worn or damaged parts is from an economic viewpoint desirable, however, usually difficult due to the poor weldability of these alloys.

The coating technology Cold Gas Spray has been tested to repair such worn parts and reduce the maintenance cost. In this process heated and pressurized gas is expanded through a Laval-Nozzle. This leads to a high-speed gas jet and accelerates the powder to supersonic velocities. The operating temperature is relatively low compared to the melting point of the used alloys. The particles hit the substrate, deform and are bonded to the substrate by mechanical clamping and formation of intermixing zones. An oxide free and dense coating is formed. With an increasing coating thickness the stored elastic energy in the coating increases and can lead the delamination of the coating at a critical thickness.

In this study the alloys CMSX-4, Rene 80, Inconel 625, Inconel 713 and Inconel 738 are deposited on single crystalline substrates that are similar to CMSX-4 and polycrystalline Inconel 738 substrates. All used powders are spherical and have a diameter between 5-45 µm. To show different residual stresses that evolve during the coating process curvature measurements were performed on round Inconel 738 samples. Each powder shows different adhesion to the substrate. To characterize the differences adhesion tests were performed.

To reduce residual stresses and increase the critical thickness of the coating a heated stage is tested to investigate the influence of a heated substrate. Additional heat treatments were performed to investigate the change of porosity and microstructure within the coating and at the interface between the substrate and the coating. The evolving microstructures were examined using scanning electron microscopy (SEM) and Electron Backscatter diffraction (EBSD).

11:20am **TS1-11 Microstructure-scale Simulations of High-rate Loading of Porous, Thermally-sprayed Metal Coatings**, ***Corbett Battaile****, N Moore, S Owen,* Sandia National Laboratories, USA

The properties of most engineering materials depend on the characteristics of internal microstructures and defects. In metals, these features can include grains in the polycrystalline aggregate, impurities, multiple phases, and in the case of thermally sprayed coatings, significant levels of porosity. The microscopic details of the interactions between these internal defects, and the propagation of applied loads through the body, act in concert to dictate macro-observable properties like strength, conductivity, spall, etc. In order to achieve a comprehensive understanding and control of a material's high-rate properties, the relevant structure-properties relationships must be understood. In this work, we used Sandia's Alegra finite element software [1] to simulate the high-rate loading of metal coatings manufactured by thermal plasma spraying. These simulations include a direct representation of the microstructural details of the material, such that internal features like second phases and pores are represented and meshed explicitly as individual entities in the computational domain. We will discuss the dependence of the high-rate mechanical properties of these materials on microstructural characteristics such as the shapes, sizes, and volume fractions of the second phases and pores. We will also examine the effects of pore collapse on high-rate response, and how the details of the microstructural representation affect the microscopic material response to the applied load. In particular, we will discuss the effects of using "stairstep" (on a cubic finite-element "grid") versus comformal (smooth) interfaces created via Sandia's SCULPT capability in CUBIT [3].

1. <http://www.cs.sandia.gov/ALEGRA/Alegra_Home.html>

2. <http://www.sandia.gov/mst/pdf/LENS.pdf>

3. <https://cubit.sandia.gov/>

11:40am **TS1-12 Simulation and Visualization of the Aerosol Deposition Process**, ***EdwardP. Gorzkowski****, S Johnson, T Martin, R Saunders,* U.S. Naval Research Laboratory, USA*; A Borgdorff,* U.S. Naval Academy, USA*; D Schwer,* U.S. Naval Research Laboratory, USA*; E Patterson,* ASEE Postdoc, U.S. Naval Research Laboratory, USA

Aerosol deposition (AD) is a thick-film deposition process that can produce layers up to several hundred micrometers thick with densities greater than 95% of the bulk. Though this process has been used for two decades the precise mechanisms of bonding and densification is still debatable. Therefore, we have used a combination of computational fluid dynamics (CFD) and finite element (FE) modelling and high speed videography to help understand the flight of the particles as well as the interaction of the particle and the substrate. The CFD model results show the flight of particles from the nozzle to just before the substrate. At the point just before impact, the velocity and direction is collected and used to inform the FE model of the flight of the particle. Initially the FE model is run with the parameters obtained from the CFD model but the work is extended to include variations in particle size, velocity, and material to show their effects on the deposition process. The model is developed as full 3-D implementation with symmetric boundary conditions applied when/where appropriate. The particle and substrate materials are independent and each is varied between Al_2O_3, SiC, and float glass. Each material is simulated using a Johnson-Cook constitutive model, which includes plasticity, damage initiation and evolution, and failure. The mechanical properties of each material are taken from bulk properties. The particle velocity is varied from 100 m/s to 300 m/s with sizes between 0.5 µm and 1.5 µm. The bounds were informed by the results of the CFD analysis. High-speed videography will help validate this model and to better understand the process as a whole.

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