CHARACTERIZATION OF CERAMIC MATRIX COMPOSITE VANE SUBELEMENTS SUBJECTED TO RIG TESTING IN A GAS TURBINE ENVIRONMENT

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ABSTRACT

Vane subelements were fabricated from a silicon carbide fiber-reinforced silicon carbide matrix (SiC/SiC) composite. A cross-sectional slice of an aircraft engine metal vane was the basis of the vane subelement geometry. To fabricate the small radius of the vane's trailing edge using stiff Sylramic SiC fibers, a unique SiC fiber architecture was developed.

A test configuration for the vanes in a high pressure gas turbine environment was designed and fabricated. Testing was conducted using a pressure of 6 atm and combustion flow rate of 0.5 kg/sec, and consisted of fifty hours of steady state operation followed by 102 two-minute thermal cycles. A surface temperature of 1320°C was obtained for the EBC-coated SiC/SiC vane subelement. This paper will briefly discuss the vane fabrication, test configuration, and results of the vane testing. The emphasis of the paper is on characterization of the post-test condition of the vanes.

INTRODUCTION

Ceramic matrix composites (CMCs) are being evaluated for hot sections of advanced gas turbine engines because of they have the potential, improved performance, such as lower emissions and higher cycle efficiency, relative to today's engines with superalloy hot section components. The capability of one ceramic matrix composite for use as combustor liners, silicon carbide fiber-reinforced silicon carbide matrix composite (SiC/SiC), has been demonstrated through rig[1,2] and engine tests[3].

In order to gain full engine system performance benefits from these advanced materials in combustor liner applications, a high temperature first stage vane assembly must be successfully introduced to the engine. A recent study demonstrated fabrication of an exhaust guide vane from a SiC/SiC composite having 3D fiber architecture[4]. The resulting vane had a fiber architecture which accounted for the inherent low through-thickness strength of CMCs. However, it did not have the aerodynamic shape (including the sharp trailing edge) required to maintain engine performance.

The overall objective of this research was to demonstrate the scale up of the SiC/SiC material system from the panels and simple component architectures previously produced[5,6] to the more complex architecture of a turbine vane. This activity included the development of a unique SiC fiber architecture for the vane's sharp trailing edge, fabrication of two SiC/SiC prototypical vane designs, development of an advanced environmental barrier coating (EBC) for airfoils, and rig testing in a turbine environment. This paper will summarize the vane fabrication, test configuration, and results of the vane testing. These results are discussed in detail elsewhere[7,8]. The emphasis of the paper is on characterization of the post-test condition of the vanes.

VANE GEOMETRY AND MATERIAL

Turbine vanes possess a rather complex geometry to optimize engine efficiency. In today's engines, a vane design typically incorporates trailing edges with radii less than 0.50 mm, and a cross section that is often tapered in the radial direction, and cantered in the circumferential direction of the engine. Our
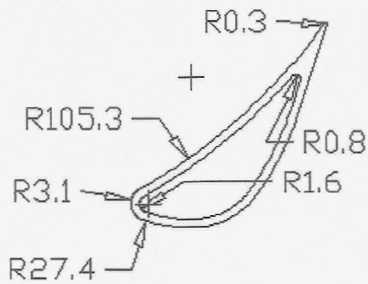
Figure 1- Geometry of vane subelement. Dimensions are in mm.

R0.3
R105.3
R0.8
R1.6
R3.1
R27.4

approach to fabricate the turbine vane was to first demonstrate that a prototypical shape could be manufactured utilizing the material processing established for multiple ply lay-ups of two-dimensional cloth. In order to have a vane geometry considered relevant to actual engine hardware, a cross-sectional slice of an aircraft engine metal vane served as the basis for the vane dimensions used in this fabrication demonstration. This representative slice was then extruded to produce the vane subelement geometry with a constant cross-section as shown in Figure 1. The SiC/SiC material used in this activity was developed under NASA's Enabling Propulsion Materials and Ultra Efficient Engine Technologies programs[5-6]. The vane subelement consisted of BN-coated Sylramic™ SiC fiber cloth reinforced with a CVI/slurry-cast/melt infiltrated SiC/Si matrix.

VANE FABRICATION

Two configurations of the vane subelement were manufactured. One had internal cavities formed by a web between the suction and the pressure sides of the vane and the other had no web. Both vane types have six plies in the outside walls and the same outside dimensions. The web consists of four plies.

5HS Split Plane

Vane trailing edge
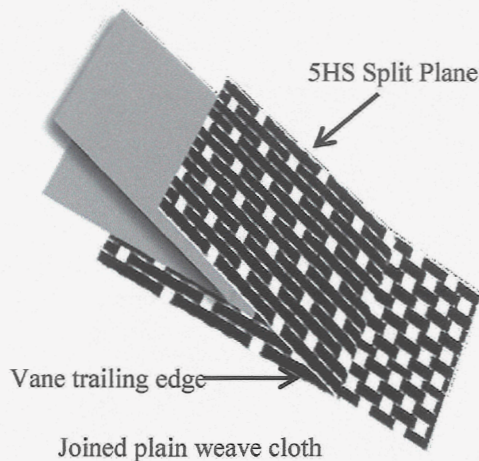
Joined plain weave cloth

Figure 2: Y-cloth fiber architecture used to form vane trailing edge.

It is difficult to fabricate components with small radii, as exists in the trailing edge of this vane subelement, using the stiff stoichiometric SiC fibers, such as Sylramic, that are currently preferred for high temperature-capable SiC/SiC composites. The challenges posed by the aggressive geometric and structural requirements associated with the vane configuration were addressed using a new Y-cloth fiber architecture shown in Figure 2. The Y-cloth provided a fiber architecture in the remaining regions of the vane that had been well characterized and successfully demonstrated in combustor liners[1,3]. As shown in Figure 2, the Y-cloth architecture was used as the solution to forming a sharp trailing edge by splitting the cloth into two planes during the weaving process. The fiber tows forming the trailing edge section are interlocked thereby enhancing the through thickness strength capability of the composite material.

For vanes constructed from the layup of six plies of Y-cloth, the length of each Y-cloth section was cut so that the two legs would wrap around the perimeter of the vane preform ID graphite tool with a 10 mm overlap. The additional length was used to join the two sections with an overlapping fringe splice. To make the external sixth ply, a standard woven cloth was cut to the required final length and a fringe splice joined the two sections of the cloth at the trailing edge. The cloth was then prepregged. The entire assembly was then placed into an aluminum compaction tool designed to form the outer net shape of the vane. After the prepreg material was allowed to dry, the preform was removed from the aluminum tooling and placed into an external graphite tool before being shipped to a vendor for matrix infiltration.

To make the preform for the vane with the internal cavities and connecting web wall, a slightly different initial approach was used. Each section forming the internal cavities (and ultimately the web) was created by first slipping two concentric layers of a two-dimensional, 2-by-2, ±45° braided tube around net-shape graphite mandrels. Both mandrels were prepregged, and allowed to dry. Four additional plies were wrapped around the assembled graphite mandrels in the same fashion used for the six ply shell vane configuration.

Two venders were selected to manufacture both vane types. Both General Electric Power Systems Composites (GEPSC) and Goodrich used their own composite processing techniques to infiltrate

Sylramic vane preforms to make completed SiC/SiC vanes. Examples of both completed vane types are shown in Figure 3.
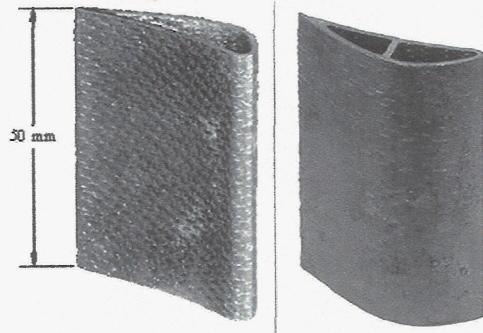

Figure 3: Completed SiC/SiC vanes using a layup of Sylramic Y-cloth, a) six ply shell configuration, b) webbed configuration.

Figure 4 – Test section configuration used for testing SiC/SiC vanes.

Figure 5- Vanes in the holder prior to testing.

To protect the SiC/SiC substrate from recession in the turbine environment, an environmental barrier coating (EBC) was applied to the vanes. The coating system consisted of a silicon bond coat, a mullite intermediate coat, and a proprietary rare earth silicate topcoat. Cooling holes were machined in the trailing edge via laser drilling prior to application of the EBC.

VANE TESTING

The test configuration was comprised of three parallel vanes contained in a water-cooled pressure section (Figure 4). The center vane was the EBC-coated SiC/SiC test specimen with superalloy vanes on either side to help establish flow around the SiC/SiC vane. The three vanes had the same external geometry and were held in place using superalloy platforms as shown in Figure 5. Vane cooling air flowed through these superalloy plates into both ends of the vanes and out through holes in the trailing edge for all three components. The test section design enabled gas temperature measurement adjacent to the vanes and downstream via thermocouples. Optical pyrometry was used to measure external vane material temperatures (Figure 4). Two six ply shell vanes were rig tested.
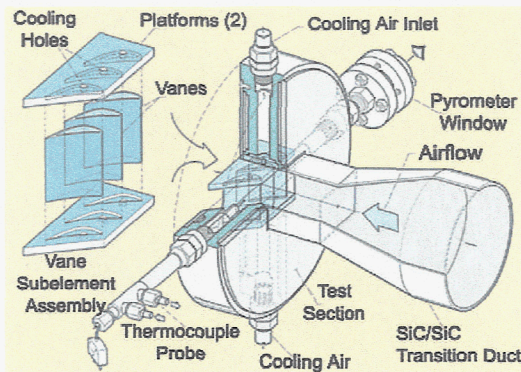
The SiC/SiC vanes were tested using NASA's High Pressure Burner Rig (HPBR). The rig burns jet fuel and enables material specimens and components to be exposed to pressures of 4 to 15 atm and gas velocities of 10 to 30 m/sec, under either lean-burn or rich-burn combustion mixtures[9]. Flow from the combustor was directed from the 150 mm inner diameter rig flow duct to the 50 mm high by 100 mm wide vane test section using a transition duct as shown in Figure 4. A rig pressure of 6 atm and combustion flow of 0.5 kg/sec was selected for testing of the SiC/SiC vane subelements. The gas velocity at the entrance of the vane test section was 60 m/sec resulting from the small cross-sectional area of the three vanes. Air flow was used to cool the internal cavities of all vanes in the test section. Gas temperature (and ultimately material temperature) was controlled through variation of the combustor's fuel/air ratio under lean mixtures.
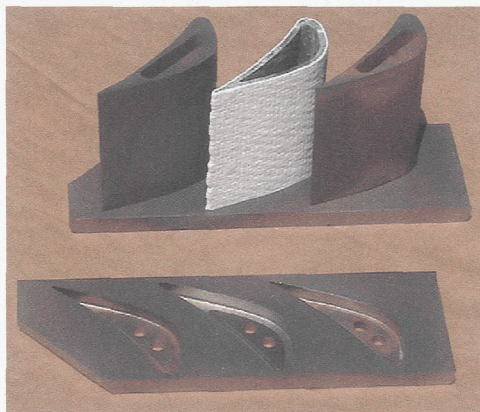
Prior to testing, computational fluid dynamics and finite element analyses were performed to predict the temperature and stress conditions present in the vane during rig testing and the results are described in ref. 8. To summarize, the predicted maximum temperature (1190 °C) was within the material capabilities (~1300 °C). Calculated in-plane tensile stresses were low (maximum axial stress of 27 MPa and maximum transverse or "hoop" stress of 105 MPa), but the interlaminar tensile (ILT) stresses predicted were found to be high enough to be of concern. ILT values in the leading edge (14 MPa) approach the flat panel measured strength value

of 17 MPa for this material. In the vane's the trailing edge, the ILT stress of 54 MPa exceeded the measured strength. However, this 54 MPa ILT stress is artificially inflated in this analysis[8]. Since the vane's Y-cloth architecture provides through thickness fiber reinforcement at the trailing edge, these stresses were considered to be less of a concern than those at the leading edge.

RESULTS

Test Results

After completion of 20 hours of rig testing using gas temperatures of about 1200 °C, the SiC/SiC vane subelement was inspected and found to have no visual degradation, whereas the superalloy vanes and other superalloy rig hardware had visually identifiable cracks. One superalloy vane was removed to enable measurement of the SiC/SiC vane temperature using optical pyrometry. Operation continued for 8 hours under the same rig conditions and a peak EBC surface temperature of about 1170 °C was measured. The third superalloy vane was reintroduced and 50 hours of steady state operation were completed.
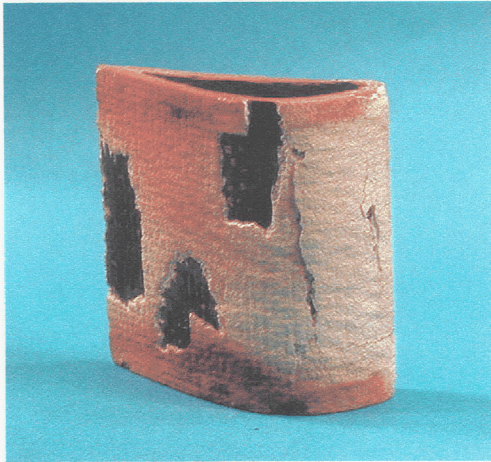
The rig was disassembled to inspect the test section after completion of 50 hours of testing. Water was found in the test section. One of the water-cooled thermocouples was found to have leaked prior to the beginning of the last 3.5 hours of testing. This lead to the accumulation of water in the test section between rig runs. During this period of time, the SiC/SiC vane absorbed some of this water. Upon restarting the test, the absorbed water vaporized, producing spallation damage (Figure 6). About 26% of the total coating surface area had spalled.

Figure 6 – SiC/SiC vane (number 909) after inadvertent water exposure followed by rig testing for 3.5 hours.

Because of the damage to the first test vane (number 909), a second EBC-coated vane subelement (number 910) was prepared for continued testing. A 2-minute thermal cycle was employed for this stage of the testing. This cycle consisted of holding the gas temperature at a constant minimum value for 45 seconds, then heating to a maximum over 15 seconds, holding for 45 seconds, and finally cooling back to the minimum temperature in 15 seconds. Initial peak temperatures were based on experience obtained during the steady state testing. However, higher gas temperatures of up to 1420 °C were used for latter cycles. Under the higher gas temperatures, a peak material temperature of 1320 °C was obtained. After 102 cycles were completed, the rig was disassembled.
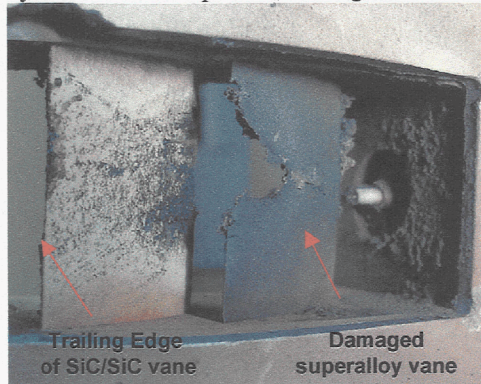

Figure 7 – SiC/SiC (number 910) and superalloy vane subelements after the cyclic testing.

Inspection of the test section after 102 cycles revealed considerable damage of the test section metal hardware. Melting of the superalloy vanes occurred, as well as other test section metal hardware. The SiC/SiC vane subelement was intact but had deposits on the EBC surface (Fig. 7). X-ray diffraction revealed evidence of the Co-based Haynes 188 vane on the suction side of the SiC/SiC vanes, (which can be seen in Fig. 7) and deposits of Ni-based Waspaloy on the pressure side. Note that both these alloys melt above 1400 °C and were used to fabricate test section hardware.

Examination of Vanes

NDE inspection via computed tomography (CT) was used to inspect both SiC/SiC vanes after completion of the testing. Images of vane 909 both in the as-fabricated state and after 50 hours of steady state rig operation are compared

in Figure 8. Spallation damage can be seen in the post-test image, particularly on the pressure (i.e. concave) side of this vane. No composite damage in vane 910 was detected after rig testing using the CT inspection technique (Fig. 9). The superalloy deposits (as can be seen in Fig. 7) appear as the irregular bright regions on the vane's outer surfaces.
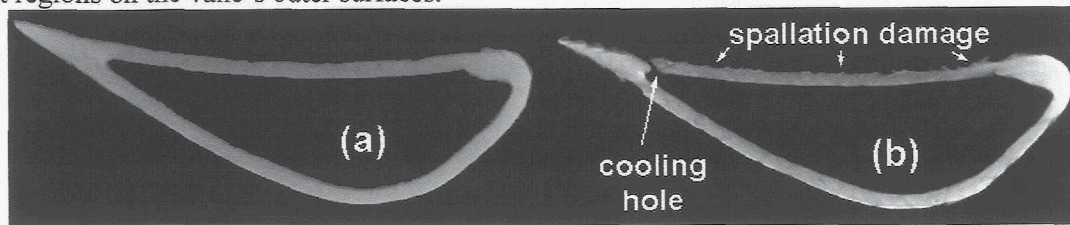

Figure 8 – Computed tomography images of vane 909, a) as-fabricated, b) after rig testing for 50 hours under steady state conditions.
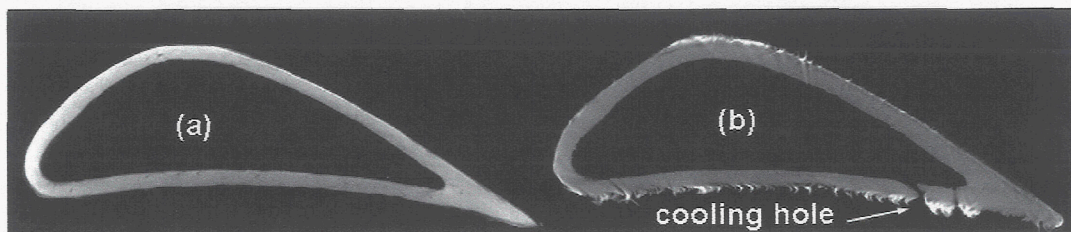

Figure 9 – Computed tomography images of vane 910, a) as-fabricated, b) after rig testing for 102 2-minute cycles.

Both SiC/SiC vanes were sliced at the midline to obtain sections for microstructural examination. A slice from each vane was mounted in florescent epoxy and polished.

Prior to sectioning, the coating was removed from the vane tested under steady state conditions (vane 909) in order to potentially re-coat it for further testing. However, since the visual and NDE inspection revealed composite surface damage, a second vane (number 910) was selected for the cyclic testing. Thus, coating microstructure of the first vane was not available, only that of the substrate. The second vane (910) was mounted in the as-tested condition.

The cross sections of both vanes are shown in Figure 10. Engineering drawings of the inside and outside vane nominal profile are superimposed over the micrographs of the vanes. Both vanes retained their shape even after exposure to severe test conditions. Cooling holes can be seen near the trailing edges of both vanes, and excess matrix is evident near the leading edge of vane 909, on the inside surface.
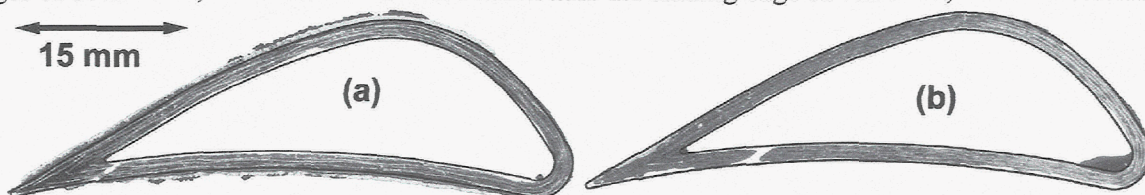

Figure 10 – Cross sections of SiC/SiC vanes after rig testing, a) vane 910 tested under cyclic conditions, b) vane 909 tested under steady state conditions.

Since the finite element analyses predicted the highest stresses to exist in the leading and trailing edges, it is important to examine the microstructure in these regions. In Figure 11, details of the leading edges are shown. A coating of superalloy can be seen on vane 910 on both the pressure and suction sides, but not at leading edge. Spallation of outer composite plies exists in vane 909 at locations away from the leading edge. However, no cracks exist. In both vanes, the gap on the ID between the actual vane profile and the drawing near the leading edge are the result of the manufacturing process.
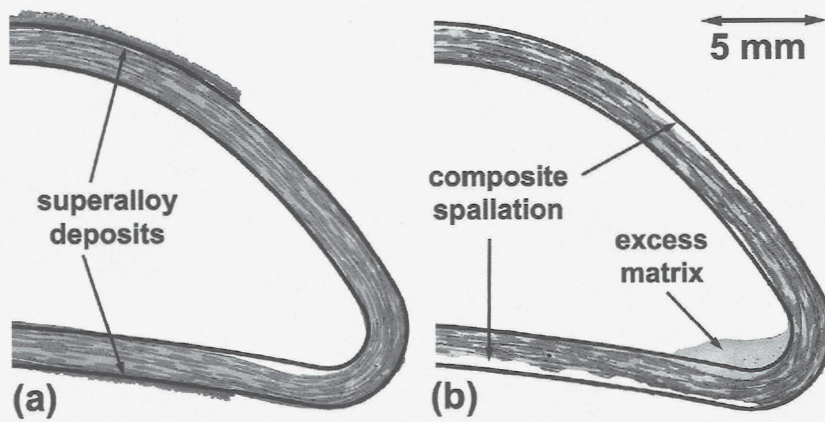
Figure 11 – Microstructure of the leading edge of SiC/SiC vane subelements after rig testing, a) vane 910 tested under cyclic conditions, b) vane 909 tested under steady state conditions.

Details of the trailing edge microstructures (Figures 12 and 13) revealed features similar to those seen in the leading edge. Superalloy deposits of about 0.4 mm thickness extend toward the trailing edge radius in vane 910. The deposits cover the EBC but no obvious reaction with the SiC/SiC substrate is evident (Fig. 13a). Composite ply spallation and a crack are visible near the trailing edge of vane 909 (Fig. 12b). The outer ply is missing near the cooling hole while three outer plies spalled off in the most damaged regions. Figure 13(b) shows a region with one missing ply. The EBC exists in a region with the original six plies. It is likely that this spallation, which occurred during rig start up, resulted in higher stresses in the trailing edge of vane 909 during subsequent rig operation, leading to the cracks as seen in Figs. 12 and 13. In spite of this damage, the trailing edge of vane 909 remained intact.
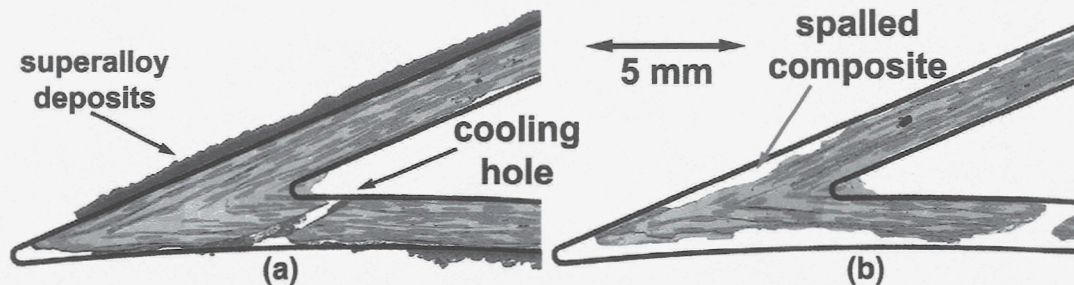

Figure 12 – Microstructure of the trailing edge of SiC/SiC vane subelements after rig testing, a) vane 910 tested under cyclic conditions, b) vane 909 tested under steady state conditions.
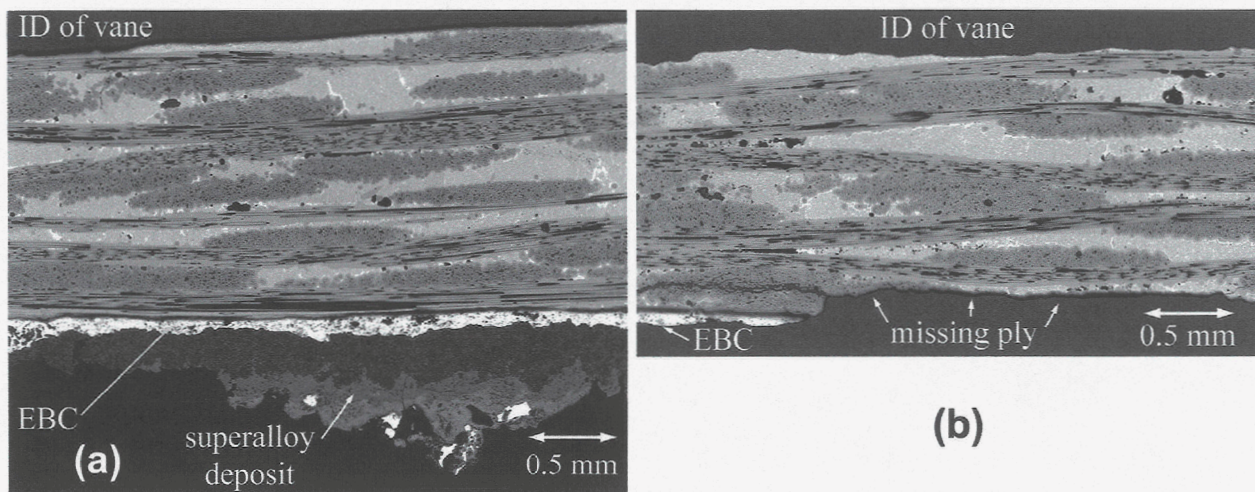

Figure 13- Microstructure of the pressure side of the vanes, 20 mm away from the tip of the trailing edge, a) vane 910 tested under cyclic conditions, b) vane 909 tested under steady state conditions.

SUMMARY AND CONCLUSIONS

Vane subelements were fabricated from a SiC/SiC composite. The Y-cloth fiber architecture was developed at NASA Glenn Research Center to provide a straightforward means to form the sharp trailing edge using stoichiometric SiC (Sylramic) fibers. This approach also utilizes mature composite processing methods used for standard ply lay-ups of two-dimensional cloth, such as panels. Vane subelements with and without an internal web connecting the pressure and suction walls were fabricated.

Two vanes without internal webs were tested in a simulated turbine environment. Testing consisted of fifty hours of steady state operation and 102 2-minute thermal cycles. A surface temperature of 1320°C was obtained for the EBC-coated SiC/SiC vane subelement. The vanes were inadvertently subjected to extremely severe test conditions (such as exposure to standing water prior to combustion exposure and deposition of molten superalloy parts) which lead to damage in the vanes. NDE and microstructural examinations revealed the extent of spallation in one vane due to vaporization of absorbed water, and deposition of molten metal on both the pressure and suction sides of the second vane. Both vanes retained their shape even after exposure to these severe test conditions and they maintained full functionality. These encouraging results show the potential of SiC/SiC composites for turbine airfoil applications.

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