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DESIGN AND TESTING FOR CERAMIC MATRIX COMPOSITE TURBINE VANE

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ABSTRACT

Ceramic matrix composite (CMC) have higher temperature capability and lower density than nickel based alloys which have been used for hot section components of gas turbine engines. These properties are expected to bring many benefits, such as higher turbine inlet temperature (TIT), reduction of cooling air, and reduction of weight, when it is used as the material for hot section components of gas turbine engine.

The authors have been developing CMC turbine vane for aircraft engines. In this paper, the authors present the summary of design, manufacturing, and testing, which were conducted from 2010 to 2012.

The purpose of this work was to verify that the SiC-SiC CMC which IHI has developed has the applicability to aircraft turbine vanes. The concept was planned for CMC hollow turbine vanes, in which the airfoil and the platform are fabricated in CVI process. As the demonstration of this concept, the first stage turbine vane was designed with CMC for IHI IM270 that is the 2MW-class small industrial gas turbine engine.

Bending rig test was conducted at room temperature in order to check the structural feasibility of the airfoil-platform joint. The outer platform of vane was fixed in the same way with the engine parts, and the load simulating the aerodynamic force was applied at the airfoil portion. The fracture load was higher than the load which the vanes receive in the actual engine.

Burner rig test was conducted in order to check the durability against thermal cycle. A CMC vane was set between dummy metal vanes, and cyclically heated by gas burner. The maximum airfoil surface temperature was set to 1200 degree C, and the maximum temperature difference between airfoil and platform was about 700 degree C. The minimum airfoil temperature at the interval of heating was about 300 degree C. The time of one thermal cycle was 6 minutes that consisted of 3 minute heating and 3 minute natural cooling. The test was conducted for 1,000 cycles. In post-test inspection there was no defect like a crack.

Engine test for CMC vanes was conducted using IHI IM270. The four CMC vanes were mounted into the first stage turbine nozzle assembly in place of the normal metal vanes. The test was conducted for 400 hours. The inlet temperature of CMC vanes were measured by thermocouples installed at the leading edge, and the measured temperature was about 1050 degree C at the steady state.

From this work, the applicability of the design concept for the CMC vane to actual engine was verified in which airfoil-platform are fabricated in CVI process.

NOMENCLATURE

CMC	Ceramic Matrix Composite
SiC-SiC	Silicon Carbide fiber reinforced Silicon Carbide
TIT	Turbine Inlet Temperature
IHI IM270	2MW-class small industrial gas turbine engine
CVI	Chemical Vapor Infiltration
SPI	Solid Phase Infiltration
PIP	Polymer Impregnation and Pyrolysis
EBC	Environmental Barrier Coating
TBC	Thermal Barrier Coating

INTRODUCTION

Ceramic matrix composite (CMC) have been developed as a material for high strength and toughness at high temperature [1]. SiC-SiC CMC has higher temperature capability and lower density than nickel based alloys, which have been used for hot section components of gas turbine engines. These properties are expected to bring many benefits, such as higher turbine inlet temperature (TIT), reduction of cooling air, and reduction of weight, for gas turbine engines, when CMC replaces current metal alloys as materials for hot section components [2].

Therefore many works for development of CMC components have been conducted, and their results were documented in many publications [3, 4]. In addition, some works for applying CMC to turbine vanes have been published [5,6,7,8]. As described in these papers, there are many challenges to design CMC turbine vane. Designers have to select a configuration in consideration of thermal / mechanical stress, sealing, assembling, and manufacturing (weaving and molding) feasibility. The latter is the greatest limitation of CMC components design. For example, a separate airfoil-platform type concept is easy to manufacture, in which the airfoil and the platform are separately manufactured and assembled. On the other hand, the fully integrated concept in which platforms are integrated with an airfoil has no sealing issue, but it is hard to manufacture and has high stress issue at airfoil root portion.

The authors have studied various concepts for aircraft engine's CMC turbine nozzle guide vanes. And they have downselected the airfoil-platform integrated fabrication concept.

In this paper, the authors present the summary of design, manufacturing, and testing for CMC turbine vane of IHI-IM270 engine (small IGT engine). The purpose of this work was to demonstrate that SiC-SiC CMC and the airfoil-platform integrated fabrication concept which IHI have developed have the applicability to aircraft engine's turbine vanes.

DESIGN CONCEPT AND MATERIAL SYSTEM

As a result of various concept studies, the downselected design for CMC turbine vane was the fully integrated (airfoil-platform integrated) fabrication concept as shown in figure 1. In this concept, there is no leakage path between airfoil and platform. Moreover the easiness to assembly and the weight reduction can be also expected, because of its simple configuration. But a significant challenge of this concept is the difficulty to manufacture.

The authors devised the manufacturing method using multiple woven fabrics. Braided fabrics were used for the hollow airfoil portion, and 2D-woven cloth and 3D-orthogonal woven fabrics were used for the outer / inner platform portion as shown in figure 2. This method was developed based on the research of CMC exit guide vane [9].

Material system is as below. Reinforcing SiC fibers are Tyranno ZMI fibers that were commercialized by Ube Industries Ltd [10]. The interface coating, which is a layer between the fibers and matrix is boron nitride, and it was formed by chemical vapor infiltration (CVI) at IHI. Fiber architecture is shown in table 1. As mentioned above, braided fabrics are used for airfoil and 2D-cloth and 3D-orthogonal woven fabrics are used for platform. The fiber volume fraction is 40-45%. SiC matrix was formed by chemical vapor infiltration (CVI), solid phase infiltration (SPI), and polymer impregnation and pyrolysis (PIP) at IHI. Considering advantages and disadvantages of these processes, IHI have developed the process of forming a matrix as below. First the matrix is formed by CVI to cover the fibers with dense structure. Then the matrix is formed by SPI to fill the large pores remaining after CVI. Finally the matrix is formed by PIP to fill the small pores remaining after SPI.

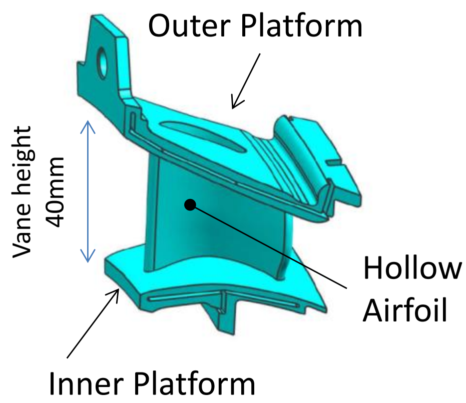


Figure 1. The fully integrated CMC vane concept

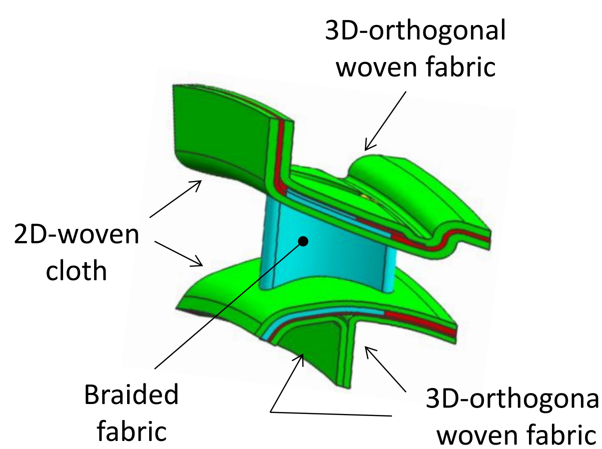


Figure 2. The schematic view of fabric arrangement
(The shape before machining)

Table 1. Summary of fiber architecture

Portion	**Fabric**	**Fiber volume fraction**	**Schematic view of fabric**
Airfoil	Braided fabric	40%	
Platform (flowpath and inside)	2D-woven cloth	45%	
Platform (other)	3D-orthogonal woven fabric	40%	

DESIGN

In this work, IHI IM270 that is a 2MW-class industrial gas turbine engine was used as a demonstrator of CMC turbine vane concept. Maximum turbine inlet temperature of this engine is about 1200 degree C. Ni based super alloy are used and cooling system are applied for turbine stg.1 nozzle guide vanes. CMC vane was designed assuming to replace current metal stg.1 vane to conduct engine test. Mechanical interface was basically same as current metal vane configuration, but gaps between the CMC vane and the metal casing at the outer band forward flange and aft hook were changed to minimize thermal stress that occurs due to thermal expansion mismatch between CMC and metal. Spline seals were applied to minimize leakage through inter-segment gaps in the same way as metal vanes.

Airfoil shape was also basically same as current metal vane, but trailing edge was modified to enable to be realized without wrinkles or creases, in consideration of the deforming limitation of cylindrical braided fabrics as shown in figure 3. Hollow airfoil consisted of 6 plies of small diameter cylindrical braided fabrics (inner layer) and 2 plies of large diameter cylindrical braided fabrics (outer layer). This concept, in which seamless cylindrical braided fabrics are used, realizes high burst strength against differential pressure between internal cavity and flow path surface, but gives limitation to trailing edge thickness.

Cooling holes and EBC (Environmental Barrier Coating) / TBC (Thermal Barrier Coating) system were not applied because from coupon test data the material was expected to have enough strength and life properties at 1200 degree C environment without them.

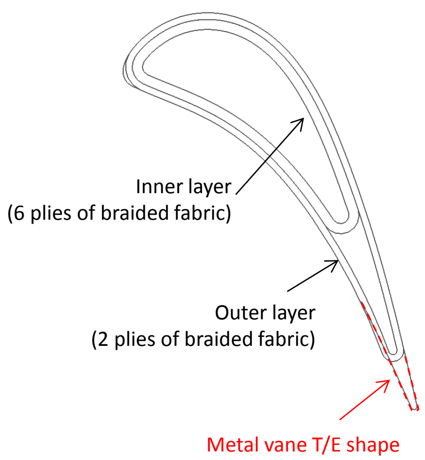


Figure 3. The cross-section of airfoil at 50% span

THERMAL AND STRESS ANALYSIS

FEM analysis was conducted. Anisotropic material properties were reflected to FEM analysis model using element coordination system. Material properties were based on the results of coupon tests using braided fabric specimens and 3D-orthogonal woven fabric specimens. Static pressure distribution was calculated by CFD and input to stress analysis model.

The result of thermal analysis for steady state condition is shown in figure 4. Airfoil surface temperature is about 1200 degree C (that is almost equal to gas temperature), and large thermal gradient through the thickness of outer / inner platform occurs.

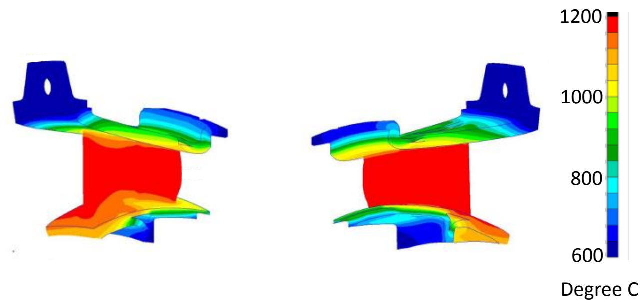


Figure 4. Temperature distribution at steady state

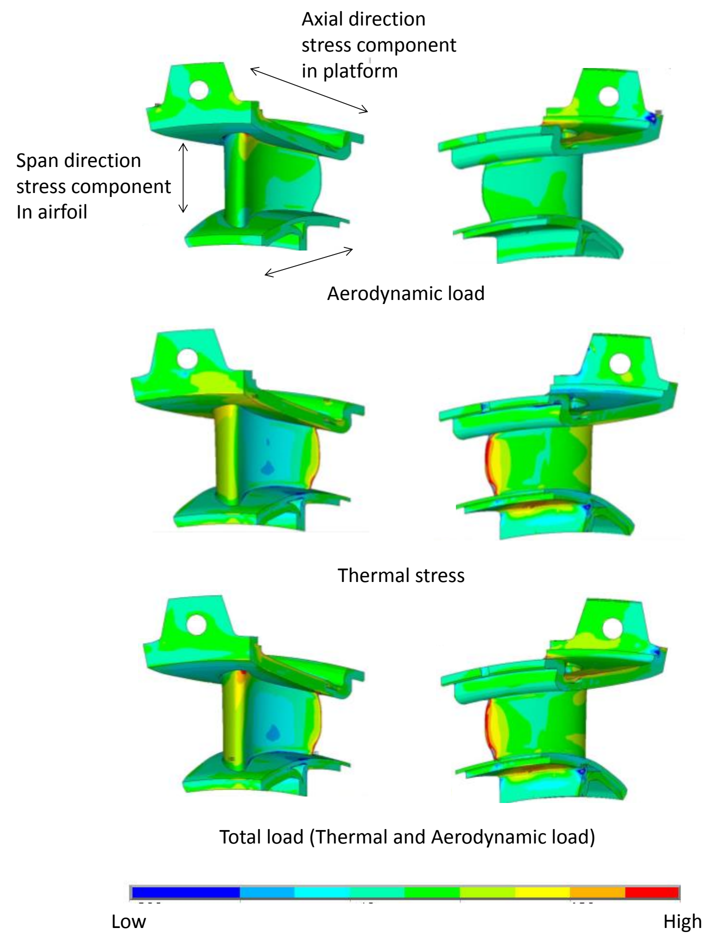
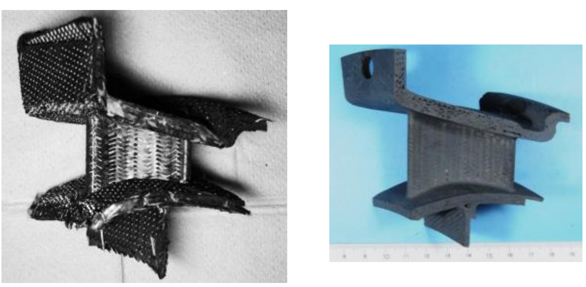


Figure 5. Stress distribution in airfoil span direction and platform axial direction at steady state

The result of stress analysis at steady state condition is shown in figure 5. Aerodynamic load causes high stress at the outer root point of airfoil leading / trailing edge. Thermal gradient causes high stress over the span direction of airfoil trailing edge. Therefore the highest stress occurs at the outer root point of trailing edge due to both aerodynamic load and thermal gradient. From this result and material coupon tests data, the CMC nozzle was expected to have about 100cycles and 500hrs life, which was the target of the engine test. This target was decided as the appropriate life for the first demonstration of CMC nozzle concept, although the required life for the actual engine parts is longer.

MANUFACTURING DEMONSTRATION

Before making engine test parts, manufacturing trials were conducted to reduce various manufacturing risks. The initial configuration was different in some points from the final parts for engine test. The design of final parts was improved by feedback of manufacturing trials. The result of manufacturing trials is shown in figure 6. The molded shape was in good agreement with the designed shape. Thereby the molding process of such a complex shape was basically confirmed. Through the trials, it also became clear that the stitching is needed to realize enough interlayer strength of bonded face between 3D-orthogonal woven fabrics and other fabrics. Void content was reduced to the target level. All surfaces including flow path were machined by electroplated diamond tools in the trials, and there was no issue in the machining process. In the final design configuration, flow path surfaces were changed to be not machined because the molding accuracy was confirm to be excellent. The appearance and the X-ray CT image of the final parts is shown in figure 7. Through the manufacturing trials and feedback to design, the manufacturability of the fully integrated CMC vane concept was demonstrated.



As molded　　After machining

Figure 6. The result of manufacturing trials

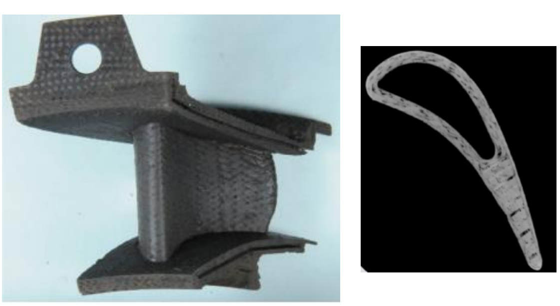


Figure 7. The appearance and the X-ray CT image of the final part

BENDING RIG TEST

Bending rig tests were conducted in order to verify the structural feasibility of the airfoil-platform-integrated CMC vane concept. The test set-up is shown in figure 8. A CMC vane was fixed at the outer platform by the same cantilevered mount system as the engine, and the mechanical pull load simulating the aerodynamic force was applied at the airfoil portion by Instron 5565 tensile testing system.

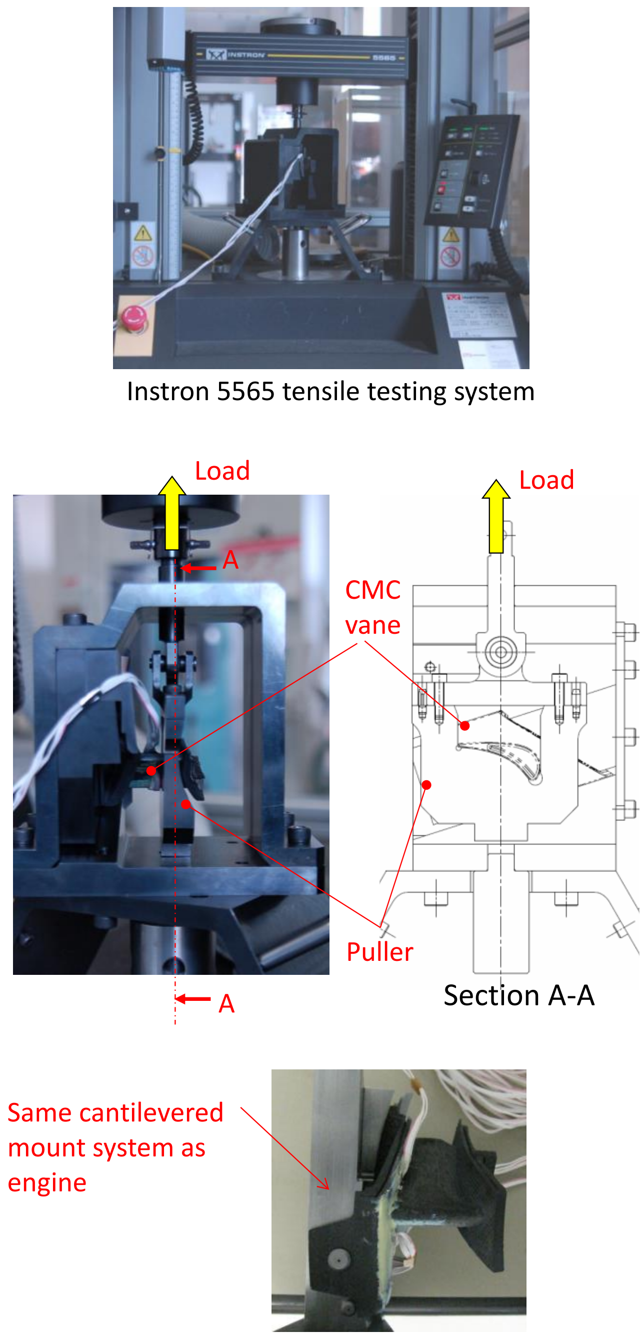


Figure 8. The set-up for bending rig test

Two kinds of the test were conducted at room temperature. The purpose of the first test was to verify that CMC vane has enough strength against the aerodynamic force which the vane receives in actual engine operation. The airfoil was pulled at a crosshead speed of 0.5mm/min. Figure 9 is a load-displacement curve of the first test. Non-linear behavior was shown at more than 3000N, and the fracture load was about 4100N. The fracture load was much greater than the estimated aerodynamic force which the vane receives in actual engine operation (575N). The failure mode was the interlayer fracture at the internal bonding face of the outer platform. Figure 10 is the X-ray CT image of post-test CMC vane. The cracks were found at the bonding face between 3D-orthogonal woven fabric and braided fabric that is continuous to the airfoil portion, although FEM analysis shows the highest in-plane stress occurs at the outer root point of airfoil leading / trailing edge as shown in figure 11. From this result, the failure mode was identified and the structural capability of this concept against aerodynamic force was confirmed.

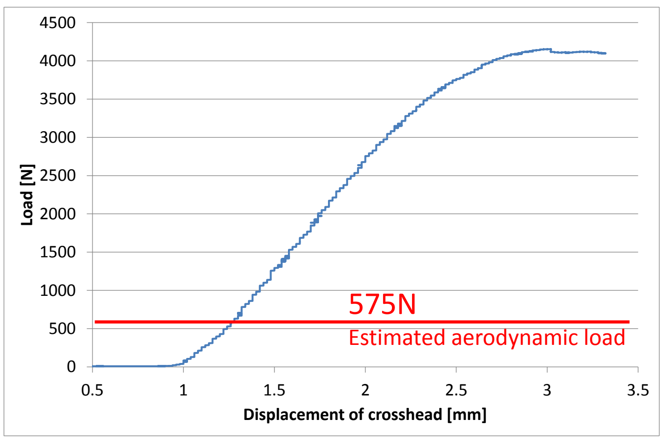


Figure 9. Load-Displacement curve of the first bending test

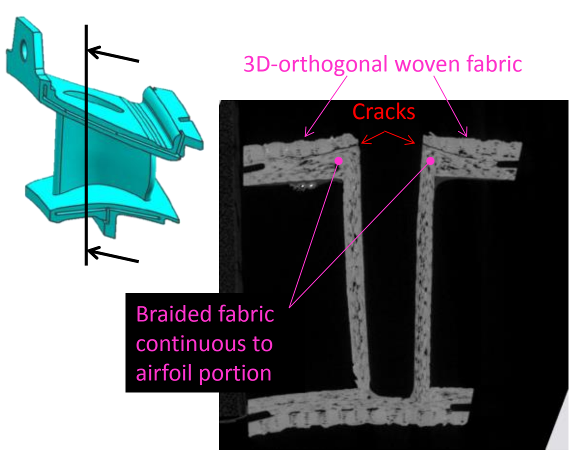


Figure 10. The X-ray CT image of post-bending test

The purpose of the second test was to check the accuracy of the stress analysis. The strain in airfoil span direction at the outer root was measured by 9 strain gauges. Figure 12 is the comparison of the measured strain and the calculated strain at the load of 200N. The calculated strain was in good agreement with the measured strain, except at trailing edge (No9). The disagreement at trailing edge was caused by the inhomogeneity of the fabric base composite material. Because the strain gauge is smaller than the “unit cell” size of braided fabric, the measured value depends on where the strain gauge was put in “unit cell”. This disagreement was judged to be measurement issue, so the accuracy of the analysis was confirmed to be sufficient.

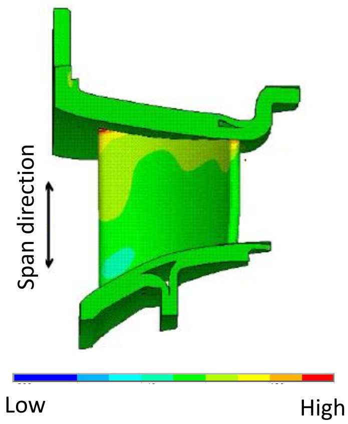


Figure 11. Calculated stress distribution in airfoil span direction of bending test for CMC vane

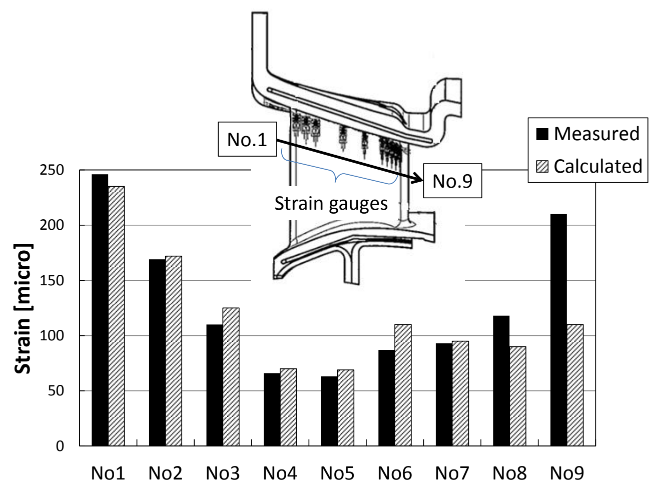


Figure 12. The comparison of the measured strain and calculated strain

BURNER RIG TEST

Cyclic thermal test for CMC vane was conducted by gas burner rig. The purpose of this test was to reduce the durability risk before engine test.

Preliminary test was conducted for the initial manufacturing trial parts before the test for the final configuration part. The airfoil concave surface was heated cyclically, and the maximum temperature was set to 1200 degree C as shown in figure 13.

Temperature distribution of airfoil surface was measured by an IR camera and was set to cause the same thermal stress at trailing edge as that occurs at engine steady state. Figure 14 is the result of thermal analysis, and figure 15 is the result of stress analysis. The time of one thermal cycle was 6 minutes, and 1,000 cycles test was conducted. Figure 16 shows the appearance of post-test CMC vane. Cracks in span direction were found at leading edge, although the analysis showed that very small stress in chord direction occurs. The cracks were formed at the boundaries of the braided fabric layers which were surfaced as a result of machining. This result shows that the machining might cause a decrease in fatigue capability of surface in the case of braided fabric-based CMC. This is one of the reasons that flow path surfaces were changed to be not machined in the final configuration as described previously.

After the preliminary test, the final configuration part was tested. The test set-up is shown as figure 17. A CMC vane was set between dummy metal vanes and heated cyclically from leading edge by a gas burner. The maximum airfoil surface temperature was set to 1200 degree C, and the minimum airfoil temperature at the interval of heating was about 300 degree C. The time of one thermal cycle was 6 minutes in the same way as the preliminary test. Figure 18 is the result of thermal / stress analysis. The maximum thermal stress at the trailing edge was simulated that occurs at engine steady state. The temperature at the trailing edge was lower than at engine steady state. Therefore the test was conducted for 1,000 cycles that was more than 10 times than the cycle planned in engine testing. After 1,000 cycles test, there was no defect like a crack in visual and X-ray CT inspection as shown in figure 19. From this result, the risk for thermal cycle was confirmed to be small.

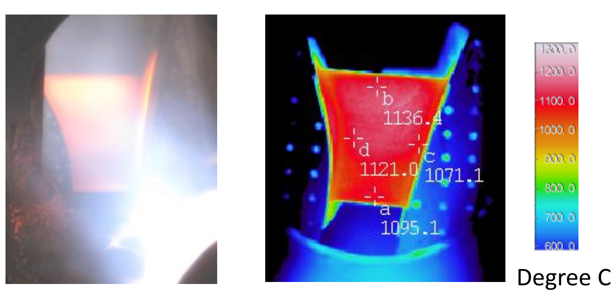


Figure 13. The appearance and the view of IR camera of vane concave surface in the preliminary test

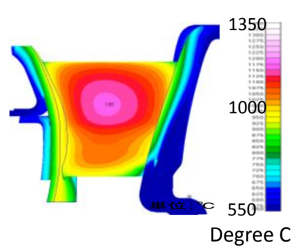


Figure 14 Thermal analysis result for the preliminary test

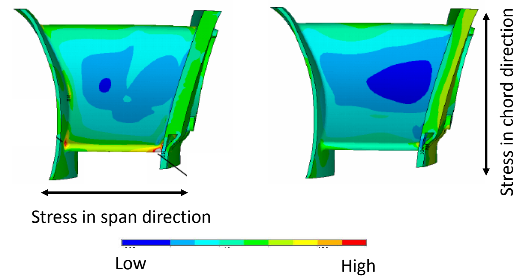


Figure 15. The calculated stress distribution of the preliminary test condition

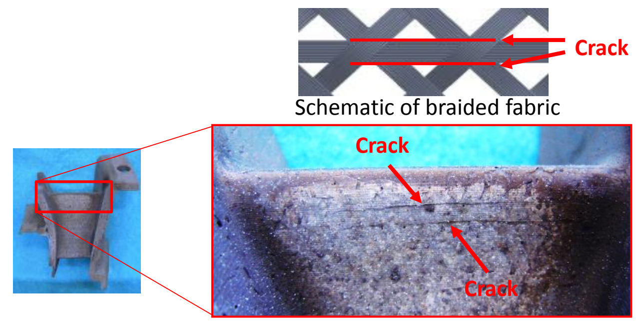


Figure 16. The appearance of CMC vane after preliminary test

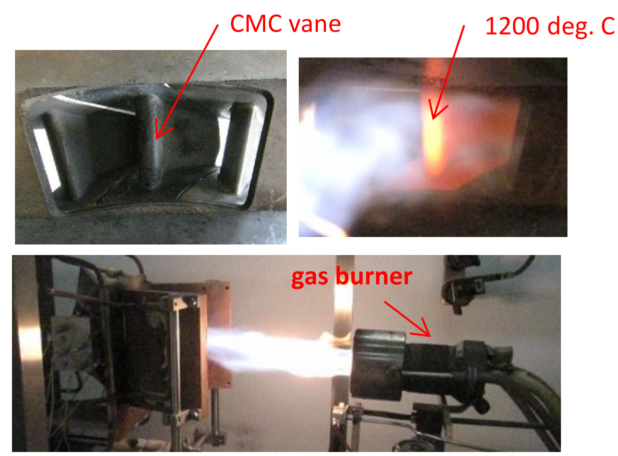


Figure 17. The set-up of the burner rig test for the final configuration part

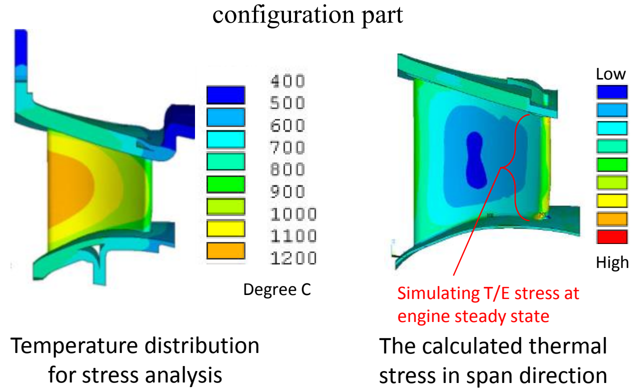


Figure 18. Temperature and stress distribution of the test for the final configuration part

Figure 19. The appearance of CMC vane after the final test

THERMAL SHOCK TEST

Thermal shock test using a nozzle cascade rig was conducted in order to reduce the risk of fracture under an engine emergency shutdown condition. Details about this test were described in [11]. Figure 20 show the cascade test rig. After the CMC vane reached a steady condition, suddenly fuel was cut-off. The temperature of main gas flow dropped to idle condition. After the test, no defect was found in visual and X-ray CT inspection.

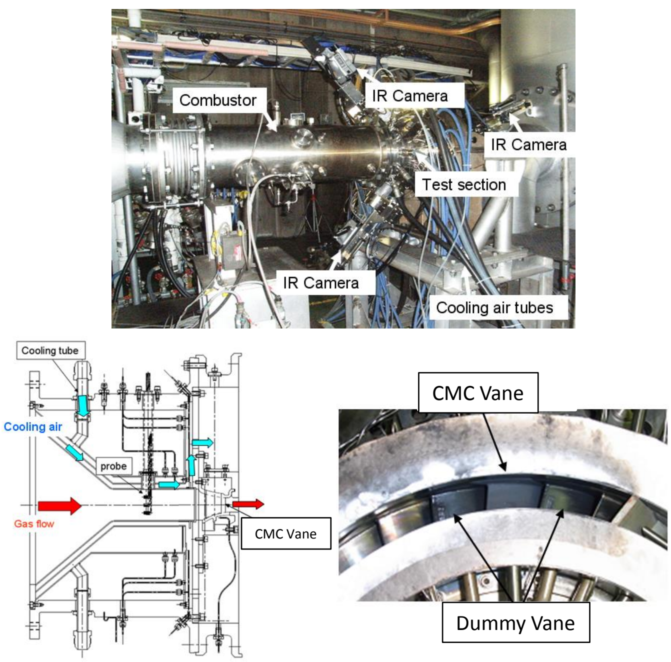


Figure 20. The cascade test rig

ENGINE TEST

Engine test was conducted using IHI IM270 that is the 2MW-class small industrial gas turbine engine (figure 21) at IHI Kure Works. The target of this test was the demonstration of 400 hours durability at over 1000 degree C environment. The four CMC vanes were installed into the first stage turbine nozzle assembly in place of the normal metal vanes as shown in figure 22. The inlet gas temperature of CMC vanes were measured by thermocouples installed at the leading edge. The test was conducted for 413 hours, including 48 starts and normal stops. The measured inlet gas temperature was about 1050 degree C at the steady state. CMC vanes were inspected by bore scope after 42Hrs, 92Hrs, 142Hrs, 241Hrs, and 330Hrs of testing. CMC vanes had functioned normally during 413 hours test and the test was finished successfully. This result was not different from the expectation by FE analysis.

From this test, the function of CMC vane in actual engine environment was demonstrated.

SUMMARY AND CONCLUSION

The authors designed CMC turbine vane with the airfoil-platform fully integrated concept. The manufacturability and the structural feasibility of this concept were verified by manufacturing trials and bending rig test. Burner rig test and thermal shock test were conducted in order to reduce the risk of engine test. Engine test was conducted, and CMC vanes had functioned normally for about 400 hours in actual engine environment. From this work, the applicability of the airfoil-platform fully integrated CMC vane concept to actual engine was demonstrated.

The establishment and the validation of life prediction method and design criteria are still challenges. In future work, full material database including various environmental and time effects will be established and life prediction method will be maturated based on the material data. Moreover, the development of manufacturing process, by which the quality of stitching multiple fabrics can be controlled to appropriate level for mass production, will be required for field introduction.

Figure 21. IHI IM270 industrial gas turbine engine

Turbine stg. 1 nozzle assembly

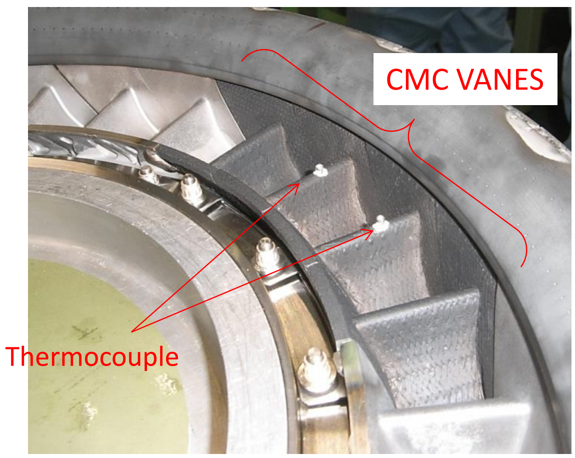


Figure 22. Installed CMC vanes

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