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

A. Specimen Preparation (All Tasks)

Introduction

In complying with the technical and scheduling requirements and objectives of Tasks 1 through 6, as provided in the Program Plan, in the current reporting period (February through March 1996) an effort has continued to procure castings, as well as ceramic and metallic powders needed to coat the test specimens. Simultaneously, the development of the corrodent processing and surface deposition techniques required for Tasks 1, 2, 3, and 6 has been initiated.

Based on the assessment of the current manufacturing process, completed in the previous reporting period (December through January), potential modifications of the process (Task 4) are being addressed by exploring the in-house casting and desulfurizing capabilities for the NiAl cathodic arc targets.

Accomplishments

- Contact being maintained with the coating facilities (both in-house and external) to ensure rapid turn-around of coated hollow burner rig test bars as they become available from the Pratt and Whitney Rapid Prototype Casting Facility (RPCF) (all tasks).
- Bond coat and top coat starting powders received (Tasks 1, 2, and 6):
  - NiCoCrAlY for low pressure plasma spraying (LPPS; PWA 286) and oxide dispersion-strengthening (ODS)
  - Y₂O₃ additive for ODS
  - 7 wt% yttria-stabilized zirconia (7YSZ) EB-PVD multilayer top coat
- Techniques were developed to process the quaternary eutectic in the Na₂SO₄-K₂SO₄-CaSO₄-MgSO₄ system. It was experimentally verified that the melting temperature is in the order of 650 to 700 deg C (1202 to 1292 deg F). The solubility of the
quaternary eutectic was determined and it was also verified that the eutectic can be reconstituted when deposited from an aqueous solution (Tasks 1, 2, 3 and 6).

- ODS (NiCoCrAlY + Y₂O₃) powder formulation and bond coat process development experiments initiated (Task 2).
- IN-792 (PWA 1483) substrate casting completed for engineered Pt–Al study; test-coupon machining in progress (Task 2).
- An external vendor’s quote received for low-sulfur NiAl cathodic arc targets; in-house low-sulfur NiAl casting capability being explored (Tasks 2 and 4).
- Standard NiAl casting completed for in-house desulfurization experiments; baseline sulfur analysis in progress (Tasks 2 and 4).
- PWA 286 coating initiated on ceramic erosion specimens; scheduling details worked out with the coating facilities (both in-house and external) for subsequent air plasma spray (APS) and EB-PVD ceramic coating (Task 3).
- Purchase orders initiated (Tasks 2 and 6):
  → High-Chromium NiCoCrAlY
  → Engineered Pt–Al
  → Al₂O₃–Cr₂O₃

B. Task 3

PWA 1483 substrates for erosion specimens were machined. The substrates are currently being bond coated with PWA 286 prior to ceramic coating application.

Uniaxial tensile and four-point bend specimen geometries were modified to the available PWA 1483 cast slabs. The cast slabs are not entirely good single crystal material and some adjustment to the specimen geometries are needed to minimize specimen fabrication costs. Additional tensile specimen geometry adjustment may be necessary to ensure specimen flatness through the coating process. A trial is currently being run through the EB-PVD coater to determine the specimen thickness requirement. Bend specimen geometry will be maintained within the guidelines presented in Reference 1 wherever possible.

The role of alumina scale porosity in EB-PVD TBC spalling was briefly investigated by conducting a 2D plane strain elastic finite element analysis. The analysis consisted of two materials: bond coat and alumina scale. A single circular pore was placed at the interface between the alumina and bond coat layers. Internal stresses were developed by constraining the ends of the model and imposing a temperature change. The stress free temperature for each material was selected so that the internal stresses developed across the temperature change were the proper sign. A summary of the model and results is presented in Figure 3. The model predicts that a tensile stress perpendicular to the interface develops at the pore in the alumina layer just above the alumina-bond coat interface. The location of the tensile stress at the pore is consistent with the observed failure location of EB-PVD thermal barrier coating. Thus, growth of pores at the alumina-bond coat interface, as indicated by Reference 2, reduces the apparent strength of
the alumina layer and increases the likelihood of EB-PVD TBC spalling. This result will be investigated further during Task 3.

Generic modeling of TBC failure mechanisms is continuing. The variables were assigned to an L32 (11 variables, each at two levels) Taguchi matrix. The 11 variables are:

1) Ceramic Thickness
2) Thermal Gradient
3) Ceramic Sintering
4) Bond Coat Oxidation/Corrosion
5) Bond Coat Thermal Expansion
6) Ceramic-Bond Coat Interface Topography
7) Ceramic Phase Transformation
8) Bond Coat Creep
9) Curvature
10) TBC Type (Plasma or EB-PVD)
11) Bond Coat Thickness

Plasma sprayed and EB-PVD TBC types were collapsed into a single column (TBC Type) and bond coat creep was added as a variable based on the results from Reference 3. Ceramic-bond coat interface topography was selected to be a sinusoidal wave that forms a bump when used as a body of revolution. The peak-to-peak height of the interface wave was set to 12.7 microns (0.0005 in) and the wavelength set to 91.4 microns (0.0036 in) based on measurements from an overlay bond coat. The finite element model uses symmetry to reduce the model size to a section that includes 1/4 of a single bump. The initial flat plate finite element model is presented in Figure 4 and its associated finite element mesh around the ceramic-bond coat interface region is presented in Figure 5. The full mesh consists of over 2000 3D hexagonal (brick) elements. The geometry presented in Figure 5 is for trial number 6 in the Taguchi matrix. Definition of thermal boundary conditions is currently being worked.

References


Figure 1 Program Plan

Phase I

Develop Program Plan

Task 1: Select Candidate Ceramics

Task 2: Select Candidate Bond Coats

Task 6: Select New TBC Concepts

Task 5: Maintenance, Repair, and Inspection

Conduct Screening Tests

Combine and Evaluate as TBC

Task 4: TBC Manufacturing Process

Screening Tests

Generate Properties for Analytical Model

Task 3: Analytical Model

Phase II

Phase III

Selected Hot Section Specimen Bench Test

Selected Airfoil Testing in Product Line Gas Turbine

Phase IV (Optional)
Figure 2 Phase II Overview
Figure 3  Effect of a Pore at the Alumina–Bond Coat Interface in an EB-PVD TBC

Alumina  $E = 413.7$ GPa (60e6 psi)
$\nu = 0.25$
Strain = −0.001 m/m
$S_x = S_z = -552$MPa (−80 ksi)
$S_y = 0$

Bond Coat  $E = 137.9$ GPa (20e6 psi)
$\nu = 0.35$
Strain = +0.0005 m/m
$S_x = S_z = +106$MPa (+15.4 ksi)
$S_y = 0$

$S_y = +276$MPa (+40 ksi) at Location 1

Blowup of Pore Deformed Shape
In addition to the shown fixed displacement boundary conditions, all nodes that lie along the top surface are tied in the y-direction and all nodes that lie along the back (unseen) surface are tied in the x-direction.
Figure 5  Typical 3D Finite Element Mesh for Taguchi Matrix Analysis