NATIONAL ENERGY TECHNOLOGY LABORATORY

EROSION-RESISTANT NANOCOATINGS FOR IMPROVED ENERGY EFFICIENCY IN GAS TURBINES

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Cover Photo: A compression section blade coated with the erosion resistant nano-coating installed on an industrial gas turbine for a field trial. Blades with the nano-coating applied to the surface appear grayish in color.

Executive Summary

The objective of this Stage Gate IV project was to test and substantiate the viability of an erosion-resistant nanocoating for application on compressor airfoils for gas turbines in both industrial power generation and commercial aviation applications. To effectively complete this project, the National Energy Technology Laboratory's Office of Research & Development teamed with MDS Coating Technologies Inc. (MCT), Delta Air Lines - Technical Operations Division (Delta Tech Ops), and Calpine Corporation.

The coating targeted for this application was MCT's Next Generation Coating, version 4 (NGC-v4 - with the new registered trademark name of BlackGold®). The coating is an erosion and corrosion resistant composite nanostructured coating. This coating is comprised of a proprietary ceramic-metallic nano-composite construction which provides enhanced erosion resistance and also retains the aerodynamic geometry of the airfoils.

The objective of the commercial aviation portion of the project was to substantiate the coating properties to allow certification from the FAA to apply an erosion-resistant coating in a commercial aviation engine. The goal of the series of tests was to demonstrate that the durability of the airfoils is not affected negatively with the application of the NGC v4 coating. Tests included erosion, corrosion, vibration and fatigue. The results of the testing demonstrated that the application of the coating did not negatively impact the properties of the blades, especially fatigue performance – which is of importance in acceptance for commercial aviation applications.

The objective of the industrial gas turbine element of the project was to evaluate the coating as an enabling technology for inlet fogging during the operation of industrial gas turbines. Fluid erosion laboratory scale tests were conducted to simulate inlet fogging conditions. Results of these tests indicated that the application of the erosion resistant NGC-v4 nanocoating improved the resistance to simulated inlet fogging conditions by a factor of 10 times. These results gave confidence for a field trial at Calpine's power plant in Corpus Christi, TX, which commenced in April 2012. This test is still on-going as of November 2013, and the nano-coated blades have accumulated over 13,000 operational hours on this specific power plant in approximately 19 months of operation.

1. Introduction

Gas turbine compressor section airfoil surfaces are subjected to a hostile, erosive environment. For instance, gas turbines powering aircraft ingest dust, abrasive and fluid particles during takeoff and throughout the flight envelope. This results in degradation of the compressor airfoils from erosion, resulting in a marked decrease in engine efficiency – and concomitant decrease in fuel efficiency and increase in CO₂ emissions.

There are over 9,000 power plant units operating in the U.S. that generate over 600,000 MW of power annually. Approximately 1,000 units are coal driven and over 5,000 units are either petroleum or gas driven. These units produce over 2M thousand metric tons of CO₂ emissions. The Electric Power Industry has been utilizing inlet fogging as a method to augment power output and to offset power decrease associated with increased ambient temperatures during hot summer days. Evaporation of the water droplets increases air density and mass flow resulting in up to 8% increased power output without additional consumption of fossil fuel and a reduction in carbon emissions. A further variation of inlet fogging is high fogging where the water fog continues downstream through the compressor resulting in an additional power increase between 5 to 7 percent. However, an adverse impact of inlet and high fogging is the erosion of the compressor airfoils due to the impingement of the fine water droplets along the leading edges of the blades.

Erosion resistant coatings are needed to enable higher efficiency in both commercial aviation and industrial gas turbines. Erosion resistant coatings can be (and are) applied to compressor airfoil surfaces to significantly reduce material loss during service, leading to improved engine performance, and resulting in huge reductions in fuel costs for industry. Engineered nano-structured coatings have the ability to tailor features of material to achieve specific properties, such as strength, durability and reactivity among other material characteristics. Using proper techniques, scientists and engineers can now design materials on the nano-meter scale and produce materials with a specific blend of properties. Of particular interest is the designing of composites on the nano-meter scale, in order to produce materials with enhanced properties. This is illustrated in Figure 1 for an erosion resistant nano-composite coating. In this particular case, the hard phase provides the hardness necessary for the coating to resist impact from the impinging erodent particle. The softer phase by itself would have little or no resistance to an erosive particle. However, when the materials are woven together in the composite, the softer, more ductile phase absorbs the impacts and keeps any initial cracks from propagating directly to the substrate material. This is the well known ductile phase toughening mechanism (for example see: Mechanical Properties of Engineered Materials, W. Soboyejo, CRS Press,

2002). Interestingly, a high hardness material is not necessarily the predictor of erosion resistance, and that lower hardness can provide superior erosion properties. The composite material provides a combination of hardness and toughness, which results in a more erosion-resistant coating than could be provided by the monolithic constituents alone. However, key to exploiting the erosion resistant mechanism is precise engineering, control, and optimization of the composite microstructure.

The objective of this Stage Gate IV project was to test and substantiate the viability of an erosion-resistant nanocoating for application on compressor airfoils for gas turbines in both industrial power generation and commercial aviation applications. Success in this project will result in verification of this nanomaterial technology as an enabler for inlet fogging in industrial gas turbines, significantly increasing machine efficiencies; and as an effective protection strategy in commercial aviation turbines, reducing the loss in fuel efficiency that results from erosion. To effectively complete this project, the National Energy Technology Laboratory's Office of Research & Development has teamed with MDS Coating Technologies Inc. (MCT), Delta Air Lines - Technical Operations Division (Delta Tech Ops), and Calpine Corporation. MCT owns the erosion resistant nano-coating technology that was investigated under this study. Delta Air Lines is a major United States flagged commercial airline carrier. Delta Tech Ops provides maintenance services to, not only, Delta's fleets, but also a variety of other commercial fleets. Calpine operates **over 70** power plants generating electricity in the United States. The combination of this national laboratory, coating manufacturer and industrial end-users increased the likelihood of transitioning the erosion resistant nano-coating into application.

The aim of the research was to: (i) generate erosion, corrosion and fatigue related data to substantiate (or qualify) the erosion resistant nano-coating for use in commercial aviation gas turbines, and (ii) substantiate the fluid erosion resistance of nano-coating in simulated inlet fogging conditions and perform a field trial in an industrial gas turbine. Note, an objective was **not** to obtain the necessary U.S Federal Aviation Administration (FAA) certification of the erosion resistant nano-coating. Clearly, however, FAA certification is a requirement prior to any commercial aviation application.

The remainder of the report is divided into the following sections: (i) Erosion Resistant Nano-Coating; (ii) Commercial Aviation Turbines; and (iii) Industrial Gas Turbines. These sections provide the technical summary of progress made on this project towards transitioning the erosion resistant nano-coating for application in gas turbines for commercial aviation and industrial gas turbines, respectively.

Figure 1. Representative nano-coating schematic applied to compressor airfoils

2. Erosion Resistant Nano-Coating

The coating targeted for this application was MCT's Next Generation Coating, version 4 (NGC-v4) with the new registered trademark name of **BlackGold®**. The coating is an erosion and corrosion resistant composite nanostructured coating. This coating is comprised of a proprietary ceramic-metallic nano-composite construction which provides enhanced erosion resistance throughout the compressor and also retains the aerodynamic geometry of the airfoils.

The tip of the blade has the greatest effect on efficiency and is also the region most affected by erosion. The coating that the material has been formulated to has a good balance of hardness and toughness to resist particle impact, as well as being sacrificial in a corrosion sense in relation to steels to provide corrosion resistance. The coatings are applied by a proprietary method using a physical vapor deposition (PVD) process, a vaporization coating technique in which a high purity solid coating material is evaporated under high vacuum and subsequently attaches onto the substrate material on a nano-level. The coating structure can be varied according to the required properties and is optimized to counter the erosion pattern exhibited on a compressor airfoil.

The total coating thickness can vary according to the engine type and compressor stage, but as a general rule these types of coatings have to be at least 10 micrometers thick to provide sufficient protection. The coating preserves the overall shape of the airfoil during operation, which in turn retains compressor efficiency.

3. Commercial Aviation Turbines

The objective of the commercial aviation portion of the project was to obtain sufficient information to allow certification from the FAA to apply an erosion-resistant coating in a commercial aviation engine, with initial tests focused on the compressor airfoils. The goal of the series of tests described here is to demonstrate that the durability of the airfoils is not affected negatively with the application of the NGC v4 coating. Tests include erosion, corrosion, vibration and fatigue on both coated and uncoated blades supplied by Delta Air Lines. These blades were coated with the NGCv4 coating, and Figure 2 shows a coated blade.

3.1 Particle Erosion

It is the experience of the maintenance group from Delta Air Lines that certain engine airfoils will typically lose approximately 2% of chord length at the tip during one typical overhaul cycle. To test the durability of airfoil coatings a comparative erosion test was conducted in order to simulate 4% chord loss on uncoated airfoils, which is equivalent to the erosion from two overhaul cycles. These erosion tests include the following experimental parameters:

- Arizona Road Dust (ARD) A4 (50 μm nominal distribution) sand directed at the blade LE and tip
- Pressure of 80 psi
- Angle of 20°

Figure 2 compares the erosion of an uncoated and NGC v4 coated mid-stage compressor rotor blade at the LE near the tip. The uncoated blade exhibits 4% chord loss while the coated blade exhibits 0.2% chord loss under the same test conditions.

Figure 3 graphs the chord loss results of the uncoated and coated blades as a function of exposure to ARD A4 abrasive media. Both qualitatively and quantitatively the NGC v4 coated airfoil demonstrates significant protection against erosion.

3.2 Corrosion

Depositing an erosion resistant coating on a steel alloy can often degrade the corrosion properties of the steel as a result of galvanic corrosion. In other words, when two dissimilar metals are in contact, the more noble, or cathodic, material (the coating) will promote corrosion of the anodic metal (the airfoil). There is no corrosion issue when depositing the **coating**

on Ti alloys. The coating is designed to be less noble than the A286 and IN718 alloys, which means that galvanic corrosion of the airfoil should not be an issue.

To confirm this hypothesis, accelerated corrosion tests were conducted to evaluate the effect of the coating on coated airfoils. The coating was applied on several IN718 (Figure 4A) and A286 (Figure 4B) airfoils and tested according to ASTM B117 standard practice. After exposure to 5% salt fog solution over a period of 14 days, the coated airfoils demonstrated significant corrosion protection as compared to uncoated airfoils. Uncoated stainless steel airfoils typically corrode within 1 day of testing. In contrast the NGC v4 coated airfoils exhibited no corrosion after 14 days of testing. Corrosion pits on uncoated airfoils are numerous and aggressively attack the substrate material; whereas, if the coating does exhibit corrosion, it is typically one (1) pit per square inch with a very shallow pit depth.

3.3. Fatigue and Vibration

Coated and uncoated airfoils were tested for fatigue. In this test, the airfoils are set on a shaker table and tested for fatigue in first bend mode. This is a fully reversed test with an alternating to mean stress ratio of $A = \infty$. The airfoils were tested either to failure or run-out conditions of 10^7 cycles.

Natural frequency and fatigue test were conducted on stainless steel airfoils. Fatigue tests on A286, nickel based stainless steel airfoils are summarized on Figure. 5. This figure plots the fatigue test points for 12 new, uncoated and coated and 12 repaired, uncoated and coated 11th stage compressor blades. These results show that the coated A286 blades have successfully passed fatigue testing – a key requirement for FAA certification. That is, the coated blades behave in a similar manner to non-coated blades, indicating that there is no debit in fatigue life of the blade due to the application of the nano-coating.

3.4 Commercial Application

The objective of the Commercial Aviation Turbines portion of the research is to generate data necessary for FAA certification. However, FAA certification is necessary for implementing the coating on commercial aviation engines. In part, due to the testing and materials properties generated by this project, Delta Air Lines' Designated Engineering Representative (DER) submitted a Statement of Compliance (Form 8110-3) on 5 January 2012 authorizing the application of the NGC v4 on the CFM56-7 8th stage compressor rotor blade. DER has official approval authority granted by the Federal Aviation Administration. Official FAA certification was

granted in October 2012. Subsequently, the remaining 5th through 9th stages in the CFM56-7 have been authorized by the DER and MCT has been supplying blades with the erosion-resistant nano-coating to Delta Air Lines. Delta presently has commercial aircraft operating with the erosion resistant nano-coating in the gas turbine's high pressure compressor section. **The project was successful, as it generated the necessary data for FAA certification of the coating, thus completing the objective of the aviation portion of the project.**

It is estimated that operating with BlackGold[®] (NGC v4) coated compressor rotor blades in the high pressure compressor section can provide between 0.5% to 2.0% fuel savings depending on an aircraft's operational environment. As the engines accrue operational hours, the compressor rotor blades erode losing chord length and thickness. This degrades the performance retention of an engine with the deterioration rate dependent on an aircraft's operational environment.

Figure 2. A compressor section airfoil with the erosion resistant nano-coating on the blade's pressure-side and covering the top 50% of the blade span.

Figure 3. Erosion resistance comparison, note the application of the nano-coating improves erosion resistance of the blades (as indicated by the reduction in chord loss with the application of the nano-coating).

#	Samples and Exposure	#	Samples and Exposure
1	1 sample after 10 weeks	5	4 samples after 3 weeks
2	1 sample after 10 weeks	6	9 samples after 3 weeks
3	3 samples after 7 weeks	7	9 samples after 2 weeks
4	4 samples after 3 weeks	8	9 samples after 2 weeks

Figure 4. BlackGold[®] coating on (A) IN718 and (B) A286 airfoils after B117 exposure.

Figure 5. S/N curve for A286 blades with and without the nano-coating. This plot includes 24 new and repaired uncoated blades and 24 new and repaired nano-coated blades.

4. Industrial Gas Turbines

The objective of this element of the project is to evaluate the coating as an enabling technology for inlet fogging during the operation of industrial gas turbines. Inlet fogging and high fogging can augment power output for an electricity producing power plant by 8% and 7% respectively. However, these operating conditions cause erosion of front stage rotor blades from the impingement of fluid particles. The aim of this research is to evaluate the evaluation of the nano-coating during operation on a Calpine GE Frame 7 gas turbine engine.

4.1 Fluid Erosion

Fluid erosion tests were conducted to confirm the nano-coatings resistance to a high-velocity water spray. Fluid erosion testing on coated coupons, with a leading edge similar to that of a large first stage fan rotor blade. A rotating disk liquid impact test apparatus was utilized to simulate inlet fogging (Figure 6). In this test, fine droplets impinged on the test coupons rotating at 14,000 rpm from which the impact velocity was calculated at 750 feet / sec. These conditions simulated the R0 leading edge impact velocity near the blade root. Figure 7 illustrates the fluid impingement on the test coupon.

Fluid erosion tests were conducted on coupons with the nano-coating applied at different thicknesses. For comparison, uncoated coupons were also tested. Weight loss versus test time (in minutes) is shown in Figure 8. The results show the significant improvement in resistance to fluid erosion of the coated coupons relative to the uncoated coupons, as the coated coupons had significantly less weight loss than the uncoated coupons. For instance the uncoated test coupon (7.2 mg) lost almost as much mass as the coated test coupon (7.2 mg) only after a running test time of 46 minutes versus 436 minutes for the coated test coupon – approximately a 10X improvement.

Figure 8 shows the condition of the leading edge of the coupons after various test times and corresponding weight loss. The focus of this test was to demonstrate the ability of the test coupon's leading edge or "rounded" area to resist fluid erosion. The erosion on the flat area of the test coupon does not replicate a blade's leading edge radius of curvature.

Figure 9 compares the erosion profile of a test coupon to the erosion profile from a 1st stage rotor blade. The results show that the test coupon and the field blade have similar erosion profiles. This is significant, as it indicates that the tests accurately replicates field conditions, giving confidence that the coating will provide similar benefit in the field as it did in the laboratory.

4.2 R0 Blade Coating and Field Trial

Based on the successful fluid erosion laboratory test results, Calpine supplied R0 serviceable blades for coating. MCT used these used blades for process optimization. Figure 11 shows an R0 blade coated with the NGC v4 erosion resistant nano-coating.

Nanocoated R0 blades were supplied to Calpine for a field trial installation. Calpine installed four (4) NGC v4 nano-coated R0 blades in the power plant turbine located at their Corpus Christi, TX facility on April 15, 2012. Figures 12 through 15 show the nanocoated blades (as evidenced by their grayish color) installed on the Calpine Frame 7 R0 stage. As of November 2013, the field trial is still on-going. The R0 blades coated with the (NGC v4) erosion resistant nano-coating have accumulated over 13,000 operational hours on this specific power plant in approximately 19 months of operation. The engine was exposed to almost daily inlet fogging between the time period of February to November and, additionally, exposed to daily compressor washes.

Figure 6 Fluid erosion rotating-arm testing apparatus and sample holder

Figure 7. Fluid erosion configuration

Figure 8. Fluid erosion showing weight loss versus time (in minutes) for the coated and un-coated coupons.

Figure 9. Leading edge conditions at various time intervals.

Figure 10. LE erosion profiles from a field blade and a laboratory test coupon. The similarities of the erosion profiles indicate the test accurately replicated field conditions.

Figure 11. Nano-coated R0 blade shipped to Calpine.

Figure 12. Rotor with nano-coated R0 blade.

Figure 13. Rotor with nano-coated R0 blade

Figure 14 . Rotor with nano-coated R0 blade

Figure 15. Installation of industrial gas turbine with nano-coated R0 rotor blade.

5. Conclusion

This Stage Gate IV project effectively transitioned erosion resistant nano-coating technology into the field. Tests were conducted to substantiate the nano-coating for industrial and aviation gas turbines. Information was generated with respect to the performance of compressor section airfoils for aviation turbines coated with the nano-coating that was necessary for FAA certification. Testing demonstrated that the application of the coating did not degrade the performance (corrosion and fatigue) of blades. Through separate work (outside the scope of the project), the application of the coating has received FAA certification and Delta is flying commercial aircraft with coated high pressure compressor rotor blades. Through these combined efforts, this project was awarded an R&D 100 award in 2013.

Laboratory scale fluid erosion tests that simulated inlet fogging conditions demonstrated the effectiveness of the nano-coating. Specimens with the application of the nano-coating were 10x more resistant to material loss due to erosion than comparable un-coated samples. This provided confidence for field trials on an industrial gas turbine at Calpine's plant in Corpus Christi, TX. Due to the availability of the turbine the field trial did not start until April 2012, and as of the beginning of 2014, the blades are still on the turbine. Coated airfoils have accumulated over 13,000 operational hours on this specific power plant in approximately 19 months of operation.