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Technology Research on High Efficiency Gas Turbines Utilizing Melt-Growth Composite Ceramics

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ABSTRACT

A unique ceramic composite produced by unidirectional solidification from melts with eutectic composition of two oxides has been recently introduced. This composite has a microstructure in which continuous networks of two single crystals interpenetrate without grain boundaries. This material, which is called Melt-Growth Composite (MGC), can maintain its room temperature strength at temperatures of up to 1,700 ℃ (near its melting point) and has superior oxidization resistance. These characteristics are ideal for application to gas turbine systems. Our research project on MGC started in 2001 with the objective of establishing component technologies for MGC application to the high-temperature components of the gas turbine engine. This paper outlines the results of our research at the early stage of the project.

NOMENCLATURE

AFR	: Air Fuel Ratio
CFD	: Computational Fluid Dynamics
FAR	: Fuel Air Ratio
FEM	: Finite Element Method
GAP	: $GdAlO_3$
MGC	: Melt-Growth Composite
NBL	: Normalized Boundary Length
OPR	: Overall Pressure Ratio
SiC/SiC	: Silicone Carbide Fiber and Silicone Carbide Matrix Composite
TIT	: Turbine Inlet Temperature ℃
YAG	: $Y_3Al_5O_{12}$

INTRODUCTION

The gas turbine engine is a preferred energy source for the co-generation system now utilized worldwide for distributed energy systems because of its high power production and low emission and adaptability to various fuels. Due to these advantages, higher energy efficiency for the gas turbine system is being pursued. Silicone nitride and silicone carbide are widely researched in the world as prospective materials for high-temperature structures. To improve energy efficiency and curb the emission of pollutants such as CO_2 and NO_x, we examined an application of MGC to gas turbine high-temperature components.

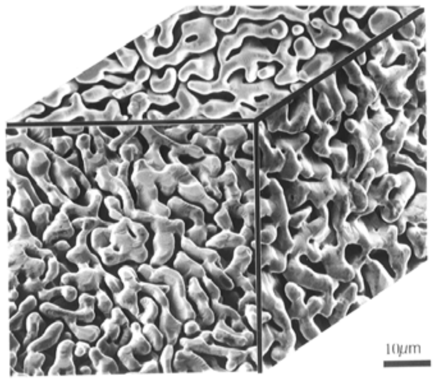

Fig. 1 SEM micrograph showing the three-dimensional configuration of single crystal GAP in unidirectionally solidified Al_2O_3/GAP eutectic composite (Al_2O_3 is removed)

Our preliminary research on MGC application to relatively small gas turbine components began in 1998 and ended three years later. It obtained the following results:

MGC can be applied to the gas turbine components. The thermal efficiency of the mid-to-small size gas turbine engines will increase about 9% (difference between 29% and 38% / 5MW class, refer to Fig. 4), if turbine inlet temperature (TIT) of a 1,700 ℃ and an engine pressure ratio of 30 have been realized without cooling of turbine nozzle.

The objective of the present research is to establish technologies for MGC application to the high-temperature section of gas turbine engines. The first phase of the research will run for five years from 2001 to 2005. The research is being carried out jointly by Ishikawajima-Harima Heavy Industries, Kawasaki Heavy Industries and Ube Industries, LTD..

MGC MATERIAL

Most conventional ceramics are produced by the powder sintering method. In many cases, they contain impurities, and amorphous phases at grain boundaries. In general, the amorphous phases increase fracture toughness and strength at room temperature, but these lead to reduction in high-temperature strength and creep resistance. On the other hand, a ceramic composite like SiC/SiC, which is considered to be a promising high-temperature material, does not include amorphous phases at grain boundaries, but improvement of oxidization resistance is important for using these materials at high temperature in an air atmosphere.

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MGC is a unidirectionally solidified eutectic composite fabricated from melts with eutectic composition of two oxides. The representative systems of MGCs are Al_2O_3/YAG and Al_2O_3/GAP.[1-4] Raw material powders are pre-melted to obtain ingot, and then the ingot is placed in a molybdenum (Mo) crucible. The Mo crucible is heated by high-frequency induction heating. After 30 minutes at around 1900 ℃, unidirectional solidification is completed by lowering the Mo crucible speeds of 5 or 10 mm/h. The MGC manufacturing process is basically similar to that of Ni-based single crystal cast superalloy.

Fig. 1 shows an SEM micrograph illustrating the three-dimensional configuration of the single-crystal GAP in the Al_2O_3/GAP MGC from which Al_2O_3 phases had been removed by heating in graphite powders at 1650 °C for 2 hrs. The configuration of single-crystal GAP is a three-dimensionally connected porous structure of irregular shape. [3] Namely the present composite has a microstructure consisting of three-dimensionally continuous and complexly entangled single-crystal Al_2O_3 and single crystal GAP. Therefore, room temperature strength of this composite can be maintained to about 1,700 ℃ as Fig. 2 shows. In addition, Al_2O_3/YAG MGC have excellent oxidation resistance with no change in mass gain for 1000 hour at 1,700 ℃ in an air atmosphere. [2,4] There were also no changes in microstructure of Al_2O_3/YAG MGC even after heat treatment for 1,000 hours at 1,700 ℃ in an air atmosphere. [2,4]

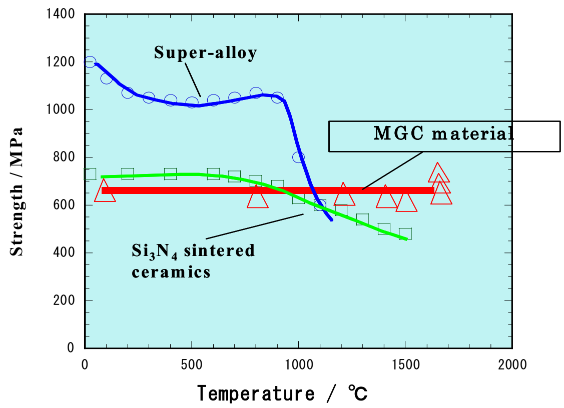


Fig. 2 Temperature dependence of strength of MGC compared with Si_3N_4 ceramics and superalloys(MarM-247)

Although MGC shows low thermal shock resistance, other characteristics are ideal for the high-temperature gas turbine engines as mentioned above. If a structural design technique to relax thermal shock resistance is successfully developed, MGC can be used widely as high-temperature parts of gas turbine systems. Table 1 shows the properties of MGCs.

Table 1 Material properties of MGCs

	MGC (Al_2O_3/YAG)	MGC (Al_2O_3/GAP)	Appendix
Density	4.2	5.7	(g/cm3)
Young's modulus	330	350	(GPa) room temperature
Flexural strength	300-350	600-650	(MPa) at 1,700℃/ YAG at 1,600℃/ GAP
Thermal expansion	$7.3x10^{-6}$	$7.8x10^{-6}$	(1/K) at 800℃
Thermal conductivity	20.8	23.9	(W/Km) room temperature

MGC GAS TURBINE SYSTEM

Efficiency of the gas turbine engine can be improved by raising TIT and pressure ratio. However widely used super alloy can stand temperatures of up to 1,000 ℃ and requires a significant amount of cooling air if the gas temperature rises above 1,000℃. Thus, the efficiency does not increase as the gas temperature increases. Ceramics were widely researched as a replacement of the metal materials to reduce cooling air amount and to increase gas turbine efficiency. As MGC is a super-heat-resistant material, it can be used at the temperature of 1,700 ℃ without cooling.

MGC is expected to be applied to the high-pressure turbine and combustor liner. Its application to the rotational blade was abandoned due to the high risk of rubbing of the blade tips or foreign object damage. MGC will be applied to the non-cooled turbine nozzle vane to improve efficiency and also to the heat shield panel of the combustor liner to reduce liner-cooling air for low NOx lean burn combustion.

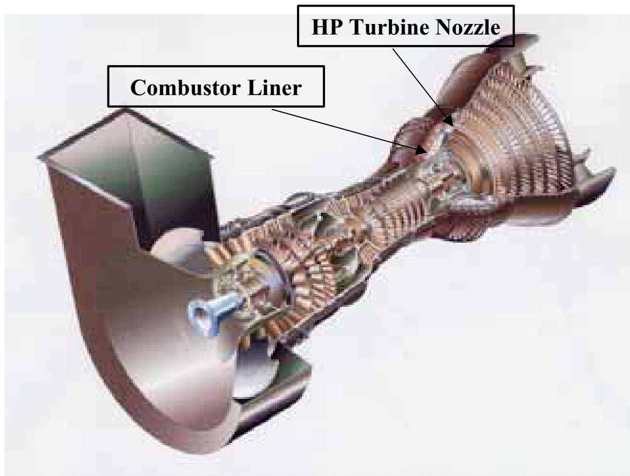


Fig. 3 Designed gas turbine and locations of MGC components

A paper engine was designed to study component requirements and to estimate its performance. Fig. 3 shows planned gas turbine engine and MGC applications. The size of the gas turbine chosen was a relatively small 5MW class. By increasing TIT from the conventional 1,100 ℃ to 1,700 ℃, without cooling the nozzle vane and raising the engine pressure ratio from 15 to 30, the thermal efficiency of the gas turbine increased from 29% to 38%. Fig. 4 shows the estimated improvement compared with a current gas turbine. Both are simple cycle gas turbines, and the efficiency is defined at the electrical output.

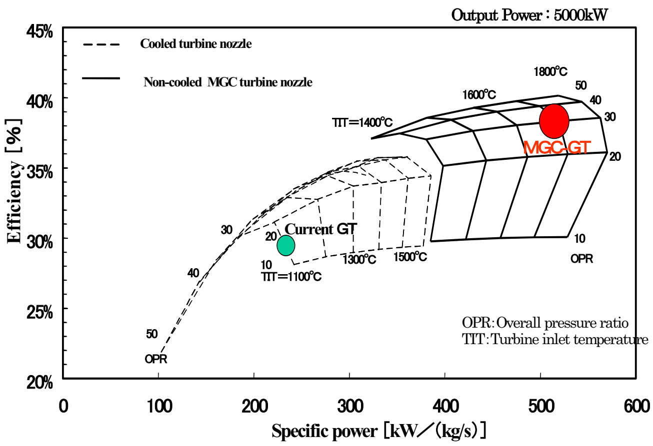


Fig. 4 Calculated performances of the MGC and current gas turbine

MGC turbine nozzle design has made progress. The difference of thermal expansion rates between metal and ceramics structure is absorbed by the metallic spring at the bottom of ceramics parts. Figs.5 and 6 show the current design of the nozzle and combustor. Both designs required ceramic heat insulations to separate high-temperature MGC parts from the metallic structure. However, the amount of the cooling air to protect the metallic structure is minimized in both cases.

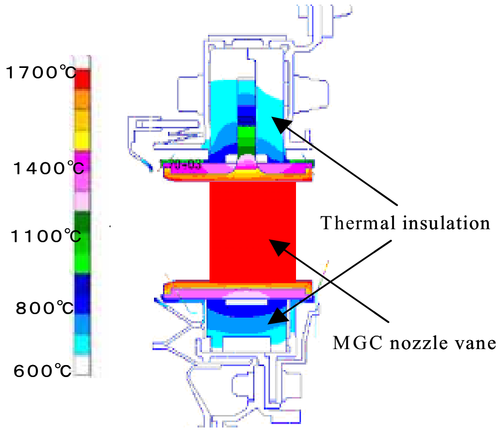


Fig. 5 Structural design of MGC turbine nozzle

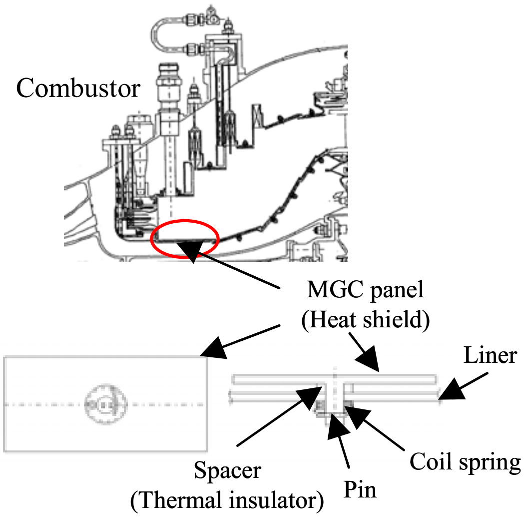


Fig. 6 Structural design of MGC heat shield panel for combustor liner

RESEARCH ON GAS TURBINE COMPONENTS

MGC Turbine

The high-pressure turbine nozzle vane was researched as a candidate for MGC application. But alleviation of thermal stresses and avoidance of difference of thermal expansion rates between MGC and the metal structure are the main concern for this application.

Thermal stress on non-cooled MGC turbine nozzle vanes was analyzed. An engine trip condition in which the gas temperature of 1,400 ℃ went to 700 ℃ in one second was assumed (1,400 ℃ is a first step of the target temperature). As a result, a hollow nozzle vane shape was selected to alleviate thermal stress caused by thermal shock. Many hollow shapes were evaluated. Based on the thermal stress estimate of the turbine vane by thermal stress analysis using the Taguchi (statistical) method, it was found that a configuration of the hollow turbine nozzle with the thicker suction side and thinner pressure side was most effective in reducing thermal stress. Even when subjected to thermal shock, this configuration would be better, because of the difference of heat transfer coefficient at both surfaces. The bowed configuration is also ideal to reduce thermal stress, but was put on hold due to manufacturing difficulty.

The hollow nozzle vane shown in Fig. 8 was tested at the gas temperature of 1,400 ℃, which is the maximum allowable temperature for the current turbine nozzle rig. Estimated maximum stress using measured temperature distribution was 211 MPa (steady state). This stress value is well below material strength, but the estimated maximum stress at 1,700 ℃ and blowoff condition went to 502 MPa, which exceeds allowable stress level of the material. The bowed configuration was re-assessed based on the test stress level. Fig. 9 shows the bowed configuration, which could be manufactured and can withstand the 1,700 ℃.

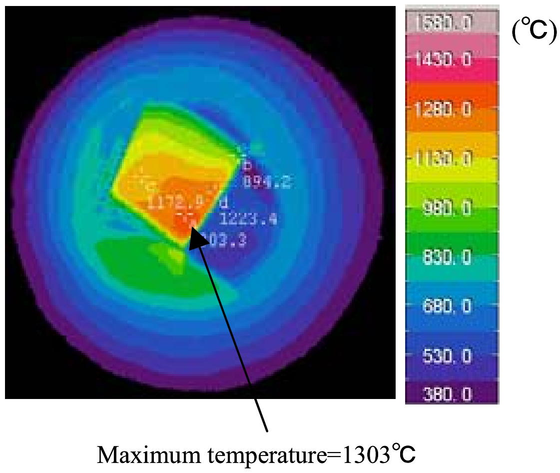


Fig. 7 Measured temperature distribution on the nozzle surface at a gas temperature of 1,400 ℃ (concave side)

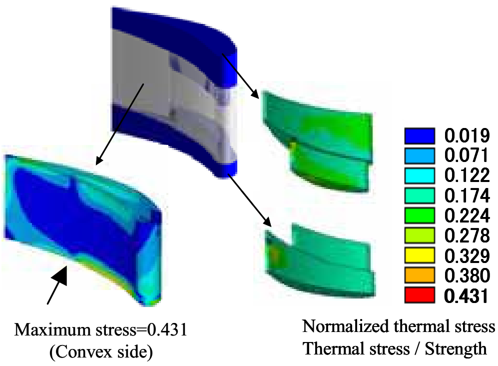


Fig. 8 Nozzle vane tested at a gas temperature of 1,400 ℃
Estimated maximum stress was 211 MPa (steady state)

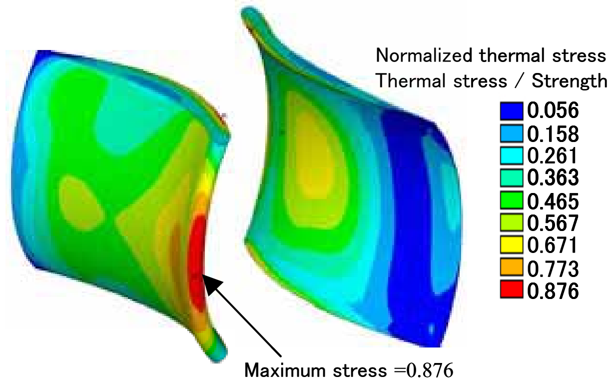


Fig. 9 Re-designed bowed thin nozzle vane configuration
Estimated maximum stress is 429 MPa (trip condition)

Low NOx Combustor

MGC material will also be used for the heat shield panel to reduce the combustor liner cooling air and to perform the leanest possible combustion. Some cooling configurations with the MGC panel were designed for the combustor liner, and one-dimensional heat transfer characteristics were analyzed for the configurations. It was also shown that the temperature gradient in the MGC panel was reduced by the coating or heat insulation on the cooling side of the MGC panel. Fig. 10 shows samples of one simple panel configuration and its calculation results. Maximum thermal stress was 397 MPa at the edge of heat insulator. This value exceeds the strength of YAG material but is acceptable on GAP material. Improvement of the configuration will be studied further. Heat transfer characteristics of the heat shield configurations were tested and results agreed with those of one-dimensional calculation.

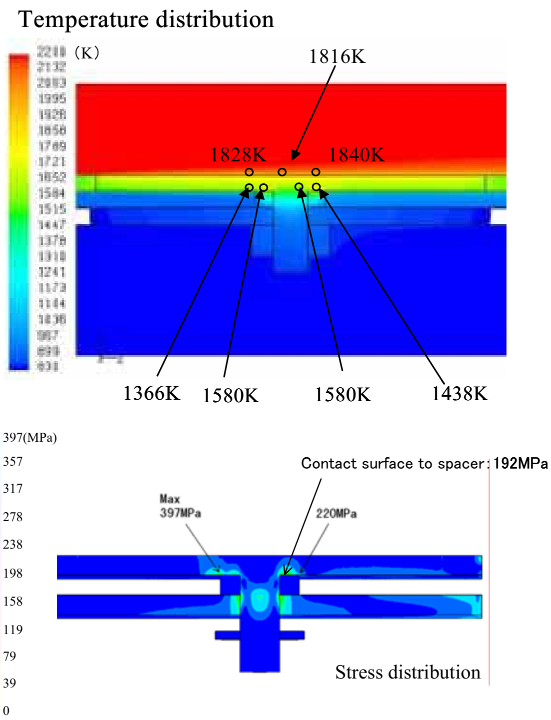


Fig. 10 Estimated temperature and stress distribution on an MGC heat shield

The combustion characteristics of the model combustor was examined at the condition of 1,400 ℃ TIT. The NOx emission was increased as the combustion temperature increased on the initial configuration of the model combustor. The injector was modified for more homogeneous mixing and shorter duration of residence time, resulting in better combustion characteristics as shown in Fig. 11.

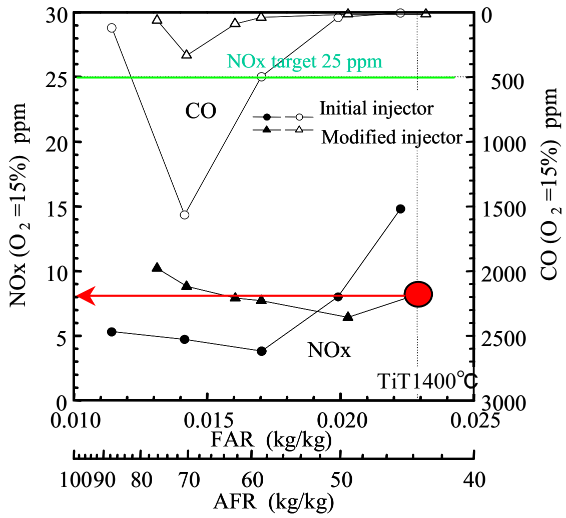


Fig. 11. Combustion characteristics of the model combustor

The preliminary combustor configuration was designed through numerical flow analyses. To optimize the staged combustion and diffuser configuration, the following investigation was performed. The airflow pattern for some shapes of the liner and diffuser configurations were further analyzed to obtain the perfect flow field. This analysis showed that the axial swirler and single pass diffuser were better than the preliminary double pass diffuser and radial swirler configuration. The pressure loss of 3% and good mixing were achieved on this configuration (refer to Figure 12).

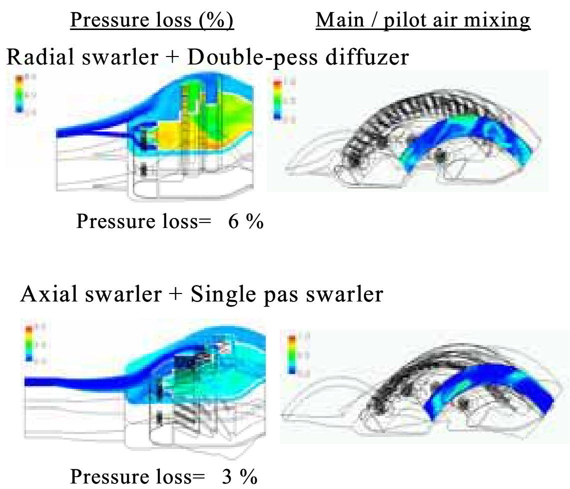


Fig. 12. Numerical calculation results on the pressure loss and mixing performance

Compressor

To improve efficiency of high-temperature gas turbine, the pressure ratio of the engine must be increased. Aerodynamic oscillation forces also increases because of the high density of highly compressed air. The interaction of aerodynamic unsteady oscillation forces is very complex in the multistage compressor. The force acting on the blade row sometimes increases due to the synthesis of both the upstream and downstream blade rows. Prediction of the stress caused by the airfoil vibration can be made by combination of Computational Fluid Dynamics (CFD) and Finite Element Method (FEM) analyses.

In the case of the multistage compressor, multistage CFD analysis by solving unsteady Navier-Stokes equations was needed to predict the interaction of the forces. The multistage CFD analysis was conducted to investigate the interaction of the aerodynamic forces. The FEM analysis system was also utilized to predict airfoil vibration stress under multistage condition using the aerodynamic forces analyzed by this CFD analysis.

The clocking effect of stator vane position and the effect of the variable pitch stator were investigated using this multistage analysis system. The calculated vibration stress of the blades was reduced about 35 % by clocking and 30 % by ±10 % of the variable pitch effect. Fig. 13 shows sample of CFD calculation on clocking effect.

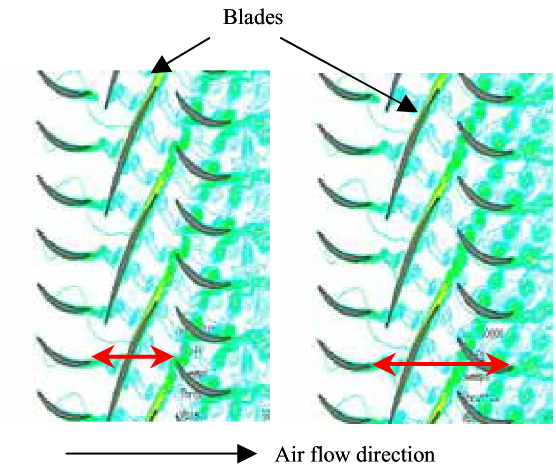


Fig. 13 Sample of multistage CFD calculation and clocking effect (Trailing to leading edges and trailing to trailing edges alignment)

MGC COMPONENTS AND RELIABILITY

Machining of the MGC material is relatively easy. However, it is very important to develop a near-net shape casting technique to fabricate MGC components of gas turbine systems. To this end, we developed a large-scale Brigdman furnace that can precisely control manufacturing factors like temperature gradient of melts and simulated solidification. In parallel, we produced a casting mold and core utilizing plasma spraying in a vacuum. Fig. 14 shows sample of the casting mold made by plasma spraying. In Al_2O_3/YAG and Al_2O_3/GAP MGC, thermal stability of microstructure and flexural strength is excellent even at 1,700 ℃ in an air atmosphere as shown in Fig. 15 and 16, respectively. Table 2 and 3 illustrate the change in dimensions of a hollow turbine nozzle (Table 2) and combustor liner panel (Table 3) at 1,700 ℃ for 500 hours in an air atmosphere, respectively. The hollow turbine nozzle is made of Al_2O_3/GAP, and the cmbustor liner panel is made of Al_2O_3/YAG. There was no change in dimensions of either part.

Fig. 14 Casting mold made by plasma spraying

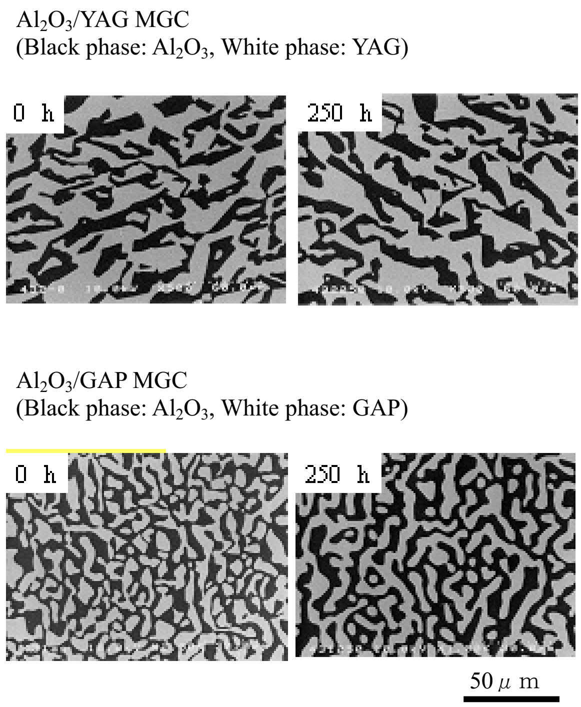


Fig. 15 SEM micrographs showing the microstructure of cross-sections perpendicular to the solidification direction of Al_2O_3/YAG and Al_2O_3/GAP MGCs before and after heat-treatment at 1,700 ℃ for 250 hours in an air atmosphere.

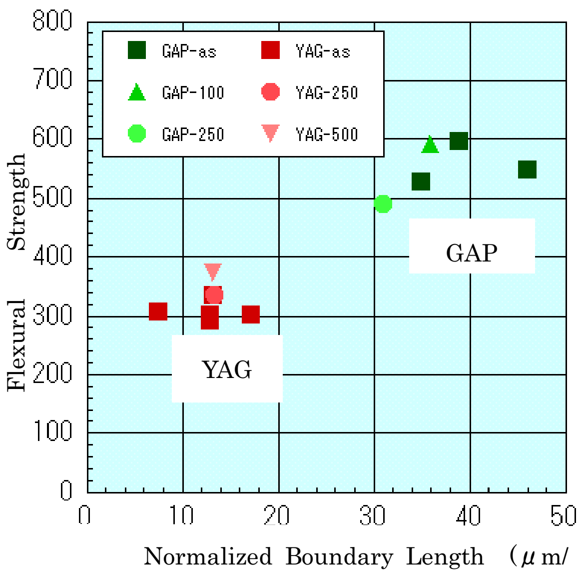
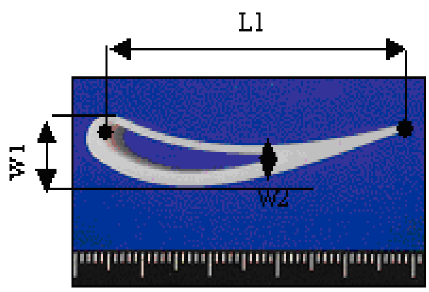


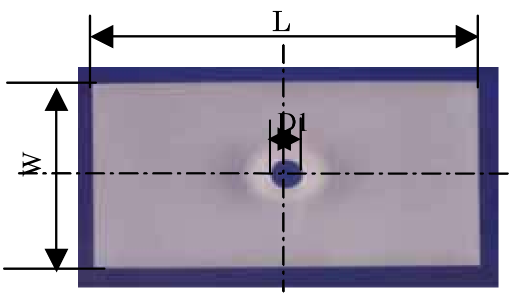
Fig. 16 Change in the strength of Al_2O_3/YAG and Al_2O_3/GAP MGCs kept for 250-500 hours at 1,700 ℃ in an air atmosphere



Hollow turbine nozzle vane

Table.2 Difference of the MGC nozzle vane after heat treatment for 500 hours at 1700 ℃ in an air atmosphere.

Length	0 h	250 hours	500 hours	Dimensional change
L1(mm)	43.971	43.975	43.977	0.006
W1(mm)	10.614	10.620	10.614	0.000
W2(mm)	5.389	5.390	5.385	-0.004
Weight(g)	26.783	26.782	26.770	-0.012



Combustor liner panel

Table.3 Difference of the MGC Liner panel after heat treatment for 500 hours at 1700 ℃ in an air atmosphere.

Length	0 h	250 hours	500 hours	Dimensional change
L(mm)	74.539	74.528	74.534	-0.005
W(mm)	38.060	38.064	38.066	0.006
D1(mm)	5.553	5.558	5.557	0.003
Weight(g)	18.561	18.562	18.564	0.003

Fig. 17 shows a schematic of the moisture corrosion apparatus. The apparatus comprises a gas supply system, a moisture supply system, a electric furnace system and a gas exhaust system. The weight, dimensions and strength of Al_2O_3/YAG MGC was almost unchanged even after 250 hours at 1700 ℃ in an air atmosphere(79% N2, 21% O2) with additional 30 %wt. moisture as shown Fig. 18 and 19.

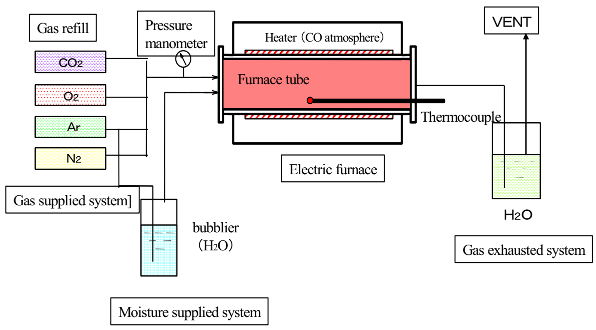


Fig. 17 Schematic drawing of the moisture corrosion test (Only N_2, O_2 and 30%Wt water vapor were used)

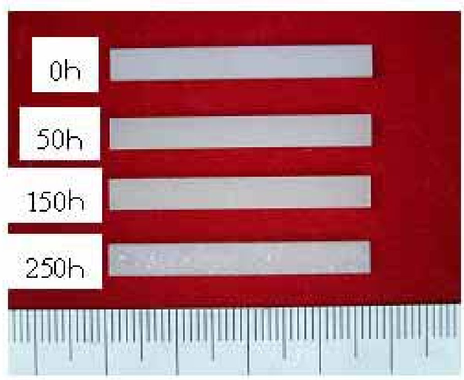


Fig. 18 Appearance of Al_2O_3/YAG MGC after moisture corrosion tests for 50-250 hours at 1,700 ℃

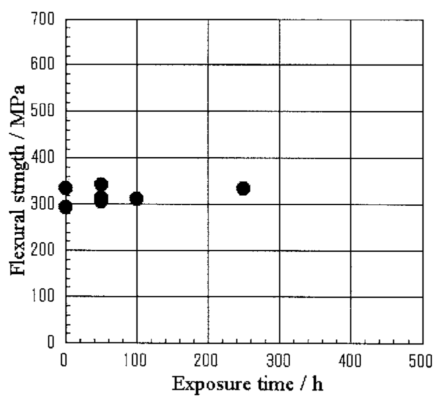


Fig. 19 Change in the strength of Al_2O_3/YAG after moisture corrosion test at 1,700 ℃

CONCLUSIONS

This research project is now at the early stage. But so far the properties of MGC seems promising for the gas turbine application.

1. The MGC gas turbine parts show superior high-temperature characteristics and thermal stability at very high temperatures, although the durability over a long period has not been evaluated yet.
2. It is probable the material can be applied to the high-temperature section(s) of gas turbines such as nozzle vanes and/or heat shields. But structural design must be performed carefully, and heat insulation is important to maintain such high-temperature material.
3. Thermal efficiency is largely improved with raising of TIT and decreasing cooling air.

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