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# ADVANCED THERMAL BARRIER COATING SYSTEM DEVELOPMENT

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TECHNICAL PROGRESS REPORT

to the

U.S. DEPARTMENT OF ENERGY

Oak Ridge Operations Office

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Submitted By

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# Advanced Thermal Barrier Coating System Development

## Program Objectives

The objectives of the program are to provide an improved TBC system with increased temperature capability and improved reliability relative to current state of the art TBC systems. The development of such a coating system is essential to the ATS engine meeting its objectives.

The base program consists of three phases:

Phase I: Program Planning - Complete
Phase II: Development
Phase III: Selected Specimen - Bench Test

Work is currently being performed in Phase II of the program. In phase II, process improvements will be married with new bond coat and ceramic materials systems to provide improvements over currently available TBC systems. Coating reliability will be further improved with the development of an improved lifing model and NDE techniques. This will be accomplished by conducting the following program tasks:

II.1 Process Modeling
II.2 Bond Coat Development
II.3 Analytical Lifing Model
II.4 Process Development
II.5 NDE, Maintenance and Repair
II.6 New TBC Concepts

Phase III of the program will proof test the best of the newly developed TBC systems on airfoil sections in a combustor test passage at the Westinghouse Science and Technology Center.

# Technical Progress Report

## Task II.2 Bond Coat Development

### *Task II.2.1 Bond Coat Deposition Process*

- The bond coat deposition optimization was completed for the high velocity oxy-fuel (HVOF), shrouded plasma spray (SPS), and gator gard (GG) deposition processes. Final coating deposition was performed using the HVOF and SPS optimized spray schedules. A standard APS 8%YSZ top coat was applied for furnace evaluation.
- Optimization trials for GG deposition of bond coats has been completed and the final analysis of the data is being prepared. Statistical analysis of the results and final coating deposition will be performed during the next report period.
- Optimization of the low pressure plasma spray is on hold pending the arrival of a pyrometer for temperature control.
- Furnace evaluation of coatings was initiated at nominal and accelerated test conditions for the following using the baseline CoNiCrAlY bond coat and TBC chemistries. An exception is the APS bond coat which uses a NiCoCrAlY bond coat.

  1. APS bond coat +APS top coat
  2. LPPS bond coat + APS top coat
  3. LPPS bond coat + EB-PVD top coat
  4. EB-PVD bond coat + EB-PVD top coat
  5. Optimized HVOF bond coat + APS top coat
  6. Optimized SPS bond coat + APS top coat

- Coating systems 1 through 5 have been tested to failure at the accelerated conditions. Coating system 6 is just entering testing. There have been no failure under nominal furnace test conditions.

- Metallography, consisting of optical microscopy, SEM, and EDS has been performed for a number of coatings which were pulled at fixed time intervals or failed under the accelerated test conditions. This work is continuing for the longer furnace exposure times.

### *Task II.2.2 Evaluate Bond Coat Chemistry*

- Work continued on the deposition of new bond coat chemistries. A series of optimization experiments were conducted to deposit five of the bond coat chemistries using LPPS. After several iterations, acceptable microstructures were achieved for four of the chemistries. Work is continuing on the remaining new bond coat chemistries.
- Using the optimized spray schedule, bond coats of the initial four chemistries were deposited on substrate superalloys. Air plasma sprayed YSZ was used as the top coat.

Test pins are being prepared and furnaces readied for testing at both nominal and accelerated conditions.

- A series of test coupons and bond buttons were fabricated to determine the role of surface roughness on the bond strength. MCrAlY bond coats were deposited with a range of surface roughness using HVOF and APS. In addition, a series of surface modified MCrAlY bond coats were fabricated. Evaluation of bond strength was initiated using thermal shock testing and room temperature tensile bond strength.

## Task II.3 Analytical Lifing Model

- Fatigue equations have been derived for each of the layers in the TBC system and have been incorporated into the TBCLPM subroutine. The effect of stain range was evaluated using these equations and TBC failure data in the open literature. The thermal cycles were classified as being either strain dominant or oxidation dominant, or a mixture of the two. Good agreement was generally seen between the developed model and the data in all three regimes. Damage accumulation as a function of the number of cycles was calculated in each of the three regimes.

- The reaction of aluminum with oxygen to form alumina is associated with a volume increase. When an oxide layer forms between the TBC and the bond coat, the oxide layer is not free to expand. As a result, a compressive stress, which is commonly referred to as the growth stress, is induced into the oxide layer due to the constraints imposed by the TBC and the bond coat. The stress distributions in the layers of the TBC system was analyzed by assuming an elastic media and solving the radial force and displacement equations, while imposing compatibility at the system interfaces. In this way the tangential and radial stresses as a function of system geometry were analyzed.

- Equations were derived to quantify the effect of surface roughness and curvature on cycles to failure. These equations are used to modify the derived fatigue equations.

- The first round of mechanical test specimens have been coated and are currently being machined to shape. The second round of specimens are currently being machined.

- The first round of APS samples have been thermally aged at Westinghouse and have subsequently been mechanically tested at ORNL.

## Task II.4 Manufacturing Process Development

### *Task II.4.2 Cooling Hole Masking Technology*

Application of coatings to industrial gas turbine (IGT) component surfaces can cause restriction of cooling holes and alter the heat management of the engine. Altered cooling air flow will lead to increased component temperatures and will shorten the life of the part. Therefore, it is critical to understand the extent of hole restriction caused by the coating process and to 1) account for the restriction in cooling hole design, 2) prevent cooling hole restriction during TBC deposition, or 3) remove the coating material from the holes after deposition.

Polymer masking trials were performed on simulated cooling hole test plates. Several types of polymer based materials were used to mask cooling holes prior to TBC deposition. Candidate materials include: silicones, filled epoxies, un-filled epoxies, and UV-cured methacrylates. The extent of hole closure was determined after deposition of the APS ceramic. Samples are being evaluated to determine the effects of the polymer on the TBC coatings near the cooling holes.

Automated spray trials were performed on simulated cooling hole test plates. Spray angles ranging from perpendicular to the plate surface to within 30° of the plate surface were used. The restriction of the cooling holes was determined for the various TBC spray conditions. Samples are being evaluated to determine the effect of spray angle on TBC structure.

### *Task II.4.3 Hole Re-Drilling*

Three techniques have been identified for re-shaping cooling holes after TBC deposition. Flat coupons, simulated cooling hole test plates, and several IGT blades are available for machining trials. Initial demonstrations of one technique have shown promising results. The machining parameters can be controlled so that 1) only TBC is removed, 2) TBC and bond coat are removed, or 3) TBC and bond coat are removed and the super-alloy surface finish is modified. Addition optimization trials will be performed, and the best technique will be demonstrated on IGT blades.

## Task II.5 NDE, Repair and Maintenance

### *Task II.5.1 Repair and Maintenance*

Localized repair of a coating system offers the potential for considerable cost savings over general stripping and recoating of a component. Two general types of local repairs have been identified and will be considered, namely major repairs and minor repairs. Minor repairs are intended for new or nearly new parts with a chipped TBC, but little if any bond coat degradation. Major repairs constitute a local TBC and bond coat stripping and refurbishment. For both types of repairs, it is assumed that the substrate has not been damaged.

- Repair techniques are being developed on flat 1.5 x 1.5 x .125 inch coupons with MCrAlY bond coats and ceramic top coats. Both single crystal and polycrystalline repair coupons have been machined and coated.
- Process parameters for one TBC stripping method have been identified. An alternative TBC removal method, that offers improved control and a higher removal rate, is currently under investigation.

- Several minor repair trials were conducted on test panels to identify variables in the repair process. Based on the results, a final minor repair test matrix was established. Three variations of minor repairs were then conducted on coupons and bond buttons.
- The bond strength of each minor repair has been evaluated. Coupons are currently undergoing non-destructive evaluation to assess the integrity of repairs. Further evaluation will consist of furnace testing and metallography.
- Major repair trials on test panels are underway to identify variables in the major repair process.

### *Task II.5.2 Off-line NDE*

Off-line NDE consists of using thermography and eddy current techniques as they apply to TBC ceramic coatings. As stated before, this work will build on current efforts being conducted as part of the ATS program. To maintain the identity and goals for each program individually, a simple boundary has been established. This boundary is the outer most surface of the metallic ( bond coat ). Task II.5.2 of this effort will solely fund, investigate and report work conducted on NDE of the TBC ( top coat ) and the bond quality of the TBC. The balance of the coating system NDE will be conducted under the auspices of the ATS program ( DOE contract # DE- FC21-95MC32267 ).

Two types of reference standards were designed for this work, the step plate and the simple standard. A total of 6 step plates, with different substrate materials have been completed. These plates have also been forwarded to the principal investigators conducting electromagnetic and thermographic NDE techniques. Preliminary results from the thermographic methods indicate an excellent correlation between temperature decay rate as a function of TBC thickness. No electromagnetic preliminary results have been issued at this time. The simple plate standard is being TBC coated by ORNL under a "User" program. ORNL will attempt to install controlled TBC debonds. Initial work on trial specimens has been started in an effort to establish the debonding method. Once established, the controlled debonds will be installed onto the simple standards. These standards will again be forwarded to principal investigators for both electromagnetic and thermographic imaging and analysis.

### *Task II.5.3 In- Frame NDE*

As a result of a Westinghouse funded investigation into the necessity and feasibility of in-frame, on-line monitoring of the TBC materials on critical components, this program has been redirected as previously reported. A presentation regarding the details of the new direction was held during the September DOE review. The change received a verbal acceptance and was followed up by a formal notification letter to the DOE, as requested. The program has been refocused on several potential methods for on-line monitoring of TBC's and well suited for investigation by Southwest Research Institute.

## Task II.6 New TBC Concepts

### *Task II.6.1 New TBC Chemistry*

- APS deposition of new TBC ceramic chemistries was initiated. Spray system modifications to date have consisted of plasma gun hardware modifications as well as numerous control setting conditions. Microstructural analysis is on-going.
- Several additional candidate TBC compositions have been identified. RFQ has been sent out for the fabrication of the new TBC materials.

### *Task II.6.2 Microstructure: Microcracked / Segmented / Columnar*

- A series of eight plasma sprayed TBC ceramic coatings with controlled microstructure were fabricated and placed into accelerated furnace testing. TBC top coats were applied over LPPS bond coats.

### *Task II.6.3 Process Optimization*

- Numerous deposition trials were conducted to identify hardware configurations suitable for the deposition of four different YSZ TBC powders. Two hardware configurations provided reasonable coatings.
- A statistical design of experiments approach was used to deposit coatings of each of the four TBC powders using the two hardware coating configurations for a total of 84 coating deposition runs. Metallography has been initiated as part of the coating evaluation