DOE/OR/22426--T2

ADVANCED TURBINE SYSTEMS—RESEARCH AND DEVELOPMENT OF THERMAL BARRIER COATINGS TECHNOLOGY

DOE CONTRACT NO. DE AC05-95OR22426

2nd Bimonthly Report
February 1996

INTRODUCTION

The objective of the Advanced Turbine Systems (ATS) Program is the development of ultra-highly efficient, environmentally superior, and cost-competitive gas turbine systems. The operating profiles of these industrial gas turbines are long, less cyclic, and with fewer transients, compared with those for aircraft gas turbine engines.

The durability and performance demands of ATS can be achieved by appropriate reduction of metal temperatures to retain the structural properties of the substrate alloy. This is accomplished by applying thermal barrier coatings (TBCs) to the substrate. Currently, TBCs are primarily processed by two methods: plasma spray (PS) and electron beam-physical vapor deposition (EB-PVD). Achieving ATS specific goals requires the TBC to be self-reliant, and stable in the thermal and corrosive environment of the industrial engine for durations up to 25000 h. The TBC requirements to meet ATS objectives, detailed in the Statement of Work, are divided into four phases. Phase I (Program Plan) includes the development of the technical plan, schedules, milestones, material selection, test selection, test parameters, and criteria for completion of each task and phase. Phase II (Development) consists of six tasks: Task 1 focuses on ceramic candidates; Task 2 on bond coat development; Task 3 on analytical modeling; Task 4 on TBC manufacturing process development; Task 5 on maintenance, repair and inspection; and Task 6 on new TBC concepts. Based upon Phase II screening test results, TBC systems will be selected for application on blades for hot section specimen bench test performed in Phase III. Actual engine testing, Phase IV (optional), will be conducted in a customer engine.

PHASE I: Program Plan

The objective of Phase I is the preparation and acceptance of the plan for conducting the development work of the project.

Progress

The program plan which included the development of the technical plan, the schedules, milestones, material selection, test selection, test parameters, and the criteria for the

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completion of each task and phase has been finalized, reviewed with and accepted by DOE.

PHASE II: Development

The objective of Phase II is to conduct the development work required to advance TBC technology for application to gas turbine hardware, to meet the high performance requirements of the ATS Program. The relationship of this phase to the overall program is shown in Figure 1. An overview of the Phase II activities is shown in Figure 2.

Progress

The effort for this reporting period is primarily directed towards the production of the test specimens required for the program, the procurement of the ceramic and metallic powders and various chemicals, and the completion of the SOWs from Team members. The following is a brief summary of the progress to date.

Procurements (All Tasks)

- All casting in progress.
- Composition and characteristics of low-pressure plasma-spray (LPPS) high-Cr NiCoCrAlY powder defined, vendor identified and procurement proceeding.
- Low-sulfur NiAl compositions are defined, target size required for cathodic-arc coater established, and procurement procedures in place.
- Howmet's statement of work for the engineered Pt-Al bond coat compositions is accepted.
- Air-plasma spray (APS) $\text{Al}_2\text{O}_3\text{-Cr}_2\text{O}_3$ solid solution powder characteristics defined for thin-layer sealing of PWA 266. Two vendors identified, and purchase orders in progress.
- All design work and procurements for the thermal gradient burner rig have been completed. The 300,000 Btu (300 MJ) oxy-acetylene torch is anticipated to be in place by the 2nd week in February. The torch will provide a flux of approximately 13,000,000 Btu/SqFtHr (40 MW/m²).

Task 3: Analytical Modeling

- Completed updating of existing nonlinear subroutines for Marc K5.
- Obtained initial PWA 1483 nonlinear material behavior constants from existing creep and tensile data and incorporated them into the nonlinear subroutines.

Task 4: TBC Manufacturing Process Development

- Completed an assessment of current manufacturing process.

Task 5: Maintenance, Repair, and Inspection of TBC Coated Airfoils

- A system to conduct alkali digestion removal of ceramic has been readied.

Further details of the Phase II progress are presented below.

A. Master Heat Composition and Property Evaluation

The chemical and mechanical properties of the Howmet master heat of PWA 1483 ordered for this program have been received. The chemical composition and mechanical properties were verified by Pratt and Whitney's Materials Control Laboratory and the material accepted.

B. Castings in progress

1. 8 slabs (1" x 1" x 6") for Phase II, Task 2 (Howmet Pt diffusion study).
2. 5 slabs (4.5" x 4" x 1") for Phase II, Task 3 (erosion and bending tests).
3. First batch consisting of 400 hollow burner rig test bars for Phase II, Tasks 1 through 6.

C. Bond Coats

1. Initial quantities of PWA 1386 powder for PWA 286 benchmarking are secured. Authorizations for additional quantities as needed are completed.
2. APS NiCoCrAlY powders are secured.
3. Oxide dispersion strengthened (ODS) NiCoCrAlY: sources identified; purchase orders are being written.
4. High-Cr NiCoCrAlY: composition and powder characteristics defined. One vendor identified; awaiting an alternative quotation from another.
5. High-velocity oxygen fuel (HVOF) plasma-spray NiCoCrAlY powders secured.
6. Target size for cathodic-arc coater established. Coater availability and schedule confirmed. Low-sulfur NiAl castings will be purchased from Howmet. The

Rapid Prototype Casting Facility (RPCF) will produce the standard NiAl composition to be desulfurized at United Technologies Research Center (UTRC).

7. Engineered Pt-Al: detailed statement of work from Howmet accepted. Howmet is in the process of establishing cost.

D. Top Coats/Ceramics

1. APS 7 wt% yttria-stabilized zirconia (7YSZ) for PWA 264 and 265 powders for benchmarking is secured.
2. Advanced Coating Technologies: Confirmed coater availability for electron-beam physically vapor deposited (EB-PVD) 7YSZ for PWA 266 benchmarking tests.
3. EB-PVD 20YSZ powders secured.
4. EB-PVD CeSZ powders secured.
5. APS $\text{Al}_2\text{O}_3\text{-Cr}_2\text{O}_3$ solid solution powder characteristics for thin-layer sealing of PWA 266 have been defined. Two vendors identified and one purchase order is in progress.

E. Task 3

PWA 1483 castings. Specimens will be machined from the cast slabs after single crystal orientation has been determined.

Kevin Walker of Engineering Science Software is working software development to enable simplified structural analysis of curved surfaces. This software will allow quick turn-time TBC life analysis.

The University of Connecticut is working on fixtures for the bending tests. The bend tests are designed to obtain the effects of sintering and corrosion on ceramic mechanical properties.

Existing nonlinear subroutines (called HYPELA) for the commercial finite element code MARC were upgraded from MARC version K-1 to version K-5 (the latest version). The upgrade consisted of: 1) an analytical investigation of whether a simplified 3D nonlinear material behavior model is adequate for single crystal materials and 2) updating the HYPELA subroutine for MARC K-5 depending on the results of 1) above. Proper selection of the substrate nonlinear model was necessary because the substrate plays a major role in determining TBC internal stresses (cyclic and residual). Substrate stiffness overwhelms TBC coating stiffness. Thus, TBC deflections and deformations are controlled by the substrate. During nonlinear substrate behavior, such as creep, the

substrate imposes different cyclic and residual deflections on the TBC than during elastic loading. The simplified 3D nonlinear material model for single crystals was based on the observation that, while single crystal materials exhibit marked elastic anisotropy, time independent (plastic) and time-dependent (creep) behavior is nearly isotropic throughout the range of orientations. Thus, the complex micro-mechanical models developed for single crystal material nonlinear deformation (e.g., Ref. 1) can be significantly simplified. The benefits of a simplified model include: material constant determination from $\langle 001 \rangle$ oriented specimens (no need to conduct non- $\langle 001 \rangle$ orientation material characterization tests), easy determination of material model constants using readily available tensile and creep data, and fewer lines of software code and a commensurate computer run time reduction. A complementary program to assess the feasibility of a simplified single crystal model approach was completed. In that program, PWA 1480 was selected for evaluation because non- $\langle 001 \rangle$ orientation material data was readily available for judging simplified model predictive capability. Simplified model constants were determined for PWA 1480 from $\langle 001 \rangle$ tensile and creep data. Simplified model prediction of a $\langle 111 \rangle$ oriented PWA 1480 thermomechanical fatigue (TMF) test is presented in Figure 3. The TMF test temperature cycle was sinusoidal and reached maximum temperature at minimum strain and minimum temperature at maximum strain (i.e., an out-of-phase TMF test). The minimum stress is slightly overpredicted, but the inelastic strain range and tensile stresses are well predicted. Based on the predicted behavior, the simplified model was judged acceptable and slightly superior to the Reference 1 micromechanical model (at least in this instance). As a result of the complementary effort, PWA 1483 simplified model constants were determined from existing tensile and creep data and the MARC K-5 HYPELA routines were upgraded accordingly. Existing bond coating and ceramic MARC HYPELA routines were also upgraded to MARC K-5 in preparation for the Taguchi matrix of 3D finite element analyses presented in Figure 4 and Table 1.

F. Task 4

The objective of this task is to ascertain manufacturability of successful TBC systems. The current manufacturing process will be assessed. The process will be adapted to new TBC, altered component geometry, and increased TBC thickness. Generic process steps will be mapped out and non-value adding steps will be eliminated/modified. An approach, developed to accomplish the objective of Task 4, was presented in the October–November 1995 report. One of the important elements of this Task is to assess current TBC manufacturing process. This assessment has been completed in the current report period. The assessment indicates that the current process is adaptable to a majority of the bond coat and ceramic top coat candidates, with minor modification. Significant additional process elements will be required for desulfurized aluminide bond coat. The future plan for this task is to address the modifications necessary for each system. In addition, the process chart, presented in the October–November 1995 progress report will be updated to include the process modification necessary.

G. Task 5

The objective of this task, in parallel with relevant tasks of Phase II, is to develop inspection and repair techniques which would include procedures/devices to ensure preliminary indication of impending TBC failure. In addition, sensor technique is to be developed, validated and demonstrated in Task 3. An approach and a detailed schedule were presented in the October–November 1995 progress report. In the current report period, scrap TBC samples have been obtained for laser holography trials. In addition, a system to conduct alkali digestion removal of ceramic has been readied. The future plan for this task is to conduct laser holography inspection on scrap TBC samples.

Reference

- 1) Nissley, D.M., Meyer, T.G. and Walker, K.P., "Life Prediction and Constitutive Models for Engine Hot Section Anisotropic Materials Program - Final Report," NASA CR-189223, Sept., 1992.

Figure 1 Program Plan

Figure 2 Phase II Overview

Figure 3 Comparison of Predicted and Observed <111> PWA 1480 Thermomechanical Fatigue Cycling

Figure 4 Thermal Barrier Coating Failure Mechanism Taguchi Matrix

Table 1 Taguchi Matrix Parameters

Parameter	Level 1	Level 2
Plasma TBC	Spherical porosity	Flat porosity
EB-PVD TBC	Fine cell size	Coarse cell size
Bond coat thickness	0.203 mm (0.008 in)	0.051 mm (0.002 in)
Ceramic thickness	0.127 mm (0.005 in)	0.508 mm (0.020 in)
Thermal gradient	Low heat flux	High heat flux
Ceramic sintering	None	Long term sintering
Ceramic phase transformation	None	Partially monoclinic
Bond coat oxidation/corrosion	None	Long term oxidation/corrosion
Interface topography	Smooth	Rugged
Curvature	Flat	OD radius
Bond coat Thermal expansion	PtAl	PWA 286

Advanced Turbine Systems
Research and Development of Thermal Barrier Coatings Technology
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Minutes: 1st monthly telephone meeting Jan 26, 1996 (submitted by N. Bornstein)
Present at Pratt & Whitney: J. Marcin, N. Bornstein, D. Nissley and M. Trubelja.

Item 1: Schedules

(1) It was agreed that the monthly meetings by telephone will be held on the last Wednesday of the month, at 3:30 PM. The next scheduled phone meeting will take place on Wednesday, Feb 28, 1996 at 3:30 PM. P&W will initiate the call to DOE at 423-576-1935.

(2) The 1st quarterly review meeting to be scheduled by DOE will be held in May.

Item 2: Technical

The program highlights, to be presented in the 2nd bimonthly progress report (due Feb 11, 1996), were reviewed. The following is a brief summary.

Phase I, Program Plan, was submitted and accepted, and this phase is now completed.

Phase II, Development, is essentially on schedule. All of the castings necessary for the program are in progress. The powders for the high-chromium modified MCrAlY, the yttria-modified bond coat, as well as the chromia-alumina sealing layer are being characterized or in production. The Statement of Work (from Howmet) for the platinum modified bond coat has been accepted, and the low-sulfur NiAl compositions and the target size required for the cathodic-arc coater established. We have completed the update of existing nonlinear sub-routes for Marc K5, and have obtained the initial PWA 1483 nonlinear material behavior constants from existing creep and tensile data and have incorporated them into the nonlinear sub-routes.

Item 3: Action Items

DOE has agreed to provide a schedule of bimonthly reports due out in 1996.