Title: Rolls-Royce Allison Ceramic Vane Project

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Abstract

First-stage ceramic vanes and their metallic mounts have been designed and fabricated for retrofit into Rolls-Royce Allison Model 501-K turbines. The ceramic vanes and mounts were successfully operated in a Model 501-KB5 turbine during engine proof tests for a total of 22 hr. After inspection of the ceramic vane assembly, the turbine was reassembled and shipped to an Exxon natural gas processing plant near Mobile, AL, for the first phase of a field demonstration. Operation for 815 hr (793 hr at Exxon and 22 hr engine proof test) was achieved for the Model 501-KB5 turbine with first-stage ceramic vanes during which the engine sustained power and performance. The metal mounts for the ceramic vanes performed successfully. However, analyses of the vanes revealed ceramic oxidation rates that are excessive for industrial turbine applications. A second phase of the ceramic vane demonstration will evaluate environmental barrier coatings (EBC) to inhibit ceramic oxidation rates.

Introduction

Use of advanced structural ceramics is a promising technology to accomplish the high performance goals for advanced turbines. Ceramic airfoils could eliminate the chargeable air required for the metal airfoils currently used in the hot sections of gas turbines and would thereby provide increased engine power at greater thermal efficiency. Consequently, the objective of this US Department of Energy (DOE)/Rolls-Royce Allison ATS project is to evaluate uncooled ceramic vanes for advanced industrial turbines.

The approach for this project is to design and demonstrate ceramic first-stage vanes in a Rolls-Royce Allison Model 501-K turbine. These vanes operate at similar (and somewhat higher) temperatures as the second-stage vanes of advanced turbines. Consequently, a successful demonstration of first-stage vanes in the current generation Model 501-K turbine could provide a stepping stone to using ceramic vanes in second-stage and downstream rows of future generation advanced turbines.

Project Summary

Activities of the DOE/Rolls-Royce Allison ATS ceramic vane project include the following:

- Design, analyses, and fabrication of ceramic first-stage vanes and their metal mounts for retrofit into Model 501-K turbines
- Thermal shock proof tests of the ceramic vanes
- Engine validation test of the ceramic vanes and their metal mounts
- Phase 1 demonstration of the first-stage ceramic vane assembly in a Model 501-K turbine at a commercial site to assess the assembly design
- Phase 2 demonstration with an improved ceramic vane assembly design

The design and drawings for the ceramic vanes and metal mounts have been completed. Thermal and stress analyses together with long term stress rupture tests for the AlliedSignal AS 800 silicon nitride ceramic have predicted acceptable vane stresses and life for the turbine demonstration under both maximum continuous power and emergency shutdown conditions. The AS 800 ceramic vanes and their metal mounts have been fabricated. Thermal shock tests of the individual ceramic vanes have been conducted.

The engine validation tests of the first-stage ceramic vanes (and their mounts) with 22 hr duration have been successfully completed. The ceramic vane assembly was removed from the engine, inspected, and reassembled into the turbine for the field demonstration.

The first phase of the field demonstration of the Rolls-Royce Allison Model 501-KB5 turbine with first-stage ceramic vanes was conducted at an Exxon natural gas processing plant near Mobile, AL. Operation of the Exxon turbine for a total of 815 hr (793 hr at Exxon and 22 hr proof test) was achieved. The Phase 2 demonstration was originally planned to accommodate a redesign of the metal mounts for the ceramic vanes because past experience has shown the challenges of integrating structural ceramic components with metallic support structures. The metallic mounts performed successfully in 501-KB5 demonstration of first-stage ceramic vanes. However, the demonstration identified a significant issue of ceramic oxidation, so the Phase 2 demonstration will address resolution of the oxidation issue.

The design, analyses, and fabrication of the ceramic vanes and metal mounts and the ceramic vane thermal shock proof tests have been described in the proceedings of previous ATS Annual Program Reviews (Wenglarz, 1997, 1998) and publications (Wenglarz, Ali, and Layne, 1996; Wenglarz, Calcuttawala, and Pope, 1997). The remainder of this paper describes the ceramic vane engine proof test and the commercial demonstration results to date.

Ceramic Vane Assembly Engine Validation Tests

Turbine validation tests of the ceramic vanes and metal mounts were conducted prior to operation at a commercial site. Objectives of these tests were to verify that (i) the metal mounts do not transmit excessive contact loads to the ceramic vanes, (ii) turbine power and performance are not adversely affected by the vane/mount designs, and (iii) the uncooled ceramic vanes do not result in excessive temperatures in the adjacent metal vane support structures. Turbine power and performance were potential issues because of the challenges of maintaining tight gaps, clearances, and airfoil positioning considering the difference of more than five times between the thermal expansion coefficients for the metal mount materials and the ceramic vane materials.

Temperature of the metal support adjacent to the ceramic vanes was also a potential issue because the mount parts common to both the metal vane and ceramic vane assemblies do not benefit from the metal vane cooling when operated with ceramic vanes.

The test approach to accomplish the above objectives consisted of a baseline performance run of the Exxon owned Model 501-KB5 engine with metal vanes, performance tests of the same turbine except with the metal first-stage vane assembly replaced with the ceramic first-stage vane assembly, thermocouple measurements of the temperatures of the metal vane support during ceramic vane runs, and comparisons of the performance of the turbine with the metal and ceramic vane assemblies. The turbine was disassembled and inspected after the final ceramic vane test to determine whether the metal mounts had transmitted excessive loads to the ceramic vanes.

The total operation time of the turbine with the ceramic vane/mount assembly was 22 hr. Post test visual and fluorescent penetrant analyses revealed no fractured or cracked vanes. However, two vanes had platform chips, one of which was suspected to have occurred during disassembly. Evaluations of the other chipped vane and the few vanes that experienced chips during the later demonstration led to the conclusion that the ceramic vane/mount design provided stress relief of inevitable localized contact loads at platform edges associated with both ceramic and metal part tolerances. Oxide scale formation observed on chipped platform surfaces during the later demonstration inspections indicated that the vanes operated many hours after chipping and cracks had not propagated from the chips.

All six performance calibration point measurements referenced to standard day conditions for the Exxon owned engine with the ceramic vane assembly indicated greater power than for the same turbine operated with the metal vane assembly. The average calculated standard day power for the six ceramic vane performance runs exceeded that for the metal vane run by 1.7 %. Some of the improved performance for the ceramic vanes probably resulted from a thinner airfoil designed with more advanced aerodynamic computer codes than for the metal vanes. Also, the ceramic vanes did not experience the flow disruption of cooling air discharge from the trailing edges.

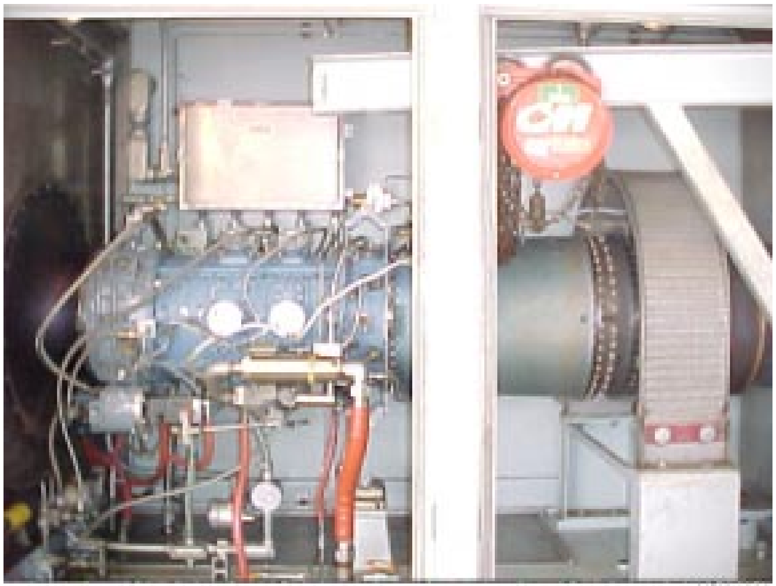
Thermocouple measurements of the metal vane support temperatures adjacent to the ceramic vanes showed temperatures well below the working limits of the vane support alloy.

Following reassembly of the ceramic vane module after inspection, the turbine used in the ceramic vane proof tests was sent to an Exxon Mobile Bay facility for the field demonstration.

Ceramic Vane Assembly Demonstration

The first-stage ceramic vane Phase 1 field demonstration occurred at an Exxon natural gas processing plant near Mobile, AL. This plant removes sulfur from natural gas supplied by wells in Mobile Bay. Three Rolls-Royce Allison Model 501-KB5 turbine skids provide power and process steam at this Exxon plant.

Figure 1 shows a Model 501-KB5 turbine inside its skid enclosure at the demonstration plant. Figure 2 shows the first-stage ceramic vane assembly that replaced a similar metal vane assembly used for the Exxon turbine. The inner vane support and an outer sheet metal band that holds the assembly together are common to both the ceramic and metal vane assemblies. All of the other parts of Figure 2 were designed for retrofit of the ceramic vanes into Model 501-K turbines. The front view of Figure 2 also shows the saddles that position the transition sections from the six can combustors of the Model 501-K turbines. Consequently, 10 of the 60 first-stage ceramic vanes are located at the exit of each of the transition sections from the six combustor cans.



VSK-1323
TE99-937

Figure 1. Exxon 501-KB5 turbine at site.

VSK-1325
TE99-938

Figure 2. Ceramic vane assembly.

The turbine with the ceramic first-stage vanes was installed and operated under normal commercial service conditions at maximum continuous power, except for preplanned teardowns and ceramic vane assembly inspections with removal of vanes for analyses. These inspections were originally scheduled at 200, 500, and 1000 hr.

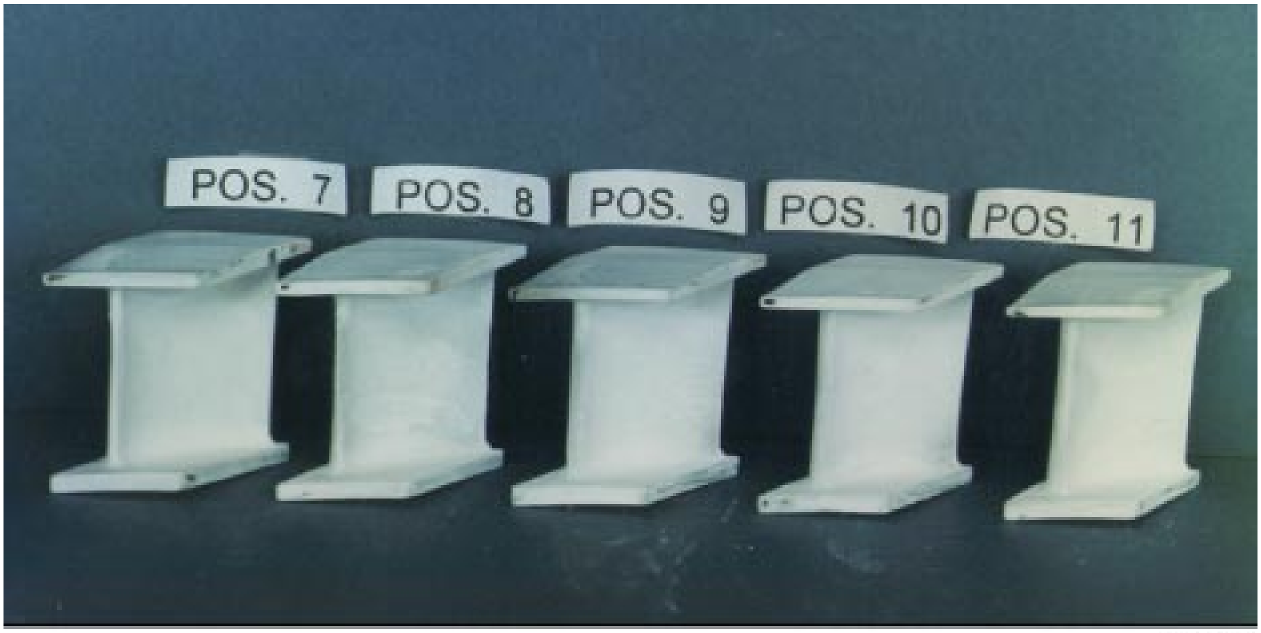
The Exxon turbine sustained power and performance throughout its operation with ceramic vanes. The turbine experienced an emergency shutdown (the highest vane stress condition) at 525 hr and a full power water wash of its compressor with no detectable adverse effects on further operation or the ceramic vanes. The cause of the emergency shutdown was a malfunctioning vibration sensor and was unrelated to the ceramic vane assembly. There was no need to shut the turbine down associated with the ceramic vanes except for the planned inspections. None of the ceramic vanes failed or cracked and the metal mount design performed successfully. As mentioned earlier, a few vanes experienced chipping at platform edges, which appeared to alleviate local contact loads and enable further operation for many hours without propagation of cracks or failure.

Analyses of the vanes removed during the periodic inspections showed unexpected rates of material loss due to oxidation of the Si_3N_4 ceramic in the turbine operation environment. These rates of materials loss were determined to be excessive for industrial turbine applications, which require part lifetimes in excess of 20,000 hr. Analyses of the vanes removed in the 222 and 522 hr inspections showed the need for additional measures (e.g., environmental coatings) to achieve industrial turbine lifetimes. Since the Phase 1 demonstration had achieved its objective of identifying redesign needs, this demonstration phase was discontinued at a total operation time of 815 hr (22 hr proof test and 793 hr demonstration) for the turbine with ceramic vanes.

Ceramic Vane Analyses

Visual evidence of ceramic oxidation was apparent during the turbine inspections. Figure 3 shows five of the ten vanes located downstream of one the turbine combustors. These vanes had operated about 815 hr in the Exxon turbine. The color of the vanes had changed from tan/grey to white. Figure 4 compares the color of an as-processed vane (on the right) to a vane (on the left) that had operated for 815 hr in the turbine. The inspection at 222 hr operation showed that the ceramic vanes were covered by a white powder. The metal rotor blades and vanes in the two rows downstream of the ceramic vanes also had a dusting of white powder. The white powder on the ceramic vanes was analyzed by Oak Ridge National Laboratories (ORNL) and found to be an oxide of silicon and lanthanum from the intergranular phase of the ceramic. Figures 5 and 6 illustrate oxidation material losses visible to the unaided eye on vane concave and convex surfaces, respectively. These vanes had experienced 815 hr operation in the turbine.

All 60 vanes removed from the assembly after 815 hour (793 hr in the demonstration and 22 hr in the engine proof test) operation were measured for trailing edge thickness losses. The decreases in trailing edge mid span thickness ranged from 0.005 in. to a maximum loss of 0.024 in. Percentage decreases in trailing edge thickness range from 12% to 50% of original values. The trailing edge thickness measurements indicated that the rate of oxidation might have been decreasing with time.



VSK-1887
TE99-939

Figure 3. Five adjacent vanes after 815 hr operation in the turbine.

VSK-1328
TE99-940

Figure 4. Ceramic vanes before and after 815 hr operation in the turbine.

VSK-1327
TE99-941

Figure 5. Ceramic material loss on concave surface.

VSK-1329
TE99-942

Figure 6. Ceramic material loss on convex surface.

Oxidation Versus Position on Airfoil Surface

AlliedSignal took profile measurements of several of the ceramic vanes that had operated 815 hr in the turbine and compared those to profiles measured on the same vanes after fabrication. Figure 7 gives the mid span profile comparisons at mid span for the vane that had the greatest materials loss. Although the gas velocity near the airfoil surface varies from near zero at the nose stagnation point to about 1880 ft/sec at the trailing edge, the loss does not greatly differ over the airfoil surface. This suggests that gas velocity is a secondary factor in the rates of oxidation and that relatively expensive high velocity rigs (e.g., cascades) might not be needed for ceramic materials oxidation tests. However, materials tests do need to replicate the water vapor content and pressures of the turbine flow path environments.

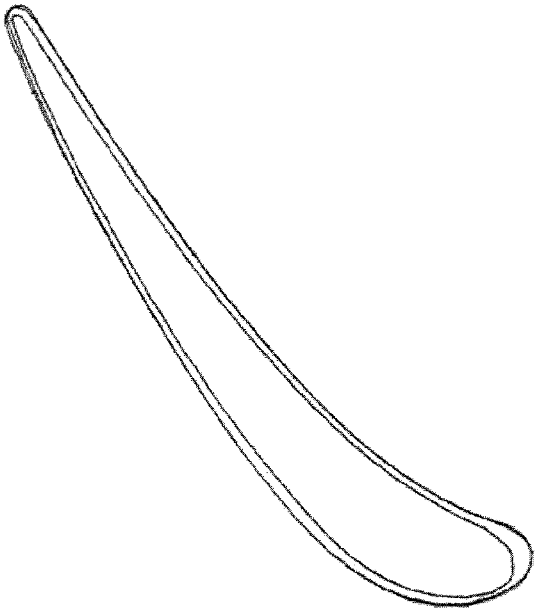


Figure 7. Midspan profile loss.

<u>Retained Strength of Ceramic Vanes</u>

Several of the ceramic vanes removed at various operation intervals from the demonstration turbine were sent to ORNL for retained strength measurements. Small disks (about 6 mm dia. and about 0.6 mm thick) cut from the vanes were then fractured using a load at their centers. Figure 8 shows results of the ORNL retained strength measurements versus operation time. The retained strength after 22 hr exposure to the turbine environment (in the engine proof test) increased over the as-processed strengths (zero time exposure). The average retained strength of specimens did not greatly change from initial values for increasing exposure times although the scatter in the strength measurements did increase with time. The lowest retained strength measurement in Figure 8 of about 500 MPa is approximately 2.4 times greater than the maximum calculated vane stress of 207 MPa at the highest stress vane location and the worst (emergency shutdown) condition. Consequently, the ORNL data suggest that the vane oxidation is a surface phenomenon that does not substantially affect the strength of the underlying substrate material. Much longer vane lifetimes appear possible if the loss of surface material by oxidation can be inhibited (e.g., through use of environmental coatings).

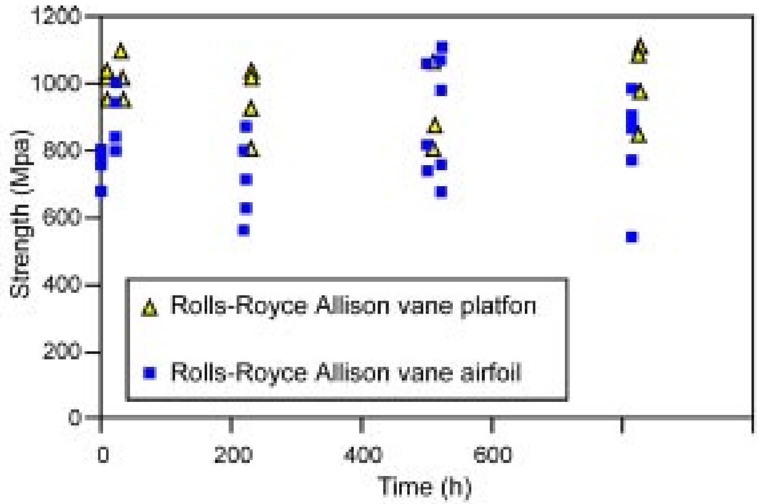


Figure 8. Strength versus time for specimens from vanes.

Summary and Conclusions

A first-stage ceramic vane and metal mount design has been developed and demonstrated for 815 hr under commercial industrial turbine conditions. This design appears to have successfully addressed many of the challenges of integrating stationary structural ceramics with metallics in an industrial turbine. However, the ability to operate a turbine for extended durations afforded by the ceramic vane/mount design showed there is an issue of excessive long term ceramic oxidation in the industrial turbine flow path environment. Inspection of the vanes at 222 hr operation showed that the color of the vanes had changed to white. A white lanthanum silicate powder covered the vanes and dusted the blades and vanes of the two downstream turbine rows. Although measured trailing edge thickness losses were minor at 222 hr, the vanes had lost from 12 to 50% of their midspan trailing thicknesses at 815 hr. Additional measures are needed for acceptable materials durability so that commercial lifetimes of at least 20,000 hr can be achieved for industrial turbine ceramic parts. Measures to inhibit surface oxidation should advance structural ceramics toward this life goal since the strength of the ceramic structure underlying the oxidizing and recessing surfaces exposed to the flow stream was not observed to be markedly decreasing.

Future Work

A cooperative effort involving the DOE, National Labs, ceramic suppliers, coating organizations, and other turbine suppliers in addition to Rolls-Royce Allison is being planned to develop and test environmental barrier coatings (EBC) to alleviate oxidation of ceramics. Phase 2 of this project will be coordinated with that cooperative effort and will demonstrate ceramic vanes from two suppliers coated with up to three EBC coatings in a Model 501-K turbine at a commercial site.

Acknowledgements

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