

Improving The Efficacy & Economics Of Candidate Hypersonic Materials

Final Performance Report

Award No. N00014-18-1-2516

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Reporting Period: July 1, 2018 to June 30, 2023

Reference Number: REDD-2023-487

REPORT DOCUMENTATION PAGE

*Form Approved
OMB No. 0704-0188*

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1. REPORT DATE (DD-MM-YYYY) October 27, 2023		2. REPORT TYPE FINAL PERFORMANCE REPORT		3. DATES COVERED (From - To) 7/1/2018 - 6/30/2023	
4. TITLE AND SUBTITLE IMPROVING THE EFFICACY & ECONOMICS OF CANDIDATE HYPERSONIC MATERIALS				5a. CONTRACT NUMBER N00014-18-1-2516	
				5b. GRANT NUMBER GRANT12598947	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) BRUPBACHER, MICHAEL, C, Ph.D Michael.Brupbacher@jhuapl.edu 240-521-9278				5d. PROJECT NUMBER	
				5e. TASK NUMBER FGD05	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) THE JOHNS HOPKINS UNIVERSITY 3400 N CHARLES ST BALTIMORE MD 21218-2608 UNITED STATES OF AMERICA				8. PERFORMING ORGANIZATION REPORT NUMBER REDD-2023-487	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) OFFICE OF NAVAL RESEARCH ERIC J. WUCHINA SEA WARFARE & WEAPONS S&T DEPT 875 N. RANDOLPH ST. ARLINGTON, VA 22203-1995				10. SPONSOR/MONITOR'S ACRONYM(S) ONR	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED					
13. SUPPLEMENTARY NOTES GRANT					
14. ABSTRACT The overall goal of this project is to improve the efficacy, i.e. relevance to Naval hypersonic applications, of economical candidate hypersonic materials systems through basic materials science research improvements in material properties and performance. Atmospheric-plasma-sprayed (APS), environmental barrier coatings (EBCs) on refractory substrates have been identified as economical candidate hypersonic materials systems but improvements to material properties and performance are warranted. Specifically, improvements in material properties and performance at the coating-substrate interface and at the interface between the outermost surface of the coating and its surrounding environment (i.e., oxidative hypersonic flow) are warranted. This project pursues, as separate objectives, improvements in material properties and performance at these targeted locations in this specific candidate hypersonic materials system.					
15. SUBJECT TERMS Hypersonic materials					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			MORGAN TREXLER
U	U	U	U	5	19b. TELEPHONE NUMBER (Include area code) 301-395-7227

I. Project Overview

The goal of this effort was to improve the efficacy and economics of candidate hypersonic materials systems through basic materials science research. As proposed, this effort was to focus on materials systems based on atmospheric-plasma-sprayed (APS) thermal barrier coatings (TBCs). On a separate effort, comparative arc-jet testing in the NASA Langley Research Center Hypersonic Materials Environmental Test System (NASA LaRC HYMETs) arc-jet facility between APS TBCs and APS environmental barrier coatings (EBCs) was being conducted by the JHU/APL team at the early stages of this effort. The results of these tests indicated that APS EBCs were capable of withstanding higher incident heat fluxes on sharp leading edges when refractory substrates with sufficient thermal and thermomechanical properties were utilized. As such, the focus of this ONR effort was shifted away from materials systems based on APS TBCs and towards those based on APS EBCs. This shift represented, in all instantiations envisioned, significant reductions in cost due to the use of exotic materials as oxygen diffusion barriers in multilayer systems based on APS TBCs. Having satisfied the economical component of our goal, the remainder of this effort focused on improving the efficacy of materials systems based on APS EBCs. Through exploration of various EBC powder feedstocks and their APS deposition parameters, a “baseline” APS EBC was developed on this effort and transitioned to the Defense Advanced Research Projects Agency Materials, Architectures and Characterization for Hypersonics (DARPA MACH) program through a license to Plasma Processes Inc. (PPI), a subcontractor to Lockheed Martin (LM), a performer on the program. This “baseline” APS EBC was critical to the success of the LM concept as evaluated against the Phase 1 metrics of the DARPA MACH program. Despite early success in transitioning to industry, two performance metrics were expected to be limiting to its operational envelope for the “baseline” APS EBC. Increasing the oxidation resistance of the substrate at the APS EBC-substrate interface and the aeroshear resistance of the APS EBC at the flowfield-APS EBC interface was expected to expand the operational envelope of next-generation material systems based on APS EBCs, and therefore were pursued for the remainder of the effort as separate objectives.

II. Technical Accomplishments

Environmental barrier coatings deposited via APS are inherently porous in nature, often with interconnected porosity through the thickness of the EBC. Therefore, in operational conditions of high oxygen partial pressure, there is the potential for oxygen permeation through the thickness of the “baseline” APS EBC via interconnected porosity, resulting in oxidation of the substrate which can lead to coating spallation/delamination due to volumetric changes associated with substrate oxidation. To overcome this limitation in next-generation materials systems based on APS EBCs, the surface of the substrate was converted, through collaboration with Dr. John Perepezko of University of Wisconsin Madison, to the same EBC following grit blasting of the substrate but prior to APS EBC deposition. By comparative aerothermal screening of the same flat-faced coupons at nominally the same test condition in the JHU/APL high-velocity oxy-fuel (HVOF) supersonic torch facility, it was demonstrated that thin, “baseline” APS EBCs deposited without preconversion of the substrate to the same EBC would suffer from substrate oxidation and resultant coating spallation (Fig. 1), while substrates that were preconverted to the same EBC prior to thin, APS EBC deposition would not suffer from the same coating failure mode. In these comparative tests, APS EBCs were deposited in a thinnest-achievable, still-continuous form specifically to stress this coating failure mode driven by oxygen permeation and demonstrate the solution that preconversion of the substrate to the same EBC prior to APS EBC deposition likely represents in terms of expanded operational envelope towards conditions with high oxygen partial pressure. While not demonstrated in this effort, preconversion of the

substrate to the same EBC prior to APS EBC deposition also likely represents increased tolerance to APS EBC manufacturing defects and APS EBC defects introduced by other means (e.g., improper handling).

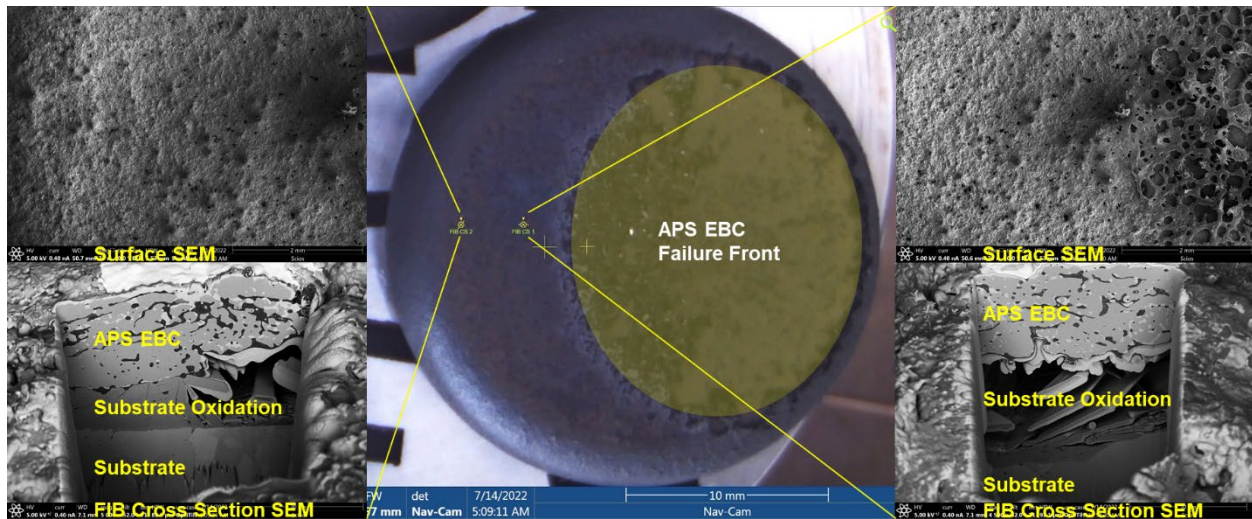


Figure 1. High-velocity oxy-fuel (HVOF) superonic torch screening demonstration of thin, atmospheric-plasma-sprayed (APS) environmental-barrier-coating (EBC) failure due to substrate oxidation. Preconversion of the substrate to the same EBC following grit blasting but prior to thin, APS EBC deposition was demonstrated as a solution to this coating failure mode in nominally the same HVOF test condition.

Environmental barrier coatings, independent of deposition method, are often at some aerothermal load and resultant thermal response susceptible to aeroshear-driven failure. Atmospheric plasma spray, however, is a highly flexible deposition methodology that allows for “doping” of feedstock powders to target enhancements in specific performance metrics. To increase the aeroshear resistance of next-generation material systems based on APS EBCs, each particle that the EBC feedstock powder consisted of was “doped”, prior to APS deposition, with phases specifically targeting this critical performance metric. By comparative aerothermal screening of the same wedge shapes at nominally the same test condition in the JHU/APL HVOF supersonic torch facility, it was demonstrated that the leading edges of “baseline” APS EBCs suffered increased damage depth relative to those of APS EBCs “doped” for increased aeroshear resistance (Fig. 2). Through collaboration with the DARPA MACH program, comparative aerothermal testing of the same wedge shapes (in the context of this specific test series) at nominally the same test condition also occurred in the Boeing Large Core Arc Tunnel (LCAT) arc-jet facility. These arc-jet tests also indicated that “doped” APS EBCs have increased aeroshear resistance relative to that of “baseline” APS EBCs (not shown here). The results of these HVOF and arc-jet tests taken together likely also represent an expanded operational envelope for next-generation material systems based on APS EBCs towards conditions with high aeroshear.

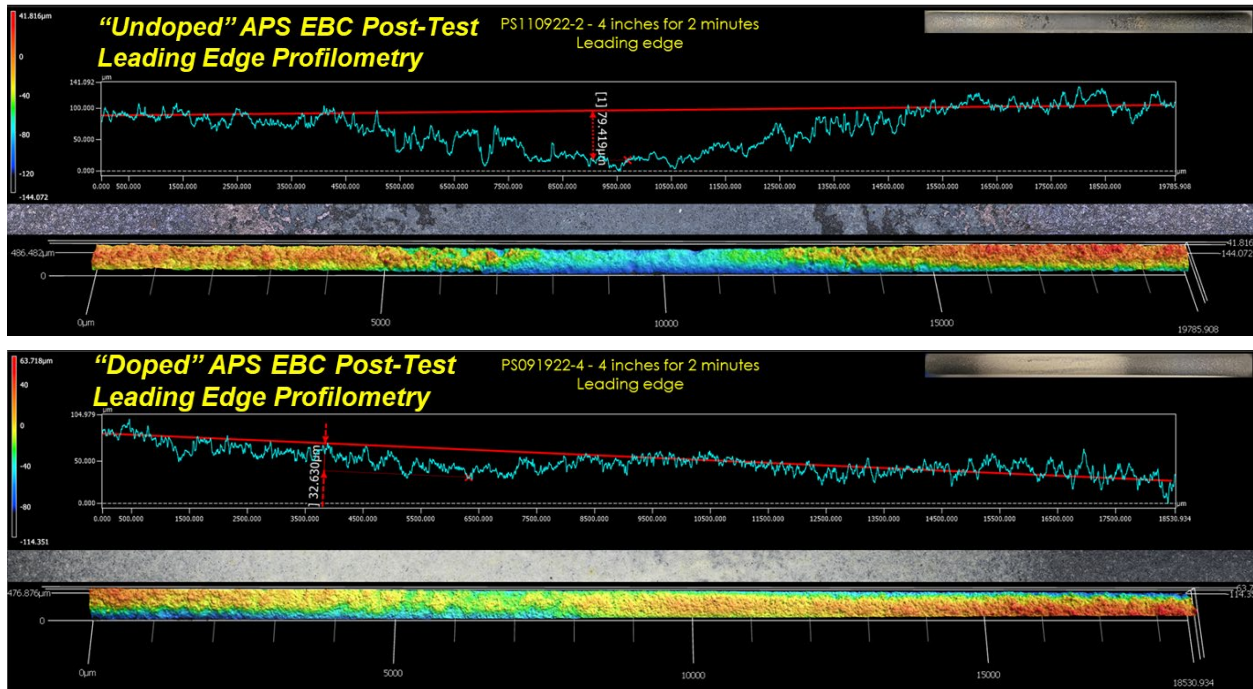


Figure 2. By comparative aerothermal screening of the same wedge shapes at nominally the same test condition in the JHU/APL high-velocity oxy-fuel (HVOF) supersonic torch facility, it was demonstrated through profilometry that the leading edges of atmospheric-plasma-sprayed (APS) environmental-barrier-coatings (EBCs) “doped” for increased aeroshear resistance exhibited decreased damage depth relative to that of “baseline” APS EBCs.

III. Conclusions

Through judicious pooling of resources and knowledge products, the JHU/APL team was successful in revectoring this effort in its early stages, in coordination and communication with ONR, towards a more fruitful research area relative to that which was originally proposed. As a result, this effort generated a “baseline” APS EBC that was both successfully transitioned to industry and had tangible impact on the success of another program in the hypersonic materials community. Thereafter, the JHU/APL team continued to push the performance boundaries of APS EBCs beyond those of the transitioned “baseline” APS EBC by increasing the oxidation resistance of the substrate at the APS EBC-substrate interface and the aeroshear resistance of the APS EBC at the flowfield-APS EBC interface. Taken together (not demonstrated on this effort) these improvements are expected to greatly expand the operational envelope of next-generation material systems based on APS EBCs towards conditions with high oxygen partial pressure and high aeroshear.

IV. Future Opportunities

A framework for “doping” APS EBCs for increased aeroshear resistance was demonstrated but optimization of the total amount of “dopant” phases and the relative contributions of “dopant” phases within the total amount is suggested as a component of a follow-on activity. The aforementioned comparative testing of “baseline” and “doped” APS EBCs in JHU/APL’s HVOF supersonic torch facility and Boeing LCAT’s arc-jet facility also indicated that the optimal “doping” characteristics for increasing aeroshear resistance while maintaining other important properties and performance metrics (e.g., mismatch in coefficient of thermal expansion) might in some cases be substrate specific. Since the culmination of testing

for this effort, characterization of shear stress magnitude (and direction) of the JHU/APL HVOF supersonic torch was demonstrated (for a specific geometrical arrangement) via a commercial shear stress sensor. The optimization of “doping” of APS EBCs for increased aeroshear resistance, even for a particular substrate, involves many variables including but not limited to the total amount of “dopant” phases, the relative contributions of “dopant” phases within the total amount, and a copious number of APS deposition parameters. Such an intensive optimization activity will require quantification of aeroshear survivability of “doped” APS EBC variants as a function of temperature via a test method that produces both relevant thermal responses and relevant shear stress magnitudes, while providing test throughput that is high enough to meet experimental demands in a reasonable timeline. It is suggested that HVOF supersonic torches in conjunction with shear stress sensors be considered as a candidate test method for the optimization of “doped” APS EBCs for increased aeroshear resistance.

V. Dissemination to Communities of Interest

2018 ONR Portfolio Review – August 2018

2019 ONR Portfolio Review – July 2019

2020 ONR Portfolio Review – July 2020

2021 ONR Portfolio Review – July 2021

2022 ONR Portfolio Review – July 2022