Demonstration of Advanced Coatings for Sustainability – Phase I & II

Final Report

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Acronyms and Abbreviations

Term	Definition
CMAS	Calcium-Magnesium-Alumino-Silicate
CTMA	Commercial Technologies for Maintenance Activities
DOD	Department of Defense
EB-PVD	Electron Beam Physical Vapor Deposition
EHS	Environment, Health & Safety
FOD	Foreign Objects and Debris
GE	General Electric
GRC	Global Research Center
HPT	High-Pressure Turbine
NCMS	National Center for Manufacturing Sciences
ngTBC	next generation Thermal Barrier Coating
ODASD-MR	Office of the Deputy Assistant Secretary of Defense, Materiel Readiness
TBC	Thermal Barrier Coating
TOW	Time On-Wing
U.S.	United States

1. Executive Summary

The development of the global economy has provided many opportunities for the American public to thrive. One large opportunity has been selling and maintaining aircraft in developing markets; this opportunity includes both military and commercial aircraft, providing jobs and boosting the U.S. economy. However, many of these new markets pose new environmental challenges for the performance and durability of aircraft engines. Maintenance costs to restore performance standards and replace deteriorated hardware decreases the competitiveness of engines operating in the worldwide market and reduces the reliability of equipment and profitability of maintenance contracts in different regions. Increased maintenance costs in harsh, austere environments also effects Department of Defense (DOD) military engines operating in these areas. Environmental concerns are mainly due to sand ingestion which damages engine parts, leading to compressor hardware erosion, compromised hot section secondary cooling, flowpath deposit buildup, and protective coating erosion & spallation.

The industry partner has developed dust mitigation coating technologies over several years. The industry partner has taken a unique approach to sand mitigation by keeping the current airfoil coating and applying additional treatments which improve the sand tolerance of the coating. This approach keeps the beneficial properties of the current coatings and adds significant additional dust capability. These additional sand mitigation treatments include both new make and tailored treatments which may be re-applied at the module level (I or O Level). It should be noted that the severity of sand ingestion varies significantly between commercial jet aircraft and military rotorcraft.

Funding was secured for the collaborative initiative through the National Center for Manufacturing Sciences (NCMS) Commercial Technologies for Maintenance Activities (CTMA) Program and the Office of the Deputy Assistant Secretary of Defense, Materiel Readiness (ODASD-MR) to demonstrate the effectiveness of the sand mitigation coating treatments for applicability to rotorcraft engines.

The execution of this project included four tasks with a T700-701D sand ingestion engine demonstration test performed:

1. Transfer prototype coating processes to T700 hardware
2. Coat newmake hardware
3. Develop on-wing dust removal process
4. Support engine test execution

Coating processing requires complex processing to get the correct key characteristics including microstructure, thickness, chemistry, etc. Transitioning these processes to new hardware geometry requires updates to key process parameters. To transition the coating processes to the T700 hardware, coating trials with lab prototype processes were completed which defined process parameters to meet the key coating requirements.

Using the defined processes, hardware was acquired and coated. Following standard engineering quality processes, inspections and quality control evaluations were performed and documented to ensure coating key characteristics were met. A contamination issue was identified for one of the coating runs. Three pieces of hardware from this run were accepted and included in the engine test to assess the impact of the contamination on the performance of the coating to understand requirements for future production.

This engine test provided a unique opportunity to pause the test and re-apply coatings on-site. On-site coating processes were developed for the coating treatments. New coating treatments were also matured and down-selected as dust removal technologies for this engine test.

The engine test was run by NAVAIR at the Pax River Naval Base. The industry partner supported by training the on-site staff for the on-site coating processes and performing coating runs for the newer dust removal technology. The industry partner also reviewed borescopes during test execution to assess the performance of the coatings and identify if any changes to the test needed to be made. The test ran as planned and degraded the hardware as desired.

1.1 Results

Advanced coating technologies to mitigate the destructive effects of austere operation have been developed and applied to the high-pressure turbine (HPT) components of a T700 engine targeted for a sand ingestion engine demonstration project. The coating technologies included: a) next generation Thermal Barrier Coating (ngTBC); b) thermal Barrier Coating (TBC) Shield; c) On-Site Coatings for Dust Removal; d) High Y and Advanced High Y. Development of the coatings for the requirements of the T700 engine and test program were successfully completed. The engine hardware was manufactured with the advanced coatings and affected parts assembled into the engine combined with baseline hardware for performance comparisons. The T700 dust ingestion engine test was successfully completed by NAVAIR.

1.2 Benefits

The T700 engine test vehicle provided the unique opportunity to utilize a specific military application to demonstrate advanced coating technologies that will provide increased durability, performance retention, and cost reduction across multiple commercial applications. Such benefits include:

- Improved aircraft availability for operation
- Reduction in aircraft maintenance costs for aviation components
- Improved durability and performance retention for operation in austere environments

By demonstrating this technology on a DOD asset, the advanced coating technologies will be more easily deployed on DOD aircraft across all Services, as these coatings are compatible with the current hardware materials and coatings across all aircraft engines. Inclusion of advanced coatings will reduce lifecycle costs and increase DOD aircraft operational flexibility, protect time on-wing (TOW), decrease engine downtime, and ultimately improve readiness. Additionally, the ability to mitigate dust buildup on nozzle and blade surfaces can protect engine performance and operability margins. This effort will also provide the data needed for future programs for the DOD; many different coating strategies and technologies are included in this effort.

1.3 Technology Transition

It is expected that these advanced coating technologies are easily transferred to various commercial and military applications.

1.4 Invention Disclosure

☐ Yes Inventions ☒ No Inventions

DD882 Invention Report sent to NCMS ☒

1.5 Project Partners

- NAVAIR
- GE Global Research Center (GRC)
- General Electric (GE)
- National Center for Manufacturing Sciences (NCMS)

2. Introduction

All machinery and equipment operating in harsh environments is subject to a much higher level of abuse, and aircraft engines are particularly vulnerable. Rotary aircraft engines are highly susceptible to foreign objects and debris (FOD), and experience limited TOW and increased maintenance costs due to sand ingestion. For example, sandy environments require 165 hours of maintenance time for every hour of flight time, versus non-sandy environments requiring 100 hours of maintenance time per hour of flight time. The most common hardware damage due to this ingestion includes compressor erosion, compromised hot section secondary cooling, flowpath deposit buildup, and protective coating erosion and spallation. Protective coating erosion and spallation is a significant contributor to hot section performance loss and downstream maintenance costs. Solutions are needed to improve the life of the protective coating as well as to decrease the amount of sand deposition. Not only do the sand deposits impact aerodynamics and cooling effectiveness, but they can also form Calcium-Magnesium-Alumina-Silicate (CMAS) deposits which infiltrate into coatings. This leads to coating spallation and further accelerates hardware degradation.

The industry partner has developed dust mitigation coating technologies over several years. This initiative provided the unique opportunity to demonstrate the industry partner's module level coating treatment technologies. The engine test would be "paused" multiple times to disassemble the engine and provide treatments at the module level. The industry partner provided experience and expertise in rapidly tailoring these treatment solutions to meet customer requirements; additionally, there was flexibility to perform these coating treatments in a variety of application environments from inserting tooling through borescope ports for on-wing applications to coating hardware in a partially torn apart overhaul engine. The greater the access to the hardware, the less complex and expensive the coating process development. To demonstrate the effectiveness of re-applying the coating treatment for the lowest cost, this project would reapply the coating treatments with the engine disassembled to expose the Stage 1 HPT rotor and stator.

The specific coatings and treatments to be included in the engine test were:

- *Thermal Spray TBC CMAS Resistant Coating Solutions* – Thermal spray TBC coating systems are typically used on combustor hardware to reduce substrate operating temperatures. "High Y" and "Advanced High Y" are the industry partner's advanced coating solutions. Hardware will be coated partly with each coating (High Y, Advanced High Y and standard baseline TBC) to assess back-to-back performance and assess the cost to performance.
- *Electron Beam Physical Vapor Deposition (EB-PVD) TBC CMAS Resistant Coating Solutions* – EB-PVD EB-PVD TBCs are typically used on HPT airfoils such as the Stage 1 HPT blade. ngTBC is the industry partner's CMAS resistant EB-PVD TBC coating system. ngTBC includes a treatment of the current standard EB-PVD TBC which provides the CMAS resistance without debiting the impact and erosion capability of the current standard EB-PVD TBC.
- *On-Site CMAS Coating Solution* – TBC Shield is a method of applying CMAS reactive particles to either coating or deposit surfaces. The CMAS reactive particles react with the CMAS to change the properties of the deposits leading to decreased CMAS infiltration into the thermal barrier coatings. The TBC Shield modifications will modify the

TBC shield to promote shedding of the deposits thereby reducing deposit thicknesses.

- *On-Site Coating Repairs* – TBC Patch is a method of applying a partial thickness of TBC in a region where TBC has spalled.

3. Project Narrative

This project included providing hardware and on-site application processes and supporting demonstration on engine test as sustainability technology to advance the current state-of-the-art and reduce maintenance burden for both commercial and military applications. T700 hardware was coated with advanced coatings and treatments. Validation of the coating processes on the T700 hardware has matured the technology implementation for improved technology transition as well provides hardware which demonstrated the desired project objectives.

3.1 Validate Shop Coating Demo Processes

This task involved transferring the industry partner developed advanced coating processes to T700 hardware. Spray trials and quality evaluations of the transferred process on T700 scrap hardware was completed demonstrating that the processes would meet engineering class quality requirements.

TBC Shield is a sacrificial protective coating applied to the surface of the current TBC coating. TBC Shield can be applied either at piece part application or on-site while built into a rotor using different application methods. To transfer the piece part process for the Stage 1 HPT blade for this demonstration vehicle, modeling and spray trials were performed to down-select spray parameters such as the spray angles, distances and motions. After trial spray runs were performed, scrap hardware evaluations were performed confirming that the down-selected parameters met requirements such as thickness and coverage.

ngTBC is a coating treatment applied to the current TBC to improve the CMAS resistance of the TBC. This coating was also applied to the Stage 1 HPT blade. Similar to the TBC Shield, coating trials followed by hardware evaluations were performed to down-select key coating parameters. To decrease cost and schedule for designing and manufacturing tooling, a manual application was down-selected in order to make demonstration hardware for this engine test. Application trials were performed and showed that the manual application was repeatable, down-selected application parameters such as the number of passes and demonstrated that the process met all coating requirements including chemistry and coverage.

For the combustor hardware, a standard thermal spray process was used to coat the hardware. The combustor liner was coated half with the standard thermal spray TBC and the other half used a thermal spray process to coat the industry partner’s CMAS mitigation coating named Advanced High Y. The combustor dome included standard Thermal Spray TBC, High Y and Advanced High Y coatings. The High Y coating is a less expensive option compared to the Advanced High Y, with a trade-off of decreased capability compared to the Advanced High Y. The thermal spray process involves utilizing a high temperature spray gun moved by a robot arm. To ensure the coating is applied at the correct thicknesses in the correct location, tooling to mask off regions not to be coated was manufactured and the robot motion program had to be iterated. The key parameters for thermal spray include the distance of the gun to the hardware, the spray angle, and how quickly the hardware and gun are moved. These key parameters were iterated by completing spray trials and evaluating the coating to determine coating thicknesses and microstructures.

The industry partner developed a TBC Patch repair method that can be sprayed on-site or on-wing in an engine; this patch repair would rebuild TBC thickness in the event of TBC spallation. For this engine demonstration, the patch was applied both in a controlled newmake situation where a spall was simulated by removing the TBC as well as demonstrating the patch in spalled regions during the actual engine demonstration. The patch repair process was transferred to the T700 hardware by grit blasting to remove TBC coating to simulate a TBC spall and then applying the TBC Patch. This simulated run was used to demonstrate the masking and spray process to achieve the correct patch thickness.

Before manufacturing the hardware for the engine test, a multi-disciplinary review was held reviewing development coating trial data, quality plans and risk reduction analysis to ensure hardware provided for engine test would meet project objectives.

3.2 Module Level Demo Coating Processes Validation and Implementation

The industry partner performed maintenance to extend coating life on certain commercial applications without removing the engine from the aircraft wing. These maintenance methods are very flexible and could also be performed in overhaul facilities with the engine torn apart to various module/assembly levels. For the T700 engine demonstration dust and CMAS treatment technologies were demonstrated both on-site and at the industry partner's facilities at set stopping points during the T700 engine test. A demo processes was developed that will then be used to spray the hardware on-site during breaks in the engine test when the engine will be torn apart to module level.

To re-apply TBC Shield to select S1Bs at defined stopping points during the engine test, an on-site coating process was developed. Enclosed automated spray equipment was designed and manufactured. To iterate on the spray parameters and control settings, an engine returned Stage 1 blade rotor assembly was acquired and utilized for iterative spray trials. Spray trials were performed on the rotor assembly and the hardware cut-ups of the blades were performed to ensure microstructure, thickness and coverage requirements were met. The spray angle had to be adjusted from the newmake set-up due to the shadowing of adjacent blades in the assembled state. The control systems were fine tuned to index each of the individual blades so that one blade could be sprayed at a time. To spray individual blades, masking was also designed and manufactured to protect the rotor and other blades from overspray. Equipment, Environment, Health & Safety (EHS) protocols, process application instruction documents and on-site training was provided to the team at the Pax River site; training was performed while coating the engine test hardware during the first engine pause. Process transfer was confirmed when the Pax River team successfully performed independent coating runs during the remaining three engine test pauses.

The Stage 1 nozzles were coated with TBC Shield modifications to assess the effectiveness of dust deposit thickness reduction, the nozzles were sprayed at the module level with the current TBC Shield and four modifications. The TBC Shield modifications were down-selected through the use of laboratory dust testing. The coatings were applied utilizing manual hand application methods. The process for hand application was iterated based on coupon thermal exposures and hardware cut-ups. Two nozzle assembles were utilized in the engine demonstration; while one assembly was run in the engine test, the second assembly was shipped to the industry partner's lab for coating re-application.

To demonstrate the ability to patch repair engine spalled regions of TBC, TBC Patch repair was performed during the middle engine test pause. This process was different than the patch repair applied to the liners before the liners were assembled into the combustor. The process used for newmake gave an ideal patch adhesion data where the process applied during the engine test in the assembled state provided a worst case application scenario. The gap between the inner and outer liners was very small giving non-ideal spray angles. The spray angles, masking and spray processes for the TBC Patch were iterated on field returned combustor assemblies to give a patch coating. Due to these spray intricacies, it was decided to spray the patch repair at the industry partner's lab by shipping to and from the lab during the pause at the halfway point of the engine test.

3.3 Manufacture Engine Demo Hardware

To procure hardware to coat for the engine test, hardware was pulled both from stores and mid-production. A full set of Stage 1 blades plus spares were identified from storage and utilized for this demonstration. To save on funding, it was decided to include one combustor assembly instead of two combustor assemblies in the engine demonstration; therefore, one inner liner, one outer liner and one set of splash plates were pulled from production prior to coating. Routers, tech plans and quality documents for all hardware was approved by the applicable certifying agent.

Ten (10) Stage 1 blades were coated with ngTBC; process documentation and hardware cut-ups were performed per the quality plan and met requirements.

Fourteen (14) blades were coated with TBC Shield at piece part level (as opposed to the on-site assembly application). Process documentation and hardware cut-ups were performed per the quality requirements. During post-coat processing, the hardware was exposed to contaminant debris. Unsure of the effects of this debris to the effectiveness of the TBC Shield, only four of the 14 blades were accepted via a non-conformance acceptance documentation. These four blades could be used to justify acceptance of this type of nonconformance in the future. Spare blades procured from engineering stores were coated in a second set of coating runs utilizing standard quality requirements of process documentation and cut-ups yielding 10 blades for engine testing.

The combustor liners pulled from production prior to TBC coating were prepared using standard surface preparation produces. The specialized masking for coating 180 degrees of each the inner and the outer rings was applied and Advanced High Y coating was performed utilizing the standard process controls and adjacent quality control tab for cut-up evaluation. The tooling was moved to mask the coated half of the liners and then the other 180 degrees was coated with standard thermal spray TBC utilizing the standard process controls and adjacent quality control for cut-up evaluation. The quality evaluations were performed to show that the processes ran as expected and cut-ups met thickness and microstructure requirements.

A patch of coating was grit blast removed on both the standard TBC and Advanced High Y TBC portions of the liners utilizing the masking procedure developed. The patch repair was applied to the liner with documentation meeting quality requirements.

The combustor splash plates pulled from production prior to coating had standard coating surface preparation procedures. Thirty-three percent (33%) of the combustor splash plates were be coated with Advanced High Y coating; 33% of the combustor splash plates were coated with High Y coating; and 33% of the splash plates were coated with standard TBC coating. The process documentation and adjacent quality control tabs were evaluated and met quality requirements.

3.4 Engine Test Planning

Utilizing prior engine test experience, the engine test plan was designed including the test cycle, and the modified start up cycle to cure the TBC patch. Test parameters were determined including dust type/concentration, Test duration, borescope intervals, and engine test pause intervals.

3.5 Engine Test Execution

Text execution was performed by NAVAIR. The industry partner evaluated borescopes and provided guidance on evaluations. As described in Section 3.2 on-site applications were performed as well as coating applications at the industry partner site.

4. Conclusions

The project provided advanced coatings and testing was successfully completed. Quality requirements were developed to ensure successful demonstration of coatings; hardware with advanced coatings was provided meeting these quality requirements. The engine test was run with degradation as expected. No infant mortality of coatings was observed giving a successful engine test result. The hardware was covered with dust; therefore, visual observations were not able to differentiate coating performance. Hardware cut-ups will be required to demonstrate differentiation. Feasibility of transferring on-site processing to NAVAIR was demonstrated.

5. Project Benefits

5.1 Benefits for the General Public

The T700 engine test vehicle provided a unique opportunity to utilize a specific military application to demonstrate accelerated technologies that will provide lower fleet lifecycle costs across multiple commercial applications. The vehicle was used to validate the industry partner's unique "coating treatment" approach; many industrial efforts are focused on developing new coating compositions, rather than providing treatments to the current coating composition. Some deployments have identified that the first generation of these technologies significantly decrease lifecycle costs of aircraft engines, but these have only begun to scratch the surface of the potential of this technology. There was an opportunity through this initiative to demonstrate applicability for multiple generations of these treatments with increasing effectiveness and broad ranges of objectives even beyond coating protection. For example, the same tooling has been used for both on-wing coating treatments as well as advanced inspections. These on-wing/module/on-site technologies are so adaptive and flexible, that the concept can be used to overcome a wide range of obstacles and could be adapted to improve durability of other technologies like power generators, vehicles, etc. Potential uses could include inspections, cleaning, repairs, lubrication, wear and corrosion protection. By demonstrating the benefit of the first generation of these coating treatments on this engine test it validates a change in coating development strategy opening up a new technology space to meet a variety of needs including performance improvements, decreased lifecycle costs, improved safety and lower cost products.

The industry partner has been working to stand-up a new industry of on-site coating processing providing new jobs and opportunities for expert maintenance skill trades development. These areas include high-tech skill set development in the fields of robotics operations, and mechanical and materials expertise.

There is a large market for commercial engines in regions that provide harsh environmental conditions for aircraft engines. Academic institutions, government labs and the aircraft industry globally have been developing solutions to improve lifecycle costs when flying in these regions. By advancing these technologies within the U.S., the American industrial base is securing our nation's competitive advantage in this field of technology, leading to improved worker skills and contributing to the support of the economy.

5.2 Benefits for DOD

Aircraft engine dust ingestion is causing maintenance issues across all of the DOD Services. By demonstrating this technology on a DOD asset, the advanced coating technologies will be ready for deployment on DOD aircraft across all the Services; these coatings are compatible with the current hardware materials and coatings across all aircraft engines. Inclusion of advanced coatings will reduce lifecycle costs and provide a higher quality of goods by increasing DOD aircraft operational flexibility, decreasing engine downtime and improving predictability, and ultimately readiness. As described in Section 2, sandy environments require 165 hours of maintenance time for every hour of flight time, versus non-sandy environments requiring 100 hours of maintenance time per hour of flight time; the goal of advanced coatings would be to decrease the required maintenance in the sandy environments to be equivalent to the non-sandy environments. Dust deposits on the hardware reduce turbine efficiency reducing the performance of the engine; by reducing dust thicknesses through the use of advanced coating solutions, the performance of the engine will be maintained for longer times reducing fuel costs and allowing the pilot greater operational flexibility. The use of on-site treatments helps with the maintenance flexibility needed by the DOD; these treatments can be applied in remote locations to extend the serviceable life of the engines.

Post-test visual inspections of the hardware demonstrated that deposit accumulation on the hardware was as expected and representative of fielded hardware. This gives high expectations that conclusive results of coating performance will be determined from subsequent cut-up evaluation. If coatings show decreased spallation or reduced deposition thickness, follow-on programs will result to implement these coatings in DOD engines.

Current DOD engines experience choking or in-flight shutdowns due to turbine blade distress; advanced coatings will reduce dust deposit thicknesses and slow down turbine distress improving the safety of the engines.

For future aircraft, these coatings allow for higher temperature of design improving the efficiency of the engine and allowing for design flexibility. Higher temperature operation enables the superiority of the U.S. aircraft by allowing for longer flights and improving margins to allow for greater maneuverability.

The testing and hardware inspection data obtained from this project are expected to be utilized for future DOD programs where sand ingestion degradation is expected to be an issue. Engine sand ingestion testing-based coating performance validation of the coating strategies allows for potential future research to be guided to develop improved capability coating systems for DOD aircraft operated in austere environments. Additionally, the demonstration of the on-site application technologies sets the stage for potential future collaborations on on-site technologies. These future collaborations could include work relating to advanced inspection, cleaning and repair technologies.