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Erosion Resistant Coatings for Polymer Matrix Composites in Propulsion Applications

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This report contains preliminary findings, subject to revision as analysis proceeds.

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EROSION RESISTANT COATINGS FOR POLYMER MATRIX COMPOSITES IN PROPULSION APPLICATIONS

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ABSTRACT

Polymer Matrix Composites (PMCs) offer lightweight and frequently low cost alternatives to other materials in many applications. High temperature PMCs are currently used in limited propulsion applications replacing metals. Yet in most cases, PMC propulsion applications are not in the direct engine flow path since particulate erosion degrades PMC component performance and therefore restricts their use in gas turbine engines. This paper compares two erosion resistant coatings (SANRES and SANPRES) on PMCs that are useful for both low and high temperature propulsion applications. Collaborating over a multi-year period, researchers at NASA Glenn Research Center, AADC, and Rolls-Royce Engines have optimized these coatings in terms of adhesion, surface roughness and erosion resistance. Results are described for vigorous hot gas/particulate erosion rig and engine testing of uncoated and coated PMC fan bypass vanes from the AE 3007 regional jet gas turbine engine. Moreover, the structural

durability of these coatings is described in long-term high cycle fatigue tests. Overall, both coatings performed well in all tests and will be considered for applications in both commercial and defense propulsion applications.

1. INTRODUCTION

Polymer Matrix Composites (PMCs) offer weight savings accompanied by strength improvements, reduced part count and reduced manufacturing costs. High temperature polyimide-based composites are of particular interest for next generation military aircraft engines because they exhibit outstanding thermal stability for many propulsion applications [1–3]. Examples of PMCs in advanced propulsion applications include the Joint Strike Fighter (JSF), JSF-Lift Fan and the Integrated High Performance Turbine Engine Technologies (IHPTET).

In most cases, PMC propulsion component applications are not load bearing or in the direct engine flow path. Components residing in the engine flow path must withstand erosion to retain structural integrity and ensure acceptable surface finish to maintain aerodynamic performance [4, 5]. The survivability of PMC components is of major concern when long term operational life requirements for fan and compressor sections involve exposure to sand and grit erosion. One goal of NASA's HOTPC Project is to develop high temperature PMCs (HTPMCs) and associated surface protection coating technologies to allow for component integration into existing engines or advanced military engines. Over a multi-year period, NASA, AADC and Rolls-Royce Engines jointly developed an erosion resistant coating technology applicable to HTPMCs. A prior study detailing the performance of candidate erosion resistant coatings on a high temperature graphite fiber polymer composite, PMR-15, was reported [6] for flat coupon specimens.

Although the use of erosion resistant coatings to reduce wear on metallic substrates is well documented, limited information is available for these coatings on PMCs [7–10]. To date, literature surveys reveal no references describing erosion coatings for these PMCs or the process to scale-up the coating process for PMC engine hardware. This paper describes a coating scale-up process, introduces a new coating system (SANPRES) that contains a new bondcoat and the testing of coated PMC hardware. Coated and uncoated PMC vanes were tested in three ways: a hot gas erosion rig, high cycle fatigue durability tests and in Rolls-Royce AE 3007 engine tests. Future testing will involve integrating this technology on high temperature PMC components for advanced engine applications.

2. MATERIAL CONSIDERATIONS

The objective of this project was to eliminate erosion wear issues and improve the durability of PMC components in order to incorporate them into civil and military engines. Therefore, two coating systems (SANRES and SANPRES) were applied to composite engine components and their performance was measured in rig and engine tests. These coatings included a bondcoat applied to the PMC substrate followed by a hard erosion resistant topcoat. The function of the bondcoat was to provide a ductile layer adhering well to both the PMC and the topcoat. Additionally, the bondcoat has a coefficient of thermal expansion (CTE) that bridged the CTE of the PMC and the topcoat. The primary difference between the SANRES and SANPRES coating

systems was that the SANPRES coating contained a bondcoat with a polymer to improve adhesion to the PMC substrate. For both coating systems, tungsten carbide cobalt (WC-Co) was the primary topcoat constituent.

The AE 3007 fan bypass vane (Figure 1) was selected due to the ready availability of this PMC component for engine tests within the project time frame. The vane material consists of a carbon-Kevlar™ fiber-epoxy resin composite with a temperature capability up to 120 ºC. A metallic strike strip is bonded onto the leading edge of the vane for added foreign object damage protection. This paper describes our approach for producing and testing coated PMC components used in subsonic engines.

3. EXPERIMENTAL

3.1 *Coating Process Development*

The coating process was selected such that prototype hardware could be fabricated for both erosion rig tests and engine tests. The SANRES coating system was applied using the combustion spray process for the bondcoat and plasma spray process for the top WC-Co coating. A plasma spray process was used for both the bond and topcoat layers in the SANPRES coating. Prior to coating, the AE3007 vanes were carefully grit-blasted with alumina to prepare the surface. Coating trials included coating a 3-vane (triplet) assembly as well as individual vanes. The manufacturing sequence was specified based on the results of extensive coating trials. The SANRES coating system was developed in earlier studies and therefore was considered the base-line coating in this study. The development of SANPRES coating system was a major focus of this research program. Another important aspect of this program was to adapt production-like coating methods for both coatings.

A Metco 12E combustion gun with oxygen/acetylene gas setup was used to apply the bondcoat of SANRES coating to a thickness of about 0.076 mm. Coating trials were conducted with the part being held stationary or rotated with the gun moving vertically through an automated ladder step control program. A Sulzer Metco 7MB plasma spray gun was used to deposit the bondcoat of the SANPRES system to about 0.076 mm. Coating trials to optimize the bondcoat thickness and adhesion were also conducted by varying the gun traverse speed, number of passes, stand-off distance, part rotational speed and argon/nitrogen gas flow ratios. Finally, process parameters were established for the topcoat WC-Co (0.076 mm). This topcoat was applied to both coating systems using the 7MB gun. Engelhard Corporation applied all coatings. Once spray procedures were established, a design of experiments (DOE) was instituted to randomly apply the SANRES and SANPRES coating systems on three different days to remove potential biases due to spray and ambient conditions. Prior to coating, vanes were randomly chosen from a larger lot at the manufacturer.

3.2 *Erosion Rig Test Procedure*

(Erosion testing was performed at the University of Cincinnati.) Specimens were cut from the coated AE 3007 bypass vanes at a set trailing edge location and placed in a test fixture (Figure 2). The fixture was designed to accommodate specimen curvature and to retain un-eroded edge area for a nondestructive evaluation (NDE) baseline after the erosion test. In addition to the high temperatures, the University of Cincinnati erosion rig facility (Figure 3)

realistically simulates all the erosion parameters that are deemed to be important from an aerodynamic point of view [4, 5]. These parameters include particle velocity, impingement angle, erodent particle and sample size. Varying the airflow in the erosion rig wind tunnel controlled particle velocities. Rotating the specimen relative to the flow stream direction set the particle impingement angles. Heating the flow stream with a combustible hydrocarbon gas or steam jacket varied the coated PMC sample temperature. The erosion test procedure used Arizona road-dust (ARD) impinging at 20^o, 60^o and 90^o angles on both uncoated and coated vane specimens at a velocity of 228.6 m/sec. Room and elevated temperature (93 ºC) tests were conducted using 15, 12 and 10 grams of ARD. A multiple correlation analysis was used to determine the effect of these operational variables on the erosion of the various coating systems.

3.2.1 *Coating Effectiveness Analysis Procedure*

The typical method to measure erosion is to weigh the mass of the specimen before and after testing. However, the SANRES and SANPRES coating systems each contain more than one constituent and each constituent has a different density. Therefore, typical erosion mass measurement methods may not provide a reliable means to evaluate erosion resistance. A more accurate method would measure the eroded volumes of the multi-component coating wear scar. Accurately measuring eroded volumes on coated materials with complex topography's is also difficult. In order to gain a high level of confidence in our erosion measurements, several methods were used to measure the amount of material eroded from the coated PMCs. Some of the methods were employed for the first time—such as the method using optical interferometry. Other traditional methods such as coating weight loss or metallurgical sectioning/photo microscopy was also used to evaluate erosion. Results from each of these methods were compared with each other to determine if statistically valid correlations existed.

Four independent response factors (Y1, Y2, Y3 and Y4) were measured to ascertain if there were significant statistical differences in the erosion resistance between the SANRES and SANPRES coating systems. The response factors for the statistical analysis were Mini-Moiré Interferometry, Optical Interferometry (both methods are nondestructive), metallurgical cross-sectioning and weight loss methods. Since the topcoat for each coating system was WC-Co, it was presumed that the comparison analyzes the performance of each coating systems' bondcoat.

The specific erosion rate (Y1) was obtained through the weight loss measurement after the erosion test at the University of Cincinnati. The erosion depth (Y2) was measured at Rolls Royce using optical Mini-Moiré fringing based 3-D digitization (by EDIS Corp.) for generation of XYZ data points of surface profiles (Figure 4). For this measurement, the test specimen is mounted on a coordinate measurement machine and the 'surfacer-software' (SDRC Corp.) superimposes the before and after erosion test data to provide the erosion depth loss. The erosion coating volume loss (Y3), a second type of erosion rate (Y5) and the average wear scar depth (Y6) were measured by optical interferometer (VEECO Corp.) at NASA Glenn Research Center in Cleveland, OH (Figure 5). The optical interferometer or profiler quantifies critical dimensions such as area and volume of the damaged erosion wear scars, topographical features such as peaks and valleys in the coating, and surface roughness. This optical interferometer has 3-D profiling capability with excellent precision and accuracy (e.g., profile heights ranging from < 1 nm up to 5000 μm with 0.1 nm height resolution). The shape and surface can be displayed as a digitally derived map from a three-dimensional interferogram of the surface. The volume

and depth losses of an eroded surface are computed directly. Finally, specimens were metallurgically sectioned to determine the maximum depth measurements (Y4) in areas that indicated maximum coating loss as determined by optical interferometry. Again, all data were statistically analyzed to determine whether or not there were significant correlations between the various measurements and more importantly between the coating systems: SANRES and SANPRES.

3.3 *Laboratory Structural Durability Test Procedure*

Structural dynamic tests were performed at NASA Glenn to test the coatings' high cycle fatigue durability, under vibration loading similar to the engine conditions experienced by AE 3007 composite bypass fan vanes. The procedure for single vane durability testing is presented in the following description. A single vane was installed in a cantilevered fashion on a rigid test fixture mounted to a model C-60 electrodynamic Shaker with reciprocating slip table (MB Dynamics of Cleveland, OH) controlled by a Ling model DMA-48B/X amplifier. A clamping fixture was designed such that the tests could be performed on individual vanes or in triplet segments. This permitted an input acceleration of up to 539 m/s^2 (55g's) at the base of the vane with oscillatory frequencies up to 3000 Hz. An individual vane's response to the range of slip table input variables was investigated using an uncoated vane instrumented with numerous strain gages and accelerometers. The strain survey provided the resonant mode locations on the uncoated vanes. A strain survey was then carried out with the coated vanes. These vanes were coated everywhere except at the gage locations by masking these areas to verify that the coating had no effect on vane dynamics. Vibratory testing was then carried out for long dwell times at the third flexural mode occurring at approximately 1500 Hz with 300–400 microstrain (με). Fluorescent Penetrant Inspection (FPI) studies were conducted to identify any coating cracks that might result from the durability tests.

3.4 *AE 3007 Engine Durability Test Procedure*

Six coated composite bypass vanes (3 each of SANRES and SANPRES) were assembled in a rainbow fashion in the AE 3007-fan section (Figure 6). The testing was conducted at the Rolls-Royce (Indianapolis) facility in an AE 3007 3000-cycle endurance test. The typical endurance test cycle is shown in Table 1. The elapsed time for each cycle was 22.5 min. Scheduled stops were made during the test to inspect the coated vanes and other components involved in this test. FPI studies were conducted to identify any coating cracks that resulted from the engine cycling.

Table 1. Engine Cycle

Condition	Time, (min)
Start to Ground Idle (GI)	2.5
Maximum Take-off (T/O)	2.0
Maximum Continuous	12.0
Flight Idle (FI)	1.5
Maximum Take-Off (T/O)	0.5
Ground Idle (GI)	2.0
Shutdown (Coast/stopped)	2.0

4. RESULTS AND DISCUSSION

4.1 *Coatings Process Development*

The coating trials defined the optimized process parameters, as well as, the manufacturing sequence. Early coating trials with the 3-vane pack bypass vane component indicated that the coating thickness was not uniform due to the line-of–sight limitations of the spray process. Therefore, the manufacturing sequence was re-defined as (1) applying the bondcoat and topcoat

Table 2. WC-Co Deposition Parameters

Powder	Praxair WC-106
Gun Type	7MB
Primary Gas	Argon
Secondary Gas	Nitrogen
Primary Flow	100 flow @100psi
Secondary Flow	10 flow @ 50psi
Nozzle	GE
Amps	400
Volts	62
Carrier	37 flow @ 100psi
Powder Port	#2
Intersect-Air	7in. @ 60psi
Stand-off	10.15mm
Feeder	Miller-1.90 rpm
Feed Rate	2.58kg/hr
Speed	1500 mm/sec
Passes	28
Thickness	0.003”
Angle	0 º
Grit	N/A
Notes	Traversed Horizontally

to individual vanes and not the 3-pack of vanes, (2) then apply the leading edge metallic strip and finally, (3) adhesively bond the individually coated vanes into a 3-pack vane assembly.

The optimum range for the critical process parameters for the bondcoats of SANRES and SANPRES were identified as 250 rpm rotational speed, 12.7 cm stand-off distance, 1200 to 1500 mm/sec gun traverse speed, 2 mm gun displacement, and 18 to 24 passes. The optimized parameters of the WC-Co topcoat used for both SANRES and SANPRES coating system are listed in Table 2. Typical microstructures of SANRES and SANPRES are shown in Figs. 7 and 8, respectively. Each coating system adhered well to the PMC substrate. Another indicator that these coatings adhered well was demonstrated during the thermal shock test. Coated samples were ramped from room temperature to 93 ºC followed by an air quench and then back to room temperature. This cycle was repeated for 10 times. Both coating systems remained intact after these tests.

Results from the rotating and static modes of coating deposition indicate that the rotating mode was the preferred approach for both coating systems. By rotating the vanes, the SANRES and the SANPRES coatings thickness were quite uniform as shown in Figure 9 (a, b). Fine powder sizes (–325 mesh) were used to obtain the smoothest surface finish for the WC-Co topcoat. Regardless of the WC-Co powder size, topcoat surface roughness is predominantly determined by the roughness of the bondcoat.

Earlier experiments showed that the surface roughness of the SANPRES coating, which contained a polymer added to its bondcoat, was 2–3 rougher than the more mature SANRES coating. However, after refining the powder size of the polymer additive, the typical surface finish for both coating systems was 350 Ra (average roughness). Note: this is a ten-fold increase in surface roughness compared to the uncoated PMC vanes. Aerodynamic analysis performed at Rolls-Royce Engines indicated that the increase in surface roughness for coated bypass vanes does not decrease engine performance.

4.2 *Coating Effectiveness in Erosion Prevention*

Several independent erosion response factors were measured (Y1–Y6), as seen in Table 3. A statistical analysis was conducted on the four responses Y1, Y2, Y3, and Y4 to quantify the effect of coating system and performance parameters on erosion (Table 3) and to determine the correlation between these four independent measurements of erosion. Since WC-Co was used as the topcoat layer for both systems, the experiments essentially compared the bondcoat performance between the two systems, SANRES and SANPRES. Because of coating

Table 3: Erosion Test Response Factors [1]

Sample ID[2]	Test Temp. (°C)	Erodent (g)	Erosion Angle	(Y1) [3]	(Y2) [4]	(Y3) [5]	(Y4) [6]	(Y5) [7]	(Y6) [8]
SD1-13	21	15	20	0.34	0.063	6.1	0.073	0.41	0.055
UD3-37	21	15	20	2.40	0.191	24.3	-	1.62	0.128
SPD1-8	93	15	20	0.69	0.140	9.8	0.157	0.65	0.076
SPD3-44	93	15	20	0.76	0.165	14.0	*	0.93	0.089
SD3-50	93	15	20	0.44	0.102	7.7	0.111	0.51	0.064
UD2-20	93	15	20	3.10	0.254	30.5	-	2.03	0.155
SPD2-27	21	12	60	0.68	0.102	6.8	0.119	0.57	0.063
SD2-33	21	12	60	0.40	0.064	4.1	0.081	0.34	0.050
UD1-3	21	12	60	1.48	0.114	14.8	-	1.23	0.077
SPD1-10	93	12	60	0.72	0.089	7.5	0.081	0.83	0.066
SD3-52	93	12	60	0.62	0.089	7.1	0.074	0.59	0.062
UD2-22	93	12	60	2.52	0.165	21.1	-	1.76	0.102
SPD3-47	21	10	90	0.39	0.064	2.6	0.076	0.26	0.044
SD1-17	21	10	90	0.37	0.064	2.6	0.046	0.26	0.043
UD3-41	21	10	90	1.23	0.114	14.1	-	1.41	0.070
SPD2-30	93	10	90	0.84	0.102	9.4	0.119	0.94	0.074
SD2-36	93	10	90	0.48	0.063	6.4	0.056	0.64	0.059
UD1-6	93	10	90	2.78	0.140	19.1	-	1.91	0.093

*Erosion Coating Breakthrough

[1] Erosion tests performed at 228 m/sec

[2] SANRES, SANPRES and Uncoated Coupons are designated by S, SP, and U in *Sample ID* column above.

[3] Y1 = Erosion rate - measured by coating weight loss (mm^3/gm = volume of coating weight loss/gm of erodent)

[4] Y2 = Wear scar maximum depth (mm) – measured by Moiré

[5] Y3 = Erosion coating volume loss (mm^3) – measured by optical interferometer

[6] Y4 = Wear scar maximum depth (mm) – measured by metallurgical cross section

[7] Y5 = Erosion rate – measured by optical interferometer (mm^3/gm = volume of coating weight loss/gm of erodent)

[8] Y6 = Average wear scar depth (mm) - measured by optical interferometer

breakthrough for SANPRES coated specimens tested at 20º-impingement angle, there was no data available for Y4 (max. depth of wear scar) especially coupon *SPD3-44.*

First, a statistical analysis compared the different methods (responses) used to calculate erosion resulted in four comparisons: the erosion rates (Y1 and Y5), the maximum eroded depths (Y2 and Y4) and maximum and average eroded depths (Y2 and Y6), and the eroded weight and volume losses (Y1 and Y3). All four of the comparisons were significantly correlated with at least 95 percent confidence. In every one of these four cases, the correlation coefficient, $r = \sqrt{R^2}$, was greater than the tabulated value for a 5 percent risk factor. In fact or all but one case, the probability that such correlations could occur by chance alone were only 0.05 percent, i.e., the confidence is 99.95 percent that the relationship is significant.

The effect of each coating system and the erosion process variables (angle of impingement and temperature) on erosion resistance were quantified for all six responses shown in Table 3. Because these correlations were all similar, only the case of Volume Loss (Y4) is summarized below. The effect of process variables (erodent angle of impingement and erosion test temperature) on the volume loss for the uncoated PMC vane, SANPRES and SANPRES coating systems are shown in Figures 10, 11, and 12, respectively. It is evident that both coating systems, SANPRES or SANRES, reduce the eroded volume by as much as 50 percent over the uncoated

substrate. It should be noted that the surface of the bare substrate material has an under-layer of Kevlar™ fabric that prevents further degradation due to erosion. A prior study on carbon fiber polyimide composites without Kevlar™ subsurface reinforcement indicated that the WC-Co topcoat, in combination with these bondcoats, exhibited 3–8 fold erosion resistance improvement compared to the uncoated carbon fiber PMC [6].

Note that the SANPRES (Figure 11) is more sensitive to erosion at the low impingement angles than the SANRES (Figure 12); whereas at 90 degree impingement, the two systems are indistinguishable. It appears that the SANPRES coating with polymer additives does not enhance performance. In one case (20 degree impingement), the SANPRES erosion resistance is significantly less than the performance of the SANRES coating. This noticeable effect could be due to the presence of residual porosity in the bondcoat and/or a weaker interface with the WC-Co topcoat layer (Figure 8). At this time, these results are considered preliminary. It is important to note that the erosion results from these 18 vane specimens are a small subset (fractional factorial) of a larger experiment (54 vanes = full factorial). The results from the full factorial experimental design will be published in the future.

4.3 *Laboratory Structure Durability Tests*

Results from this study were based on two important questions:
(1) What was the strain profile of the bypass vanes during certain flight profiles?
(2) Where was the highest level of vane erosion?
While it was not the intent of this study to fully model the flight profile experienced by the AE3007 bypass vanes, it was important to map the strain profile in the lab and correlate this strain profile to any potential coating failure. From earlier studies, specific strain responses were mapped for a given location on the bypass vanes. Therefore, two SANRES and two SANPRES coated vanes were tested to 40 million cycles while single SANRES and SANPRES coated vanes were tested to 80 million cycles (Table 4) at the third mode (1500 Hz with 300–400 με). The applied force or level of acceleration shown in Table 4 was the actual constant acceleration applied to the fixture base. This force was chosen to achieve an initial strain of 250 microstrain (με) on the vane leading edge. The planned μstrain level, 300–400 με, equates to the maximum desired strain associated with the most responsive location identified in the strain survey of the bypass vane. For the third mode, the most responsive location was around the midpoint of the vane trailing edge.

Table 4: Structural Dynamic-Vibration Test Conditions

Sample ID	Planned Excitation Conditions	Input	Total Cycles
SANRES-DS1	40M cycles at 3rd mode (~400με)	45 g	46,820,039
SANPRES-DS1	40M cycles at 3rd mode (~400με)	45 g	40,002,687
SANRES-DS2	80M cycles at 3rd mode (~400με)	45 g	80,002,851
SANPRES-DS2	80M cycles at 3rd mode (~400με)	45 g	80,002,980
SANRES-DS31	40M cycles at 3rd mode (~400με)	55 g	40,003,664
SANPRES-DS31	40M cycles at 3rd mode (~400με)	45 g	42,570,964

Figures 13 and 14 show the frequency and leading edge strain response for the third mode dwells. The resonant mode dwells were not performed at a constant frequency, the frequency of the peak resonance dropped in a roughly asymptotic fashion during the dwells. Thus, the slip

table was programmed to dwell at the 90-degree phase shift using an accelerometer located at the top of the outer vane shroud. This phase shift occurs at peak resonance.

Fluorescent Penetrant Inspection (FPI) studies on the coated vanes were conducted after 20 million, 40 million and 80 million cycles. Note the discontinuous shifts in figures 13 and 14 that correspond to the inspection of the vanes during their durability tests. One of the three SANRES vanes (SANRES-DS2) exhibited a possible crack on the trailing edge (Figure 15) after 40 million cycles. However, after this inspection, the same vane experienced an additional 40 million cycles and the crack or flaw did not extend. A small number of filet cracks (Figure 16) were seen in SANRES and SANPRES specimens after 80 million cycles. In summary, the high frequency vibrating testing revealed only minor cracking in the filet region when the SANRES and SANPRES coated vanes were tested up to 80 million cycles at strain levels representative of engine conditions. Furthermore, both coatings endured extensive vibration testing and did not spall.

4.4 *Engine Tests*

Engine tests were conducted to evaluate the performance of SANRES and SANPRES coatings in the presence of fan vibration and engine cycling. Three SANRES and three SANPRES coated triplet vane assemblies were installed in the AE 3007 endurance engine test (Figure 6) in a rainbow fashion. Two of the triplet vane packs had all three vanes coated with their respective coating systems as shown in Figure 17. While, the third vane assembly from each coating system had their two outer vanes coated and their center vane was installed without coating, as a reference for the test engineers.

The engine test was scheduled for 3000 cycles with partial disassembly at approximately 1000 cycle intervals. After the initial 1000 cycle interval, a visual examination of both the SANRES and SANPRES coated vanes indicated that the coatings adhered well to their PMC vanes. To date, the engine has completed 2088 cycles and all of the SANRES and SANPRES vane sets exhibited no coating spall. Visual examination of the engine tested vanes in their test stand show no obvious cracking. Subsequent FPI tests revealed 3–4 minor linear indications on some of the vanes trailing edge region on all three SANPRES 3-vane pack assemblies, while no indications were observed on any of the three SANRES 3-vane pack assemblies (Figure 17). There are no clear distinctions between SANRES and SANPRES coatings at this point. Further testing (up to 3000 engine cycles) of all six of the aforementioned vane sets is schedule in the near future. Additionally, vane sets that have undergone “engine-like” high cycle fatigue testing and characterization in NASA GRC labs will be inserted into the planned engine tests.

5. CONCLUSIONS

This work successfully identified the manufacturing process to coat AE 3007 bypass 3-vane pack assembly hardware. Rig erosion tests at both room and elevated temperature were conducted to verify the coating durability and erosion resistance. A new coating system, SANPRES that contains a polymer additive in its bondcoat was durable to thermal/engine cycling and erosion resistant. Optimum process parameters, in terms of coating uniformity, surface roughness and adhesion were identified for both the SANRES and SANPRES coating systems. In general,

both of the candidate coatings provided a 2X improvement in erosion resistance benefit that is considered significant for this component.

Multivariate statistical analyses of four independent response factors: erosion rate (Y1), Moiré maximum depth (Y2), optical interferometer volume loss (Y3), and metallurgical maximum eroded depth (Y4) for the 18 vanes tested indicate that there is a statistically significant difference in performance between SANRES and SANPRES. Specifically, the volume loss with SANRES is significantly less than with SANPRES at a 20-degree angle. While at 90 degrees, the performance of each coating system is comparable. Results from the full factorial design of experiments for 54 vanes will be reported in the near future. A new method was developed that uses optical interferometry to accurately determine eroded volume losses from complex coating surfaces. Verification of this optical interferometry method was correlated to three other well-established methods. Laboratory structural durability tests indicated that both SANRES and SANPRES coatings had good adherence and durability up to 80M cycles while at 300–400 microstrain (με) levels. Engine tests conducted to date (2088 cycles, ~800 hr) indicate that both SANRES and SANPRES coatings have good durability and adherence on PMC vane structures. Because of their two-fold improvement in erosion resistance and their durability for these bypass vanes, these coatings are being considered for several propulsion applications where PMC components suffer from erosion.

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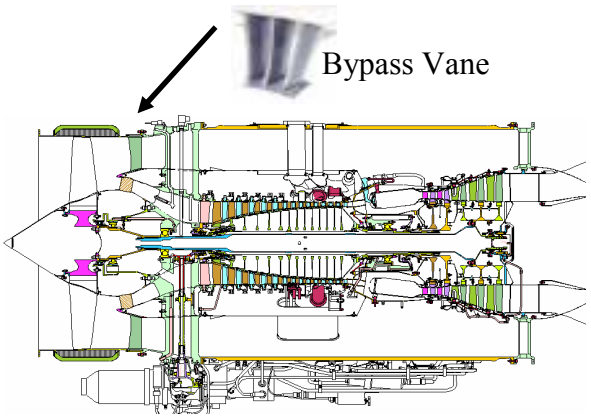


Fig. 1: AE 3007: Location of Bypass Vanes

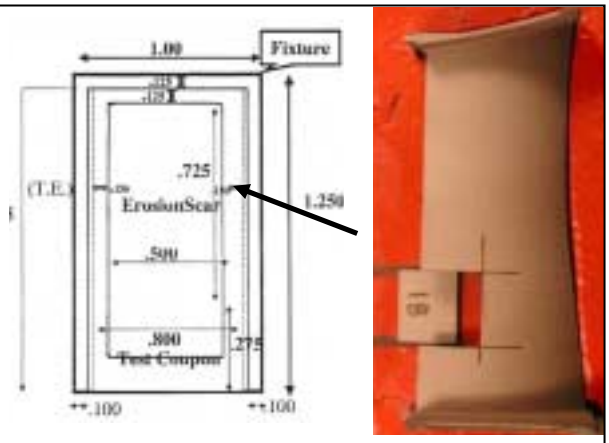


Fig. 2: Erosion Specimen – trailing edge

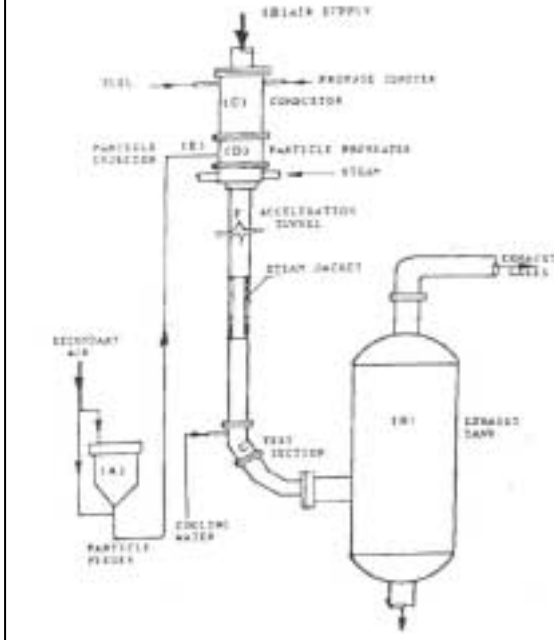


Fig. 3: Univ. of Cincinnati Hot Erosion Rig

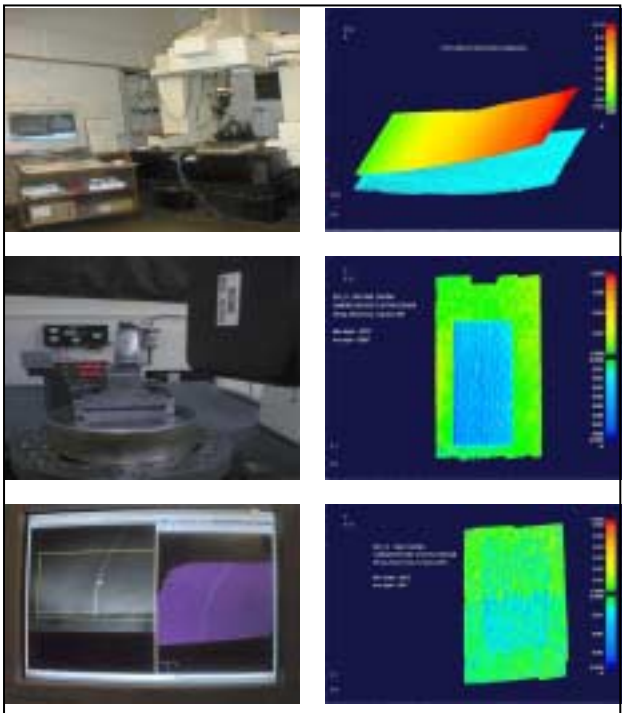


Fig. 4: Moiré Optical Scanning System

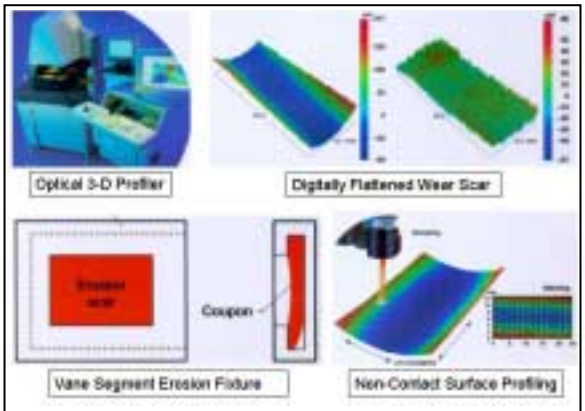


Fig. 5: Optical Interferometer System



Fig. 6: AE3007 Engine - Coated Vanes

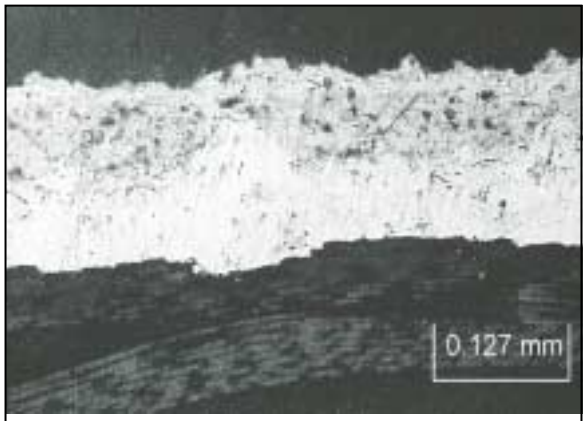


Fig. 7: Typical SANRES microstructure

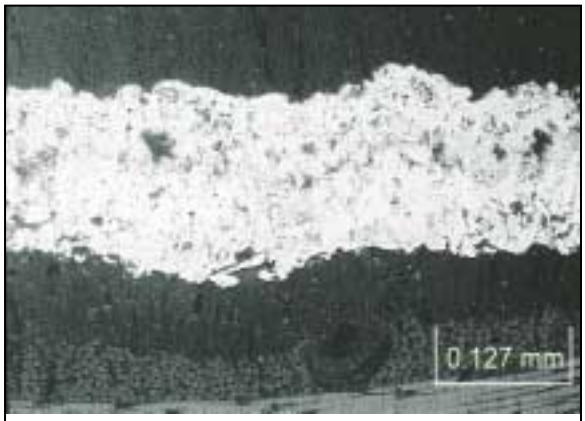


Fig. 8: Typical SANPRES microstructure

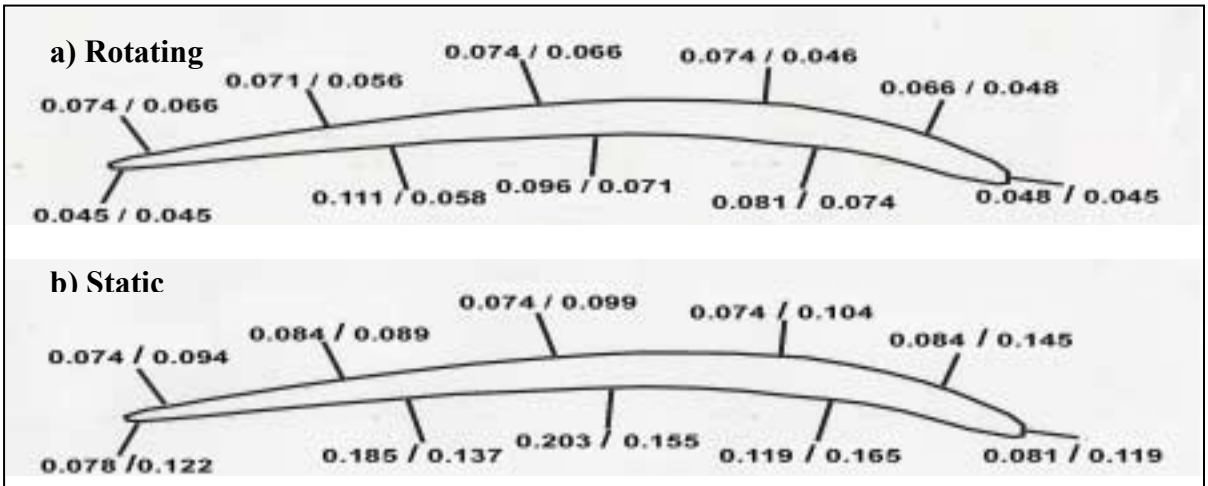


Fig. 9: Coating thickness comparison between a) rotating and b) Static Specimen Spray methods (bondcoat/topcoat thickness measured in mm)

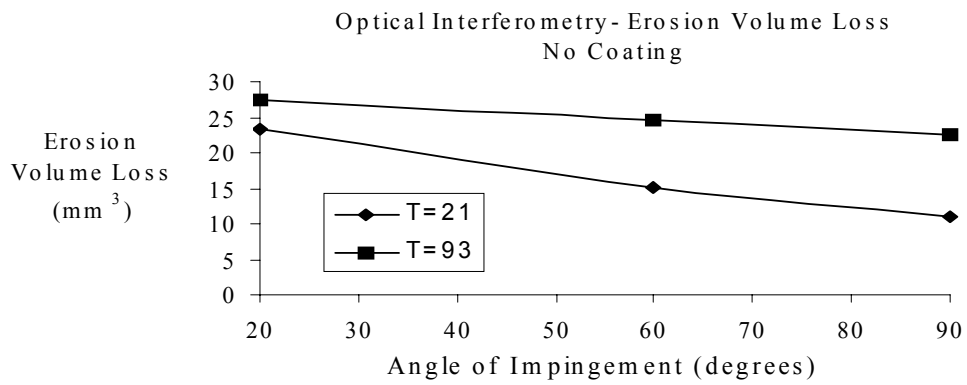


Fig. 10. Optical Interferometry Erosion Volume Loss – No Coating

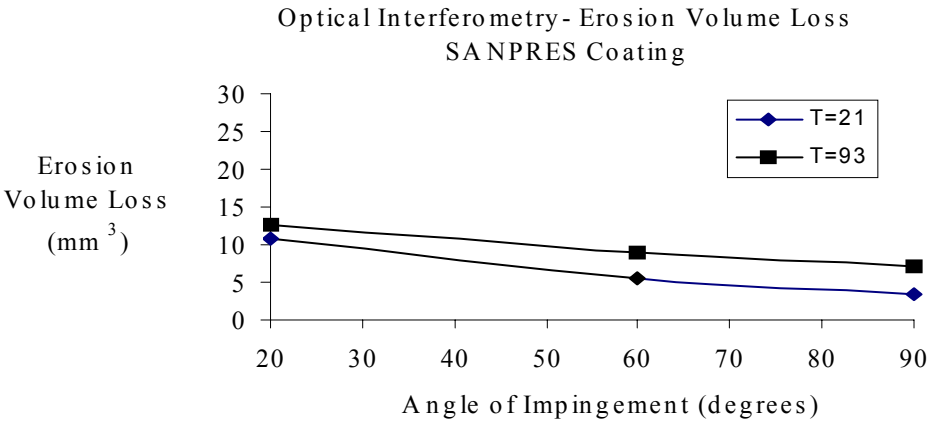


Fig. 11. Optical Interferometry Erosion Volume Loss – SANPRES Coating

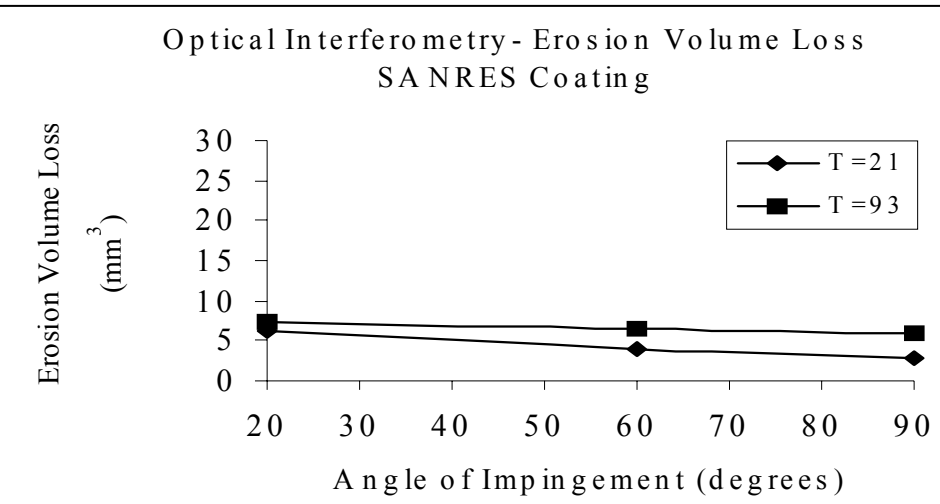


Fig. 12. Optical Interferometry Erosion Volume Loss – SANRES Coating

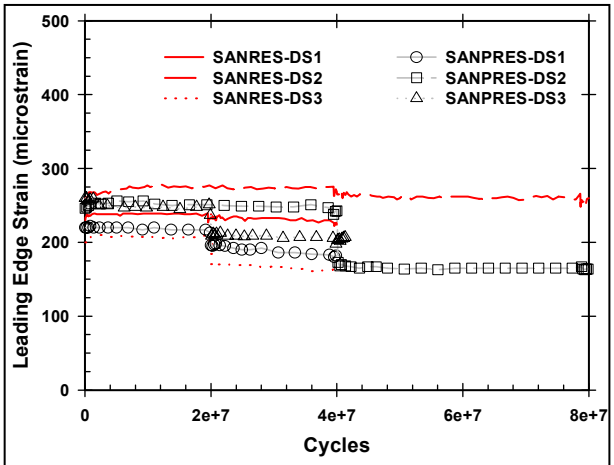


Fig. 13. Leading edge strain response for third mode dwell

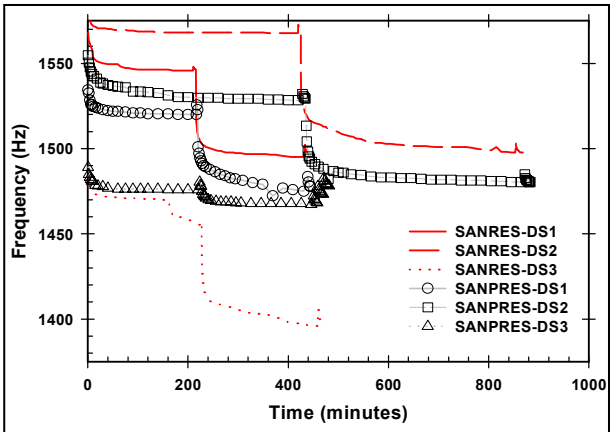


Fig. 14. Frequency response for third mode dwell

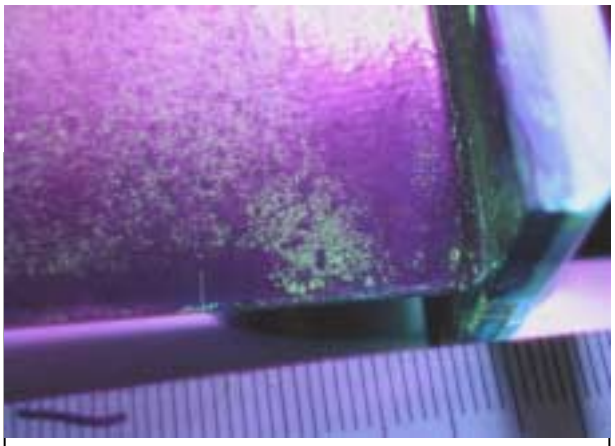


Fig. 15. FPI linear indication on SANRES-DS2 after 40M cycles

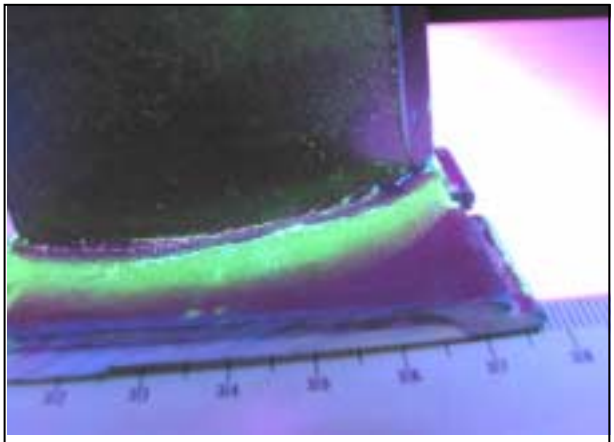


Fig. 16. Minor indications in filet for SANRES & SANPRES after 80M cycles

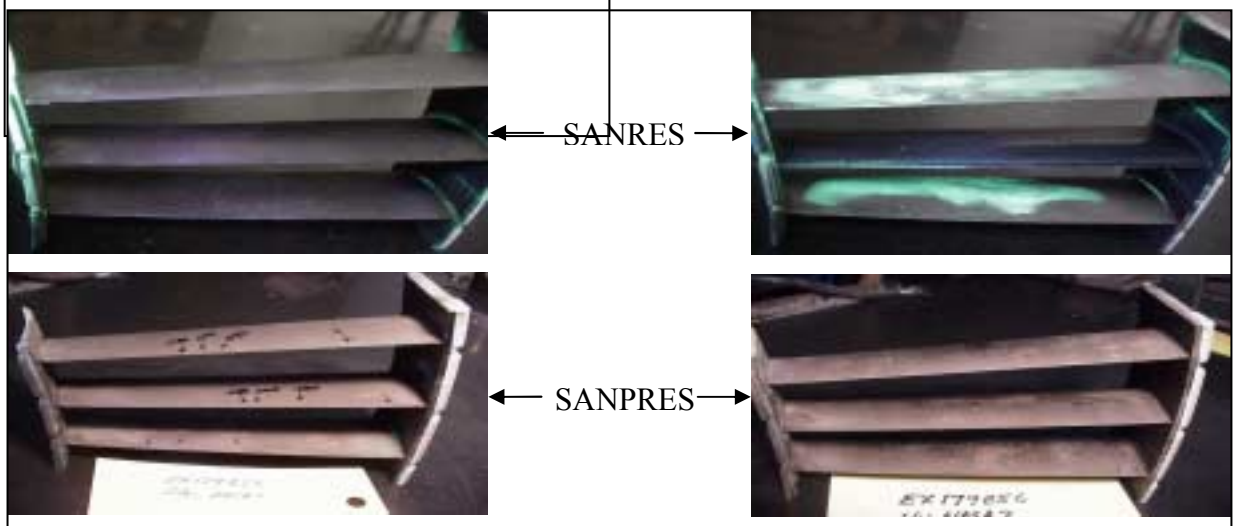


Fig. 17. FPI tests on AE3007 vanes after 2088 engine test cycles. No Linear indication on SANPRES. No coating spall for either SANPRES or SANRES.

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13. ABSTRACT ***(Maximum 200 words)***

Polymer Matrix Composites (PMCs) offer lightweight and frequently low cost alternatives to other materials in many applications. High temperature PMCs are currently used in limited propulsion applications replacing metals. Yet in most cases, PMC propulsion applications are not in the direct engine flow path since particulate erosion degrades PMC component performance and therefore restricts their use in gas turbine engines. This paper compares two erosion resistant coatings (SANRES and SANPRES) on PMCs that are useful for both low and high temperature propulsion applications. Collaborating over a multi-year period, researchers at NASA Glenn Research Center, Allison Advanced Developed Company, and Rolls-Royce Corporation have optimized these coatings in terms of adhesion, surface roughness, and erosion resistance. Results are described for vigorous hot gas/particulate erosion rig and engine testing of uncoated and coated PMC fan bypass vanes from the AE 3007 regional jet gas turbine engine. Moreover, the structural durability of these coatings is described in long-term high cycle fatigue tests. Overall, both coatings performed well in all tests and will be considered for applications in both commercial and defense propulsion applications.

14. SUBJECT TERMS

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