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Stony Brook University

Center for Thermal Spray Research

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Going Beyond the Surface

LINKING RESEARCH TO PRACTICE

Message from the Director

I am pleased to introduce our annual newsletter "Going beyond the surface" highlighting important scientific and technical developments, industrial interactions and personnel/alumni updates. We are gearing for our fall industrial consortium meeting which is due to be held at Oak Ridge National Laboratory in Tennessee. Oak Ridge is part of the US National Laboratory system which conducts basic/applied research in science and engineering as well as provide specialized large scale user facilities to the scientific community at large to advanced research. Our host for this meeting is Dr. Edgar Lara-Curzio of the Materials Science and Technology division, with administrative support from Christine Goudy. We are grateful to Edgar and Christine as well as several other ORNL members in enabling this unique opportunity. Since 2010, the fall consortium meeting has been hosted at member/collaborator sites allowing expanded interaction with the said organization. In this instance, the consortium meeting will highlight extensive and on-going collaboration between Oak Ridge and the Center, bringing new insights into thermal spray research. During this meeting, we will endeavor to highlight some these interactions.

This past year has seen several important developments especially highlighting new opportunities for research and collaboration. Our advanced TBC project has continued with Oak Ridge focusing on bond coat processing and component geometry effects on coating durability. In this effort we have been fortunate to obtain support from consortium members including receiving materials from St. Gobain and Oerlikon Metco as well as superalloy and testing support from GE Aviation and Siemens Energy. Such shared activities and collaboration allows for systematic evaluation of coatings connecting performance with materials/processing. We will report on these developments during the upcoming meetings.

We have just successfully completed the 1st year of our three year program on thermal management coatings on diesel engines. This project funded by US Army along with Office of Naval Research seeks to examine thermal management coating design to meet the complex performance requirement of reciprocating engines, along with component engine testing at US Army enabling iterative feedback among design, synthesis and testing. Harnessing this opportunity can pay major dividends to the thermal spray industry while also benefiting engines from improved performance and efficiencies.

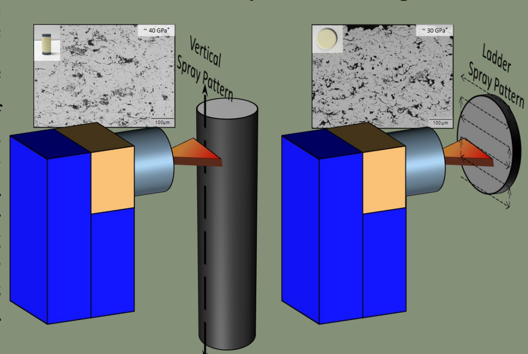
Finally, through a recently awarded project from Air Force Office of Scientific Research and in collaboration with Mexican National Laboratories, research has been initiated on multilayer TBCs and EBCs with emphasis on advancing knowledge of process induced attributes in silicate based EBC materials.

As always, I invite you to join the CTSR team to realize our common goal, to make thermal spray a household word.

- Sanjay Sampath, Director, CTSR

Capturing the Process Subtleties in TBC Deposition on Complex Geometries

Typically, plasma-sprayed TBCs have been analyzed for their properties and durability by the use of model disk geometry specimen (buttons) for furnace cycling or burner rig. Such tests are a convenient/efficient to evaluate materials and process conditions for design and manufacturing reliability. However, such tests may not fully represent the complexities component geometry point of view as well as from process-induced microstructural attributes. Industry has used a variety of strategies to capture geometry contributions. In many instances these tests tend to be expensive as they may involve deposition on actual components and may not fully capture the scientific underpinnings..



In the inset figure, impact of these issues on rod vs button substrates are illustrated along with microstructures of the coatings. Coatings produced using the raster pattern on the button results higher level of porosity and lower coating modulus (30 GPa). Coatings produced on rod specimen, which primarily receives the "sweet spot" of the plume can result in higher coating density with almost 25% increase elastic modulus (40 GPa) for nominally identical spray conditions. Initial thermal cycling results shows these variances in modulus lead to substantially reduced life in rods compared to buttons. Although industry has empirically addressed these issues, bringing new diagnostic and analytical capability can reduce development/optimization time.

One approach is through analysis of the spray plume using detailed particle diagnostics as a means to define the interaction plane between particle stream and component. Coupling this with location-specific microstructural characterization and simulated property measurements may provide fundamental strategies for describing formation dynamics and potentially enabling to emergent tools such as off-line robot programming.

CTSR researchers have been systematically examining these issues through both experiments and modeling. As a first step, the team has used particle diagnostic sensor *DPV-2000* to conduct a "grid" scan: detailing the particle state along an *X-Y plane* at the location of the component interaction. By using the grid scan, one can deduce where along an *X-Y plane* where certain particles exist in terms of their velocity, temperature, and diameter. For a typical plasma spray, it is well known that particles that ride on the periphery of the plume can have lower melting index than those that are within the core of the plume. As such deposits produced from the entire plume and truncated plume can be different. Ongoing work seeks to quantify these plume variances as a function of torch type, spray distance, powder injection both using microstructure and curvature based extraction of elastic properties.

In addition, in collaboration with Oak Ridge and through a Dept. of Energy project, TBCs on buttons and rods were subjected to thermal cycling to understand the effects of geometry-induced stress and microstructure on durability. Finite element modeling complement the experimental activities.

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Industrial Consortium News

The Consortium for Thermal Spray Technology hosted by CTSR continues to expand and provide benefits to industry across the supply chain. This past year has seem addition of two OEM members: Aerojet Rockedyne, a large and diverse aerospace company with a broad portfolio of interests has joined the group. In addition, Rolls Royce Engines is now part of the group. This is a testament to the continued interest in the consortium program and Stony Brook thermal spray activities. The Consortium is completing its 15th year starting from some 10 companies in 2002-03 to the present membership of 30 international companies.

Each company contributes $12,500 annually as membership fees to the consortium/CTSR enabling self-sustaining operations following the 11 year National Science Foundation Materials Research Science and Engineering Center grant from 1996 to 2007.

The spring consortium meeting held on Stony Brook University campus was attended by more than 90 participants from the member companies. Over the span of two-days, CTSR staff, students and collaborators presented updates on both science and technology as well as their value to industrial coating design & manufacturing.

CTSR Student Road Trip to Member Sites

On their way back from last year's fall consortium event at Mitsubishi Hitachi Power Systems in Savannah, Georgia, the students and staff had the opportunity to visit a number of consortium member sites and see first-hand spray practices in use during their long drive back to Stony Brook. The 9 students and staff also included several undergraduate students who got a chance to see 'gee-whiz' sights like large turbine assembly sections.

Tours were graciously offered at Siemens Energy in Charlotte, NC, TurboCoating, in Hickory, NC, and of course the large tours offered to the entire consortium at Mitsubishi's Savannah Machinery Works. These gave the group a glimpse at the broad processing arena – transitioning from coatings of individual turbine blades to components and large gas turbine assemblies. We are grateful to Maxim Konev (Mitsubishi), Chris Felts (TurboCoating), and Anand Kulkarni (Siemens) for their help organizing the tours. Next year's trip to Oak Ridge looks to be another exciting opportunity for the hardworking students.

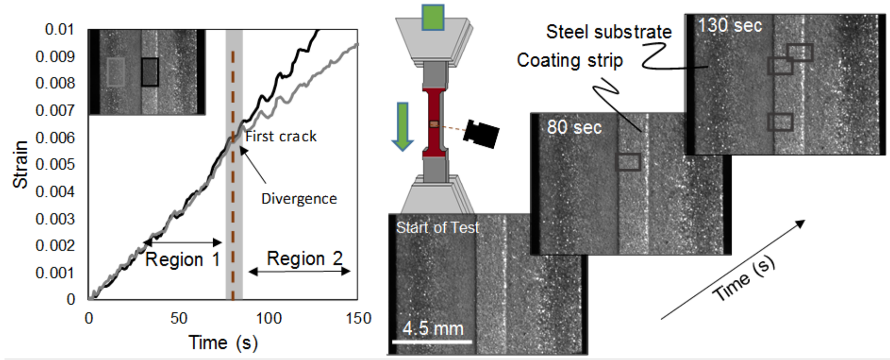
2016 Fall Consortium at Mitsubishi Hitachi Power Systems

As noted earlier, since 2010 the fall meetings are rotated around OEM partner sites to facilitate broad interest. Fall 2016 meeting was held at Mitsubishi-Hitachi Power Systems. This meeting follows successful past events at Naval Research Lab (2010), GE Aviation (2011), Boeing (2012), Tinker AF Base in Oklahoma City (2013), Applied Materials, Santa Clara (2014) and Cummins Engine Co, Columbus, IN (2015). Such offsite meetings allows expanded participation of design and manufacturing engineers from these organizations which will be crucial to enhance coating utilization in engineering systems.

Measuring Strain to Failure of Coated Materials Via Digital Image Correlation

Overlay coatings are widely used to impart a range of surface functionalities including thermal, wear, and corrosion protection, on a range of engineering components and structures. Additionally, use of selectively deposited overlays as a material reclamation solution can enable restoration of worn or damaged components. In most engineering applications, the coating's role is restricted to the surface, with limited integration to the underlying substrate. However, the situation is changing: there is an emerging need for so-called *structurally integrated coatings,* where the coating and substrate are intimately bonded, resulting in a coupled system with engendered multi-functionality.

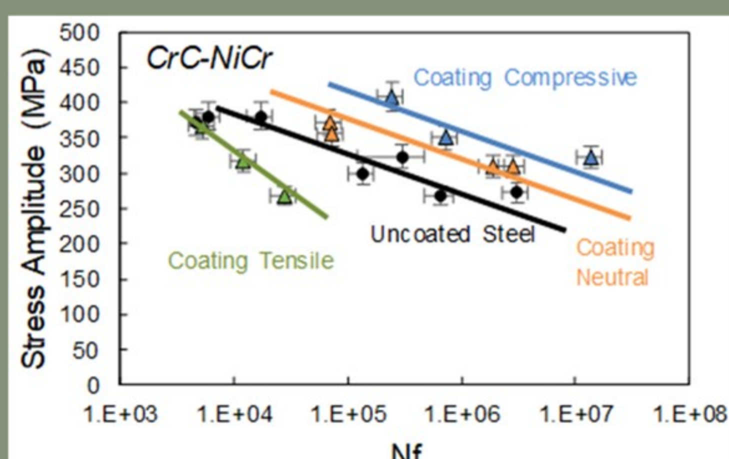
Thermal and cold spray deposits can be applied to loaded engineering components such as landing gear, heavy machinery hydraulics, and steel infrastructure, which all show promise as applications for both enhanced surface functionality and potential structural integration. However, in most cases, these even metallic coatings, respond in a brittle manner associated with their layered processing and ultra-fine grain sizes resulting from rapid quenching. The insert image shows a schematic of the uniaxial tensile testing setup in use at CTSR. Traditionally this testing process is monitored by the response of the machine load cell, with strain assessed through a clip-on extensometer. In this experiment, a thin strip of nickel coating was sprayed longitudinally on a tensile dogbone, and strain monitored through an external digital camera. This allowed frame-by-frame capture of the strain evolution, which was later processed with a digital image correlation tool, allowing the linking of crack formation events to specific time and strain events.



Residual Stress Implications in Carbide Coating Systems: Fatigue Behavior

It is well known that residual stress plays a critical role in many desirable coating properties. Wear, abrasion, and corrosion resistance can all be improved with the prevalence of high compressive residual stresses. In these scenarios, the compressive residual stress acts to resist crack opening ,which can propagate and lead to failures. Processing can play a significant role in the modulation of residual stress, and therefor has been a strong focus of past work at CTSR. Understanding process/property relationships can give large insight into new and existing TS applications. Processing changes directly affect the pre-deposit droplet particle state (temperature and velocity), the substrate surface (temperature and chemistry), environmental conditions (susceptibility to oxidation/reduction). With subsequent coating buildup, these processing effects can strongly manifest in the coating structure and eventual properties and performance.

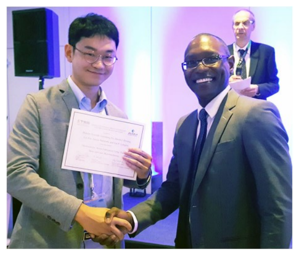
Fatigue behavior and performance is one such area where tailorable residual stresses can strongly determine lifetime. Compressive residual stresses can act to limit fatigue crack initiation and growth, which are strong concerns in applications such as landing gear or hydraulic cylinders. Testing at CTSR utilizes a few different mechanisms, however the most widely used is rotating bend fatigue. Coatings are deposited onto hour-glass shaped specimens and rotated at high speeds with an applied bending load. Failure of the coating or substrate results in complete failure of the system, which can be recorded as a function of the applied load, converted to a stress amplitude. A "map" of such behavior with HVOF CrC-NiCr coatings in various residual stress states is shown in the inset. As expected the compressive stress state sees a higher life (number of cycles, Nf) per stress amplitude as compared with the other coating states, and the uncoated steel substrates. The stress amplitude conversation compensates for the added material thickness. This assessment allows systematic analysis of coating modification, in the context of a highly repeatable and representative evaluation design.



People and Places

This year has been eventful for a number of occurrences in and around CTSR. A number of awards were received by both faculty and students this past year for their exemplary contributions. Professor Sampath was selected for the highly prestigious *TMS Application to Practice award*, reflecting his many years of persistent contributions to bring advance science to industrial practice. The nominators especially noted the importance of the Stony Brook Consortium as a unique mechanism to foster science-technology linkages, and to build human resources in specialized fields. Pictured here is Prof. Sampath receiving the award from Stan Howard during the TMS meeting in San Diego in February 2017.

CTSR also received the JTST best paper award for 2016 for the paper titled "Characterizing Suspension Plasma Spray Coating Formation Dynamics Through Curvature Measurements", co-authored by Ram Seshadri, Vaishak Viswanathan, Gopal Dwivedi and Prof. Sampath. In addition, Stony Brook Researchers also received the JTST Best Paper Honorable mention for their work titled "Thermoelectric Device Fabrication Using Thermal Spray and Laser Micromachining". CTSR has now received 6 JTST best paper awards highlighting their exemplary contributions to thermal spray. Pictured here are CTSR graduate students Greg Smith and Hwasoo Lee, receiving the best paper awards on behalf of the CTSR team during the ITSC event in Dusseldorf.



Also, notable is PhD student, Shalaka Shinde's ITSA Graduate scholarship award, continuing CTSR's successful streak of winning that award annually now for more than 20 years. Congratulations to all.

Alumni Focus: Dr. Anirudha Vaidya

In this newsletter, we are pleased to recognize, Dr. Anirudha Vaidya of Siemens Energy, Orlando, Florida. Anirudha completed his Bachelor's degree in Metallurgy at the Indian Institute of Technology, Kanpur and a Master's degree in Metallurgy from the prestigious Indian Institute of Science, Bangalore, India. After the graduate degree, he was employed in the Energy sector in India at the Bharat Heavy Electricals Limited, a leading provider of energy systems. While being employed at BHEL in 1993, he was offered a United Nations fellowship to spend a summer as visiting fellow at a US University. Anirudha sought out Stony Brook's thermal spray group under the tutelage of Prof. Herman. He soon became infected with the thermal spray virus and captivated by the Stony Brook environment. He returned to India and continued to work in turbine engine related materials for a few years. In 1998 he returned to Stony Brook to pursue full time education and research at the thermal spray center.

During his PhD he worked extensively on the development of process maps for thermal spray processes primarily through the use of process diagnostics. He benefited immensely from the accomplished network of Stony Brook faculty, post-docs and alumni – notably Dr. Rich Neiser who mentored him on statistical design of experiments for generating maps, Dr. Tilo Streibl on plasma spray diagnostics, Dr.J iri Matejicek on stress measurements and Dr. Anand Kulkarni on coating characterization. Participation and contribution in the formative days of CTSR consortium was invaluable since it provided a crucial link between the lab and industry. His process map work is highly recognized both in academia and industry.

After graduating in 2004, Anirudha continued an additional year as a post-doctoral fellow spearheading CTSR's consortium efforts which was still in its formative years during those years. Subsequently, he was recruited by the Gas Turbine division at Siemens Energy in Orlando, Florida. During his employment at Siemens, he continued to develop the tools and techniques from his PhD program and began implementation of these at various spray booths and apply them to gas turbine components. The many hats that a thermal spray engineer has to wear became clear when he had to undertake tasks and projects across the whole spectrum of coating design, testing & development, manufacturing and performance evaluation. This also provided the unique opportunity to grow his professional experience in other areas such as robotics, statistical analysis and manufacturing process control. Currently he is part of a group within Siemens that is primarily responsible for implementing novel manufacturing tools and techniques related to thermal spray coatings.

He continues to interact with current Stony Brook students, providing them insights from his wealth of application experience and industrial knowledge. We at Stony Brook are very proud of his accomplishments and look forward to seeing him grow and contribute in the field of thermal spraying. Anirudha lives in Orlando, FL with his wife Manjusha and his son Nishad, who is a college senior at the University of Florida.