Development of CMC Turbine Parts for Aero Engines

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Recently, oil prices have risen creating a need for fuel-efficient aero-engines. New materials that have low density and the ability to withstand high temperatures will contribute to improving fuel-efficiency. Ceramics have such properties but their brittleness limits their fields of application. Ceramic Matrix Composites (CMC) — ceramics reinforced with fibers — can solve this issue, and are being developed as next-generation materials for aero-engines. CMCs have been under development for more than 20 years, and will be applied to commercial fields in the near future. IHI has been working on the development of CMCs, mainly for use in turbine nozzles and blades. Through these studies, good results were obtained from spin tests and fatigue tests carried out for prototype components.

1. Introduction

Ceramic Matrix Composites (CMCs), defined as a material having a matrix of ceramic material, have a variety of material systems. However, at present, practical CMC matrices are limited to Al_2O_3 (aluminum oxide)-based and SiC (silicon carbide)-based materials. Also, in order to prevent damage due to chemical instability or a difference in coefficient of thermal expansion with those of the matrix, the reinforcing fibers are composed of the same materials as the matrices, that is, Al_2O_3 fibers or SiC fibers. Comparing these two materials, SiC has higher heat resistance, while Al_2O_3 has an advantage in cost. One of the two materials is selected according to the temperature range of the application.

IHI is considering applying CMCs to aero-engine turbines whose environmental temperature exceeds 1 000°C, and is developing SiC-based CMCs with high heat resistance.(1) Application of CMCs to aero-engines is expected to improve fuel efficiency for the following reasons.

(1) Recently, fans and low-pressure turbines have become larger along with increases in the bypass ratio of engines, but low-pressure turbines can be made lightweight by using CMCs.

(2) Since CMCs have high heat resistance, the amount of air extracted from the compressor to cool the turbine blades can be decreased.

This study presents an overview of the authors' development of a SiC-based CMC manufacturing process, as well as applications of CMCs to turbine blades and turbine vanes for aero-engines.

2. CMC materials and manufacturing process

2.1 Reinforcing fibers

SiC fibers were developed in 1975 at Tohoku University, and were later commercialized as Nicalon fibers by Nippon Carbon Co. Ltd. and as Tyranno fibers by Ube Industries Ltd. **Figure 1-(a)** illustrates the molecular formula of a polymer source material of SiC fibers, while **Fig. 1-(b)** illustrates the appearance of a SiC fiber. In either of the fiber products, a polymer containing Si (silicon) and C (carbon) is spun and pyrolyzed to produce a ceramic. Several methods exist for the spinning and sintering processes, and these methods determine the properties and cost of the obtained fibers. Fibers were selected considering factors such as characteristics demanded by the application.

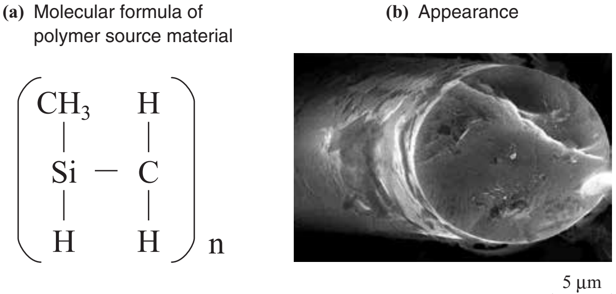
(a) Molecular formula of polymer source material
(b) Appearance

Fig. 1 SiC fiber

2.2 Interface coating

At the interface between the fibers and matrix, a layer called an interface coating is formed to prevent bonding between the fibers and the matrix. The interface coating has the effect of deflecting the progress of cracks generated in the matrix and preventing their propagation to the fibers. Known materials having this property include C and BN (boron nitride). Since C oxidizes in air at approximately 600°C or higher and dissipates, BN interface coatings, which have higher heat resistance are more suitable for aero-engine turbines.

2.3 Matrix

The material used for the matrix is SiC as discussed above. Major SiC manufacturing methods include Chemical Vapor Infiltration (CVI), Solid Phase Infiltration (SPI), Polymer Impregnation and Pyrolysis (PIP), and Melt Infiltration (MI).

In the CVI method, a SiC matrix is formed, by a pyrolytic reaction of a source gas. The formed matrix is pure SiC and cover the fiber with dense structure. It is effective at protecting the interface coating. However, there are problems in that it is necessary to lower the infiltration rate in order to uniformly infiltrate inside the reinforcing fiber yarns, and that the method is costly because of the need for special equipment.

In the SPI method, a fiber fabric is submerged in a sedimented powder mixture of the source materials Si and C, and the powder is then infiltrated into the fabric by applying vibration.(2) The key to this method is to sufficiently infiltrate the source powder into the thick portion of the fabric.

The PIP method is a technique in which a SiC matrix is formed by infiltrating a polymer source material into a fiber fabric, and then pyrolyzing the wet fabric to make a ceramic matrix. Since shrinkage occurs during pyrolyzation, the obtained matrix has a broken and clustered structure. The PIP method does not require special equipment and is low-cost, but infiltration and sintering must be repeated many times to obtain the required fill rate.

Regarding these processing methods with their advantages and disadvantages, the authors have developed the process of forming a matrix first with CVI, then with SPI to efficiently fill the large pores remaining after CVI, followed by PIP to carry out liquid-phase infiltration into the narrow pores in the matrix remaining after SPI.

Figure 2 illustrates the microstructure of a CMC manufactured by applying the materials and processes described above. The fiber volume ratio is 40% or more and the density is from 2.0 to 2.5 g/cm^3.

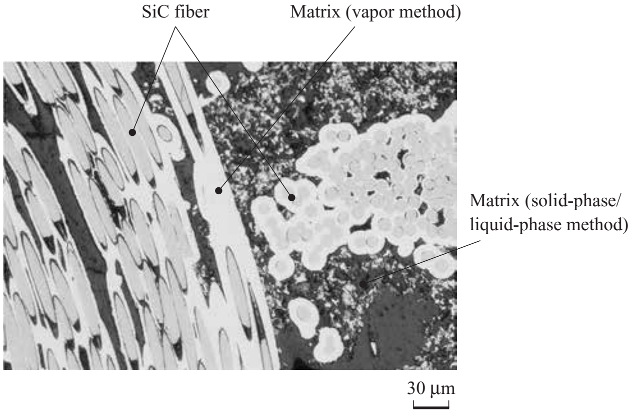

Fig. 2 Micro structure of CMC

Meanwhile, the MI method is a method of forming a SiC matrix by infiltrating a mixture of SiC powder and C powder as a filler into a fiber fabric with a slurry method, and subsequently inducing a reaction between Si and C by injecting molten Si. This enables the formation of a dense structure without pores in a short amount of time at low cost, but it is difficult to control since the speed of the reaction is high. Moreover, there is a risk of damaging the fibers by the high process temperature. For these reasons, the MI method is not selected in the development by the authors.

3. Development of CMC turbine blades

As part of the development by the authors, trial manufacture and evaluation tests were performed on each structural element of the turbine blade. On the basis of the test results, trial manufacture and evaluation tests of an entire turbine blade were then conducted. An overview is given below.

3.1 Trial manufacture of CMC blade elements

Turbine blades have a complex shape as illustrated in **Fig. 3** and their structural elements consist of a dovetail, blade, and tip. **Figure 3** also indicates the properties primarily required of each structural element. In view of the properties, strength, and element shape required of each structural element, a woven structure of reinforcing fibers was studied, trial specimens were made, and a strength evaluation was then conducted for each structural element.

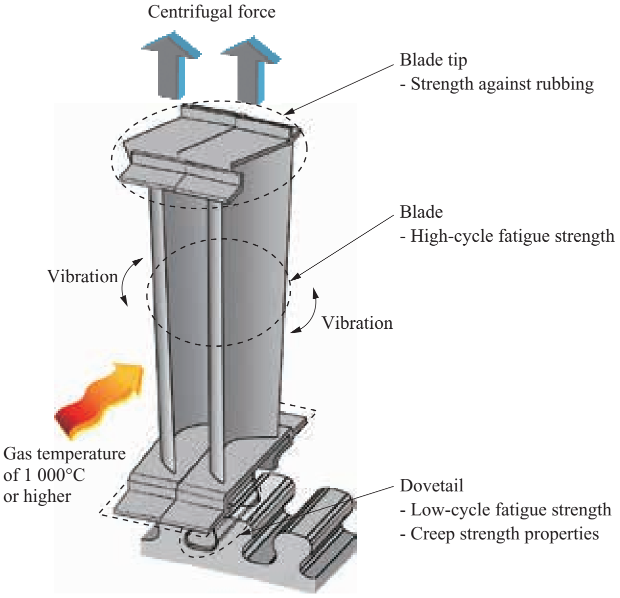

Fig. 3 Configuration of turbine blades and their main issues

3.2 Evaluation and testing of CMC blade elements

3.2.1 Dovetail element (high-temperature low-cycle fatigue, creep)

Regarding the structural feasibility of a CMC turbine blade, the high-temperature strength (low-cycle fatigue, creep) of the crucial dovetail part was evaluated by tests using the dovetail element. The estimated load experienced in an actual engine was applied to the dovetail element at the estimated temperature experienced in an actual engine of 650°C, and its ability to sustain each of the predetermined loads for a 10^5-cycle high-temperature low-cycle fatigue test and a 500-hour creep test was confirmed. In addition, no damage was observed in the dovetail element in the post-test visual and non-destructive inspections. From these test results, the dovetail element was confirmed to have sufficient durability against centrifugal loads expected in real application environment.

3.2.2 Airfoil element (high-cycle fatigue at room temperature)

Considering vibrational excitation on rotor blades with a cantilevered structure, the high-cycle fatigue strength of airfoils particularly susceptible to the effects of vibration needs to be evaluated. Therefore, a high-cycle fatigue test at room temperature was conducted for an airfoil element using a vibration exciter.

Figure 4 illustrates the appearance of the high-cycle test at room temperature. Over 10^7 cycles of vibration with a strain determined according to material test results were applied. No damage was observed in the airfoil element in the post-test visual and non-destructive inspections. The change in the natural frequency before and after the test was on the order of several percent. From this test result, the trial airfoil element was confirmed to have sufficient fatigue strength against high-cycle fatigue.

3.2.3 Tip element (high-temperature rubbing)

The behavior of a blade tip when pressed against a metal honeycomb during operation was evaluated by rubbing a CMC tip element against a metal honeycomb at high temperature. The test temperature was set to 1 000°C, equivalent to that of an actual engine, and the rotating CMC tip element was rubbed against the metal honeycomb at a circumferential velocity of 250 m/s. For comparison, a similar test was conducted for a tip element made of a Ni alloy and was then evaluated.

Comparing the CMC and Ni tip elements after the rubbing test, the CMC tip had slightly greater frictional wear compared to the metal tip, but since there was no damage or unusual burns on the tip, it was confirmed that the CMC tip maintained its integrity. From this test result, the tip of the CMC blade was confirmed to have maintained its integrity even under severe rubbing conditions against the metal honeycomb.

3.3 Trial manufacture of CMC blade and evaluation test

After evaluating each element of the CMC blade, a combined CMC blade was manufactured. **Figure 5** illustrates the appearance of the manufactured CMC blade. The accuracy of the profile satisfies the requirements for aero-engine components, and a weight reduction of approximately 65% compared to a metal blade has been achieved.

The manufactured CMC blade was subjected to a rotational test at room temperature for overall evaluation. The object of this test was to confirm the integrity as well as the fracture strength and fracture mode of the trial CMC blade under an estimated centrifugal load in an actual engine. After confirming that the CMC blade remained stable for five minutes under a load equivalent to 120% of the centrifugal force acting on the blade in an actual engine, the rotational speed was raised until damage occurred on the outer diameter of the trailing edge of the blade (near the tip) at a rotational speed producing a centrifugal load equivalent to 190%. From this test, the CMC blade was confirmed to have sufficient strength at room temperature against the centrifugal load produced in an actual engine.

4. Development of CMC turbine vanes

Component strength evaluations were primarily performed in the development of the CMC turbine blades. Thermal cycle tests and a real engine environment test were also conducted in order to evaluate component durability.

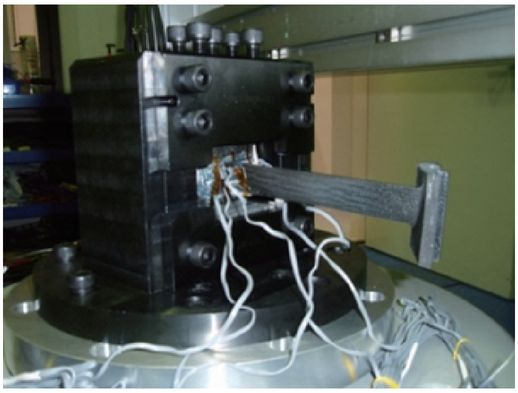

Fig. 4 Appearance of high cycle fatigue test at room temperature

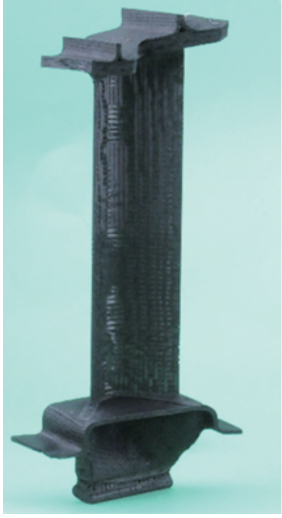

Fig. 5 Appearance of CMC blade

4.1 Trial manufacture of CMC turbine vanes

Turbine vanes also have complex shapes, and like the turbine blades, a woven structure of reinforcing fibers was studied in view of the properties, strength, and shape demanded of a turbine vane. **Figure 6** illustrates the visual appearance of a manufactured CMC vane. The dimensional accuracy satisfies the requirements of aero-engine components, and as is the case with the blades, a weight reduction of approximately 65% compared to a metal vane was achieved.

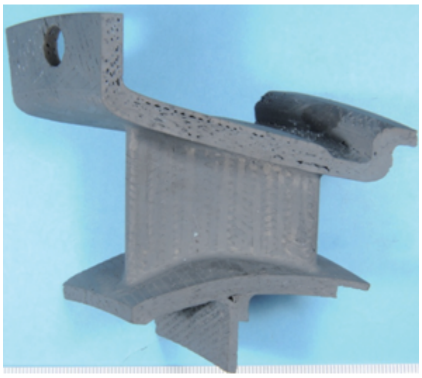

Fig. 6 Appearance of CMC vane

4.2 CMC vane evaluation tests

(1) Thermal cycle test

By using a gas burner heating device to repeatedly heat a CMC vane and then allowing the heat to dissipate, the structural integrity of the CMC vane in a thermal stress environment was confirmed. The test temperature was set to 1 200°C and a 5 000-cycle test where one cycle consists of raising the temperature over the course of three minutes and then lowering the temperature over the course of three minutes was performed. It was confirmed that no damage occurred in the CMC vane. Future analysis techniques and lifetime evaluation techniques will be established on the basis of the test data.

(2) Real engine environment test

Functional integrity was confirmed by exposing the CMC vane to a real engine environment. In this test, an actual gas turbine engine was used to expose the CMC vane to the estimated temperature in an actual engine of 1 000°C or higher for 400 hours. Note that among the 30 turbine vanes installed in the gas turbine engine used for the test, four of the vanes were CMC vanes.

The test completed the targeted 400 hours of operation without any unusual changes in temperatures and pressures measured in the gas turbine engine. This test verified that the CMC vane maintained functional integrity as a turbine vane in a real engine environment.

5. Conclusion

The authors have presented an overview of their development of CMC manufacturing processes and the development of CMC components for aero-engines.

A CMC with SiC fibers and a SiC matrix was selected. To form the matrix, the manufacturing process in which CVI is performed first, followed by SPI to efficiently fill the large pores remaining after CVI, and then the PIP process for liquid-phase infiltration into the narrow pores in the matrix remaining after SPI.

In the development for application of the CMC blade component parts composed of the CMC material that the authors developed, trial manufacture of blade elements and their strength evaluations were performed first. Then, a blade composed of a combination of the elements was then manufactured and evaluated by a rotational test at room temperature, and good results were obtained.

In addition, a CMC vane composed of the same CMC material was manufactured and subjected to a thermal cycle test and a real engine environment test. It was verified that the CMC vane maintained its functional integrity.

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