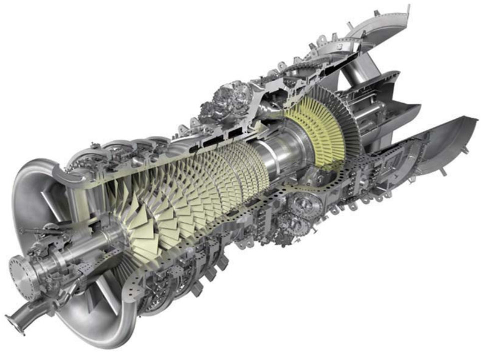
Key Technologies for 1700℃ Class Ultra High Temperature Gas Turbine



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Gas-turbine combined-cycle power generation is expected to lead to a long-term extension of power-generation markets by providing the most clean and economic thermal power plants which coexist with renewable energy. We are developing technologies for 1700°C-class gas turbines as part of a national project to further improve the performance, and some of the latest developed technologies have been applied to the development of the world's first 1600°C-class J-series gas turbine and next-generation high-efficiency gas turbines.[1] In this article, the technology development status, together with examples of technologies developed toward the application of next-generation 1700°C-class gas turbines, is described.

1. Introduction

Innovative technology development is important for the reduction of greenhouse effect gas emissions. We have conducted the development of key technologies required for the commercialization of 1700°C-class gas turbines as a national project with an eye toward the commercialization of the high-efficiency thermal power generation technology using ultrahigh-temperature gas turbines as an advanced use of natural gas. The road map of technology development for the realization of ultrahigh-temperature gas turbines is shown in **Figure 1**.

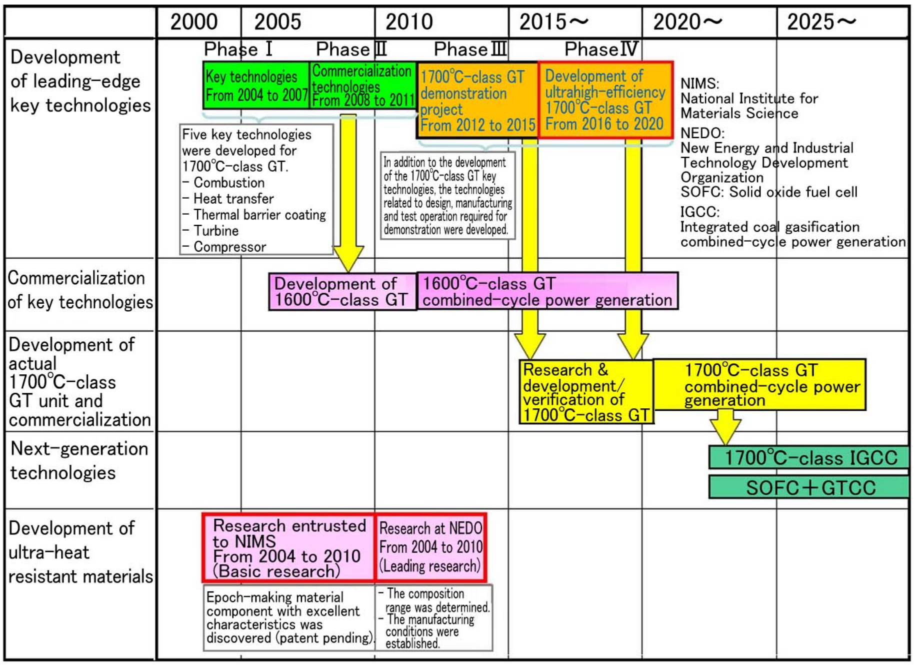

Figure 1 Technology development roadmap for ultrahigh-temperature gas turbines

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So far, the technology development has been made in Phase I (from 2004 to 2007) for the development of the six key technologies (barrier coating, cooling, combustor, turbine, compressor, heat-resistant material) for 1700°C-class gas turbines and in Phase II and III (from 2008 to 2015) for the commercialization of the technologies.[2] The achievements obtained in this project have been reflected in the development of the 1600°C-class J-series gas turbines and the next-generation high-efficiency gas turbines. Currently, in Phase IV, as shown in **Figure 2**, with the increased 13 key technologies, the technology development has been continued toward the development, manufacturing and test operation of an actual unit. In this article, the development status of the eight key technologies and the achievements obtained so far are introduced (Figure 2).

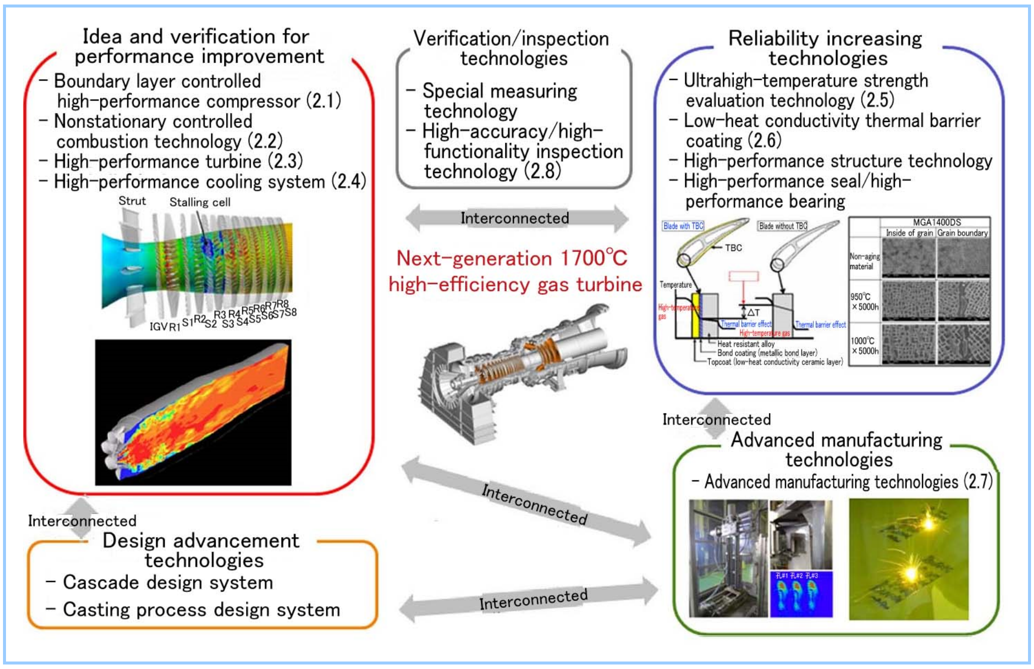

Figure 2 Development of key technologies for ultrahigh-temperature gas turbines

2. Key technologies for ultrahigh-temperature gas turbines

2.1 Development of boundary layer controlled high-performance compressor

To improve the cycle efficiency by increasing the turbine inlet temperature, the compressor is required to have a larger pressure ratio than the current one. To achieve an increase in the pressure ratio with the number of stages and an axial length equivalent to those of the conventional compressor, a higher aerodynamic loading needs to be applied to the compressor blade rows, which may cause a reduction of the efficiency, surge margin and stability at gas turbine start up. Therefore, a highly accurate numerical flow simulation method with the actual geometry being modeled in detail was developed, and we have been studying the clarification of the mechanism to increase the growth of the boundary layer associated with the increase in pressure ratio, as well as an improved design for controlling the boundary layer. In addition, a scale model of an actual machine was manufactured, and the performance verification of the improved design and the accuracy evaluation of the numerical flow simulation have been conducted, and the results have been reflected in the design of an actual machine to develop an even more reliable compressor.[3]

Figure 3 shows the verification results of the compressor instability (surge) point under the low-cycle condition, using test equipment that is a scale model of the front 8 stages of the compressor. It demonstrated that through a change of the blade shape, the target flow rate was satisfied as expected. **Figure 4** shows the verification of the number of rotating stall cells and the amplitude of pressure fluctuation that is generated under the startup condition. Stable starting characteristics were obtained as expected.

Using these technologies, we have promoted the development of a further high-performance/high-reliability gas turbine compressor.

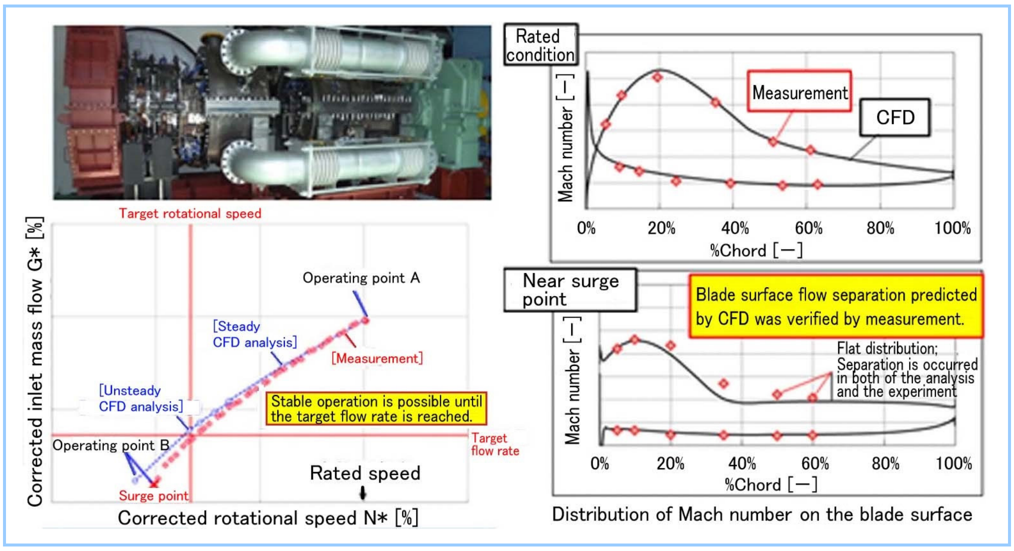

Figure 3　Verification of 8-stage compressor surge test and simulation

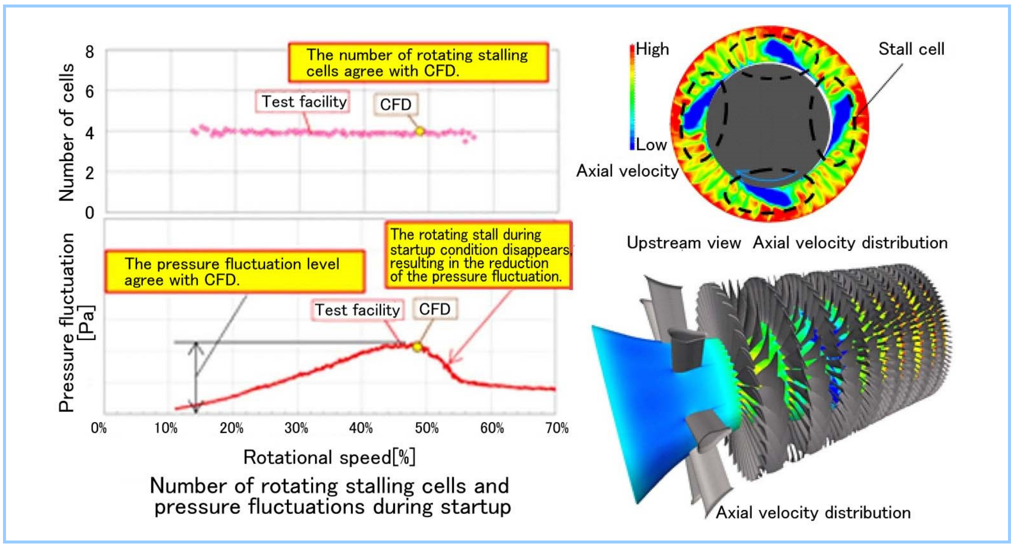

Figure 4　Comparison of measurement and simulation for rotating stall phenomena at startup condition of 8-stage compressor

2.2 Development of unsteady combustion control technology

Competition in the development of gas turbines has intensified, and we have been trying to increase the combustion temperature of gas turbines for an increase in efficiency. In addition, the reduction of NOx emissions, which increase as the temperature rises, is an urgent necessity. The lean premix combustion method is effective in reducing NOx, but in premix combustion, the flame position is unstable and combustion oscillation due to fluctuations in the heating value tends to occur. Therefore, in the development of a premix combustor, the reduction of combustion oscillation together with the rarefaction of premixed gas and the reduction of NOx through uniform premix are also important issues in design. To deal with these issues, it is necessary to identify the specific position of the flame inside an actual combustor and reflect it in the design of the combustor. However, it is difficult to determine it under high-temperature and high-pressure conditions, and the state of the inside of the combustor under actual conditions has been unknown so far. Therefore, we developed flame position evaluation technology through optical measurement and large-scale unsteady numerical simulation.

Figure 5 shows an overview of the optical measurement technology. In this measurement technology, the light emission from the flame is collected by the optical probe installed on the combustor wall face and detected by the photomultiplier, thereby estimating the heating value of the local flame. Furthermore, by installing multiple probes, the distribution of the heat release rate in the axial direction of the combustor can be measured. We developed a pressure-resistant and heat-resistant probe, which enabled the identification of the flame distribution for an actual-scale combustor under actual conditions.

At the same time, we developed large-scale unsteady numerical simulation technology using Large Eddy Simulation (LES). With this analysis technology, the application of unsteady simulation enabled flame estimation with high precision (**Figure 6**).

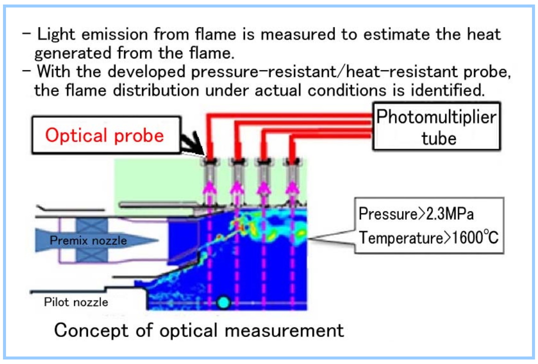

Figure 5 Overview of the optical measurement for the inside of a combustor

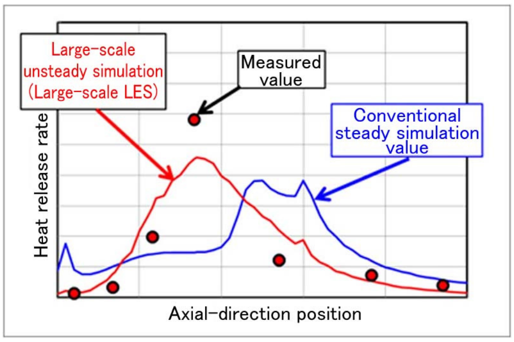

Figure 6 Measurement of the combustor heat release rate in the high-temperature and high-pressure field

These technologies enabled the evaluation of flame position under actual conditions from two aspects of measurement, and resulted in the analysis shown in the comparison results in Figure 6. The conventional steady simulation results show a peak on the downstream side, while the newly developed large-scale unsteady simulation results show a peak on the upstream side. These simulation results are in good agreement with the measured values, and we were able to verify that this analysis technology enables high-precision prediction. These technologies have been put to practical use in the development of a low-NOx combustor.

2.3 Development of high-performance turbine

The turbine exhaust diffuser (**Figure 7**) is positioned downstream of the turbine blades and has the function of reducing the turbine blade exit velocity and increasing the static pressure to atmospheric pressure. As a result, the exit static pressure of the last stage blade located upstream of the exhaust gas diffuser becomes lower than atmospheric pressure, and the substantial turbine pressure ratio (expansion ratio) and output are increased, resulting in the improvement of turbine efficiency. We studied an improvement concept through optimization by integrating the turbine and diffuser, to which the advanced simulation technology was applied, in order to increase the performance improvement of the exhaust gas diffuser, and verified the performance improvements under the rated load condition through the turbine exhaust diffuser rig test (**Figure 8**).

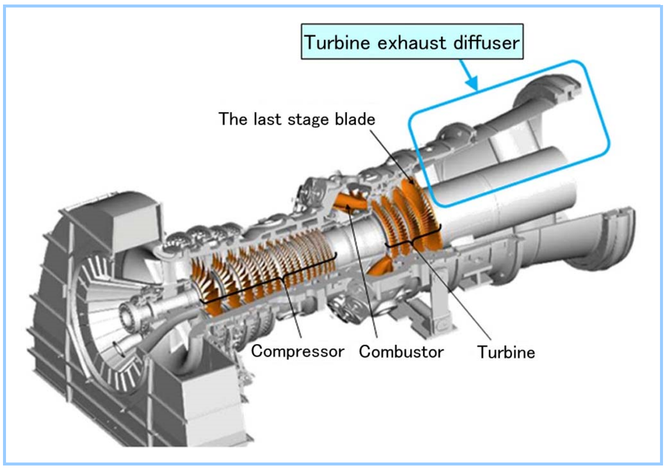

Figure 7 Turbine exhaust diffuser

Especially under the low-load condition where the flow swirl angle increases, a large amount of separation occurs on the inner wall (ID) of the diffuser, resulting in a substantial reduction in the performance of the exhaust diffuser (**Figure 8**). Concerning this issue, we clarified from the results of simulations and measurements, that the large separation is associated with the vortex structure which appears in the vicinity of the inner wall face (ID wall face) of the flow path between the struts[4] (**Figure 9**). In addition, it was verified through flow analysis and measurements that even under the same partial load condition, the large amount of separation can be effectively reduced by controlling the vortex structure between the struts (**Figure 10**).

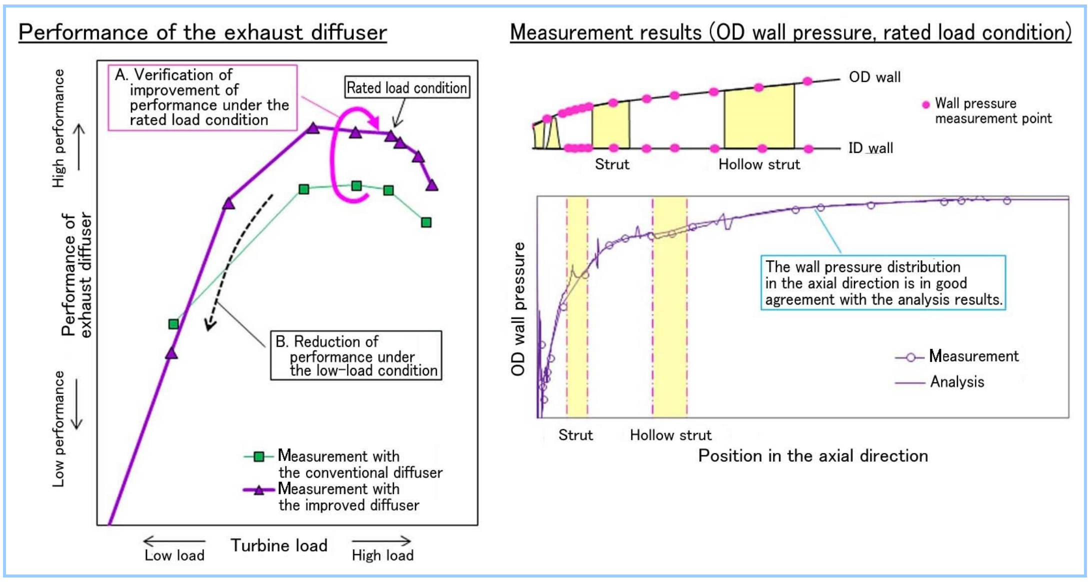

Figure 8 Verification of performance of the improved turbine exhaust diffuser

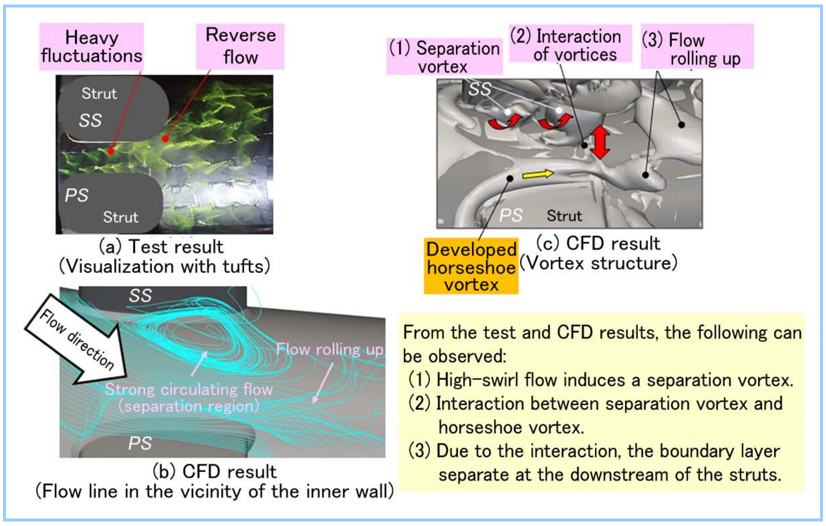

Figure 9 Flow structure in the diffuser strut inner wall (low-load condition)

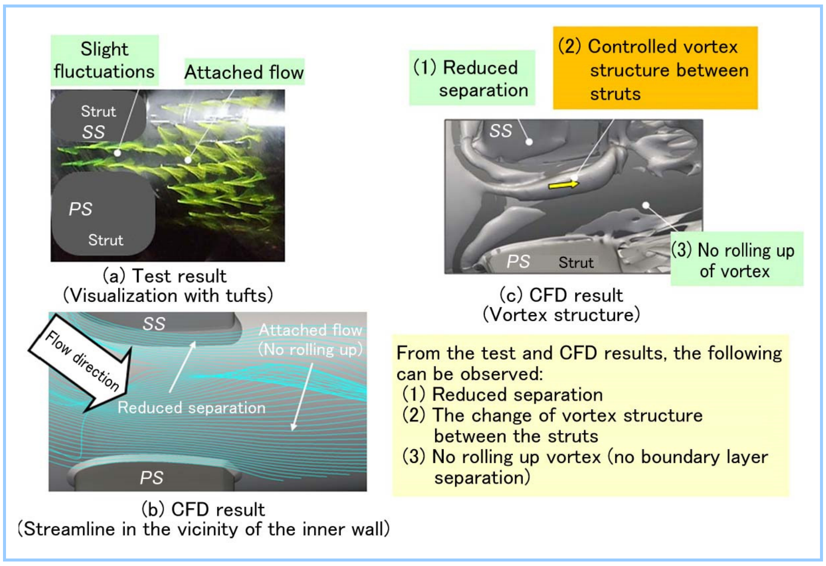

Figure 10 Effects in cases where the vortex structure is controlled (low-load condition)

2.4 Development of high-performance cooling system

A turbine blade leading edge has a cooling structure called a showerhead film hole, and a relatively large amount of cooling airflow is used. Therefore, it is expected that there is room for the reduction of airflow. By measuring the local cooling efficiency at this point, a more appropriate cooling system can be adopted depending on the cooling structure, resulting in the reduction of the cooling airflow and the improvement of performance.

As such, using a test rig that simulates the combustor and a single-stage stationary blade of an actual gas turbine (**Figure 11**), we obtained the efficiency distribution of the film around the stationary blade leading edge (**Figure 12**). We will pursue the study of further cooling airflow reduction based on these measurement results in the future.

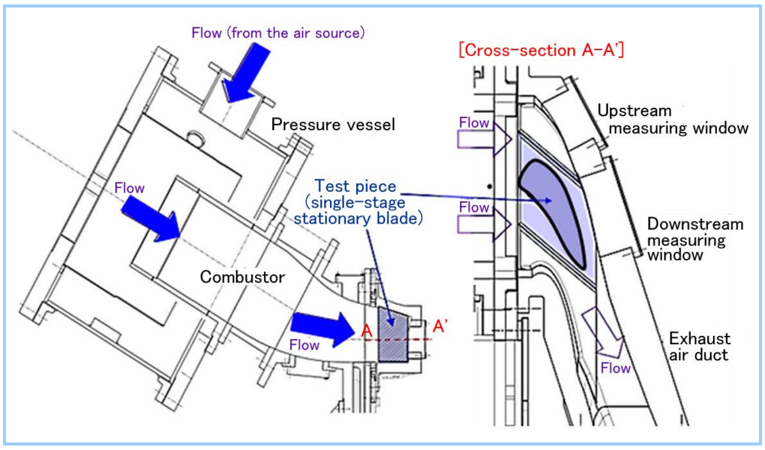

Figure 11 Schematic diagram of the device

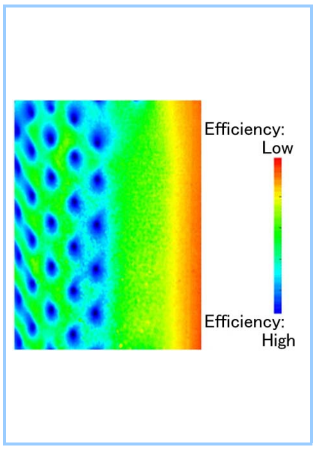

Figure 12 Test results (Film efficiency distribution)

2.5 Development of strength evaluation technology at ultrahigh-temperature

In a 1700°C-class gas turbine, the metal temperature rises, and therefore, DS (Directionally Solidified) materials, which have already been applied, and SC (Single Crystal) materials need to be used, from the viewpoint of high strength at high temperature. For DS and SC materials, the crystals of these materials have grown in a certain direction during casting. Therefore, in the strength evaluation, the anisotropy needs to be considered. On the other hand, as the metal temperature rises, the cooling performance is intensified, and especially at stress concentration areas such as cooling holes, a high amount of stress is generated. Therefore, a highly reliable and reasonable thermal fatigue evaluation method is required. To this end, through the thermal fatigue test using a test piece which simulated the stress concentration at the thermal stress field (Figure 13), we have identified the effects of the crystal growing direction and the cooling hole shape on the crack initiation life[5] and we will reflect the results in the thermal fatigue life evaluation method (**Figure 14**).

In addition, when the metal temperature is high, the material strength inevitably changes. Therefore, long-term reliability at such a high temperature is required. To this end, we have checked the material strength using a deteriorated simulation material prepared assuming that it was used in an actual unit at a high temperature for a long time, and we are developing a method of quantitatively evaluating the deterioration state after operation.

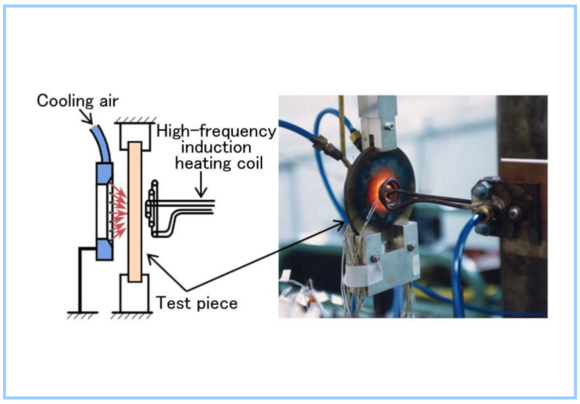

Figure 13 Apparatus of the thermal fatigue test

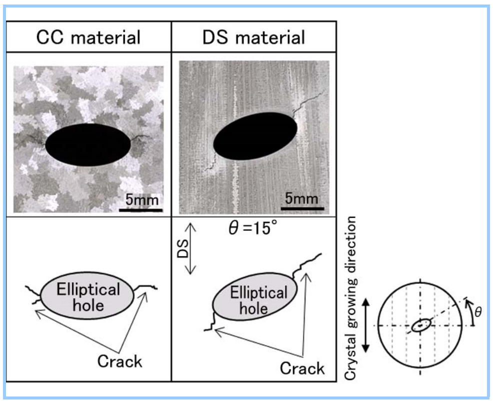

Figure 14 Thermal fatigue test results

2.6 Development of advanced thermal barrier coating

Toward the development of 1700°C-class gas turbines, we have consistently conducted material development, the optimization of thermal spraying process parameters, the development of a program for application to actual blades, and verification with an actual unit, and have also developed an advanced thermal barrier coating (hereinafter referred to as TBC) and implemented a further improvement in performance. Using the material calculation system based on the electronic structure, we conducted a computational study of candidate materials with low-thermal conductivity and superior high-temperature stability and tried to manufacture the sintered bodies with the compositions of the candidate materials and evaluated them. As a result, materials with low-thermal conductivity and superior high-temperature stability were extracted[(6)] (**Figure 15**).

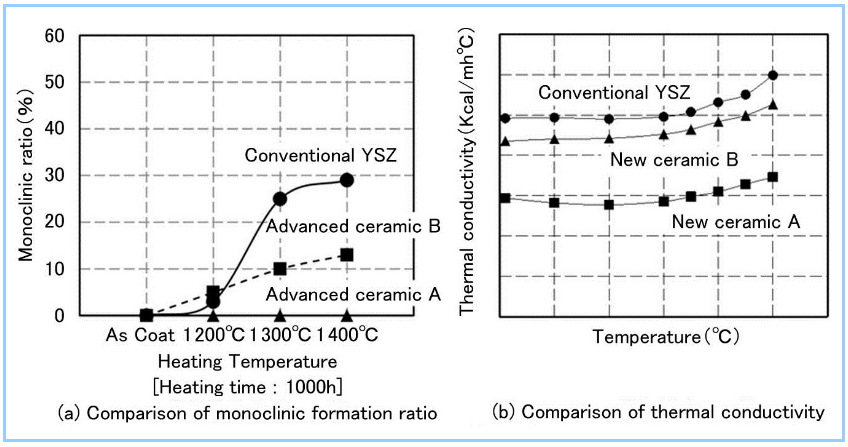

Figure 15 Measurement results of high-temperature stability and thermal conductivity of the topcoat materials (sintered bodies)

TBC used in industrial gas turbines is generally formed by the thermal spray method. Therefore, in cases where a new material is used, the spray process parameters need to be optimized. We conducted particle state measurement during spraying and in situ observation of the deposition state of the particles, evaluated TBC performances such as thermal conductivity, spallation durability, erosion resistance and oxidation resistance, identified the correlation and reflected it in the process improvement, so that the target coating performances were achieved. The hot parts of turbines have complex three-dimensional shapes, and so it is not easy to spray coating on the whole blade face as ideally and homogeneously as on the test piece. Therefore, an ideal robot program was obtained through simulation using CAD in advance, which was then reflected in the actual TBC program. The TBC microstructure on the actual parts was evaluated by destructive testing. Thus, we could shorten the lead time to develop the robot program for the actual blades. For advanced TBC, we conducted long-term verification using a demonstration power generation facility and confirmed its high thermal barrier property and reliability equivalent to the test piece[7] (**Figure 16**).

Figure 16 Verification with the actual equipment at the demonstration power generation facility

2.7 Development of advanced manufacturing technologies

(1) Welding repair technology for components subject to high-temperatures[8]

Whenever the turbine blades are damaged during operation, they are repaired for continuous use until the end of their lifetime. Accordingly, the establishment of a repair technology for the newly developed single-crystal alloy MGA1700 is also indispensable. To this end, as a tool to determine the welding conditions under which the repaired weld part forms a monocrystalline structure, MHPS and MHI considered the use of numerical simulation to estimate the geometry of a weld bead and visualize the area of the monocrystalline structure within the bead.

LMD (Laser Metal Deposition; Figure 17) by which dilution with the base material is easily controlled, was used for welding, and an analysis was conducted using general-purpose thermal fluid analysis software (Flow-3D). The welding consumable used was a powder with the same composition as the base material (MGA1700).

To produce a weld metal structure with the same single-crystal orientation as the base material, it is necessary to appropriately control the temperature gradient (G) and the rate of solidification (R) in the fusion boundary and results in a large G/R value during solidification. Accordingly, through the analysis, the area where a single crystal structure produced on the fusion boundary face to the base metal can normally grow was estimated from the G/R value. The estimation results for the height of the sound growth area under each welding condition are shown in **Figure 18**. In Figure 18, welding is not applicable in the lower right zone because the welding heat input is too little, and welding is not applicable in the upper left zone because the welding heat input is excessive. It was found that the welding operation should be controlled so that the laser output is increased and the welding speed is reduced to increase the area where the weld metal is made into a single crystal structure with the same crystal orientation as the base metal.

The structure of the cross section of the bead in the case of LMD applied under the proper conditions obtained by the analysis is shown in **Figure 19**. Since the weld metal portion exhibits a sound single crystal structure, it was confirmed that good results were obtained.

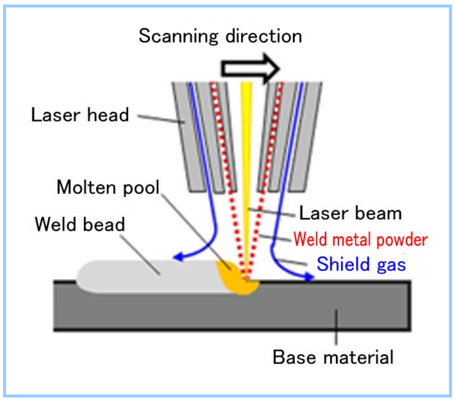

Figure 17 Schematic diagram of LMD

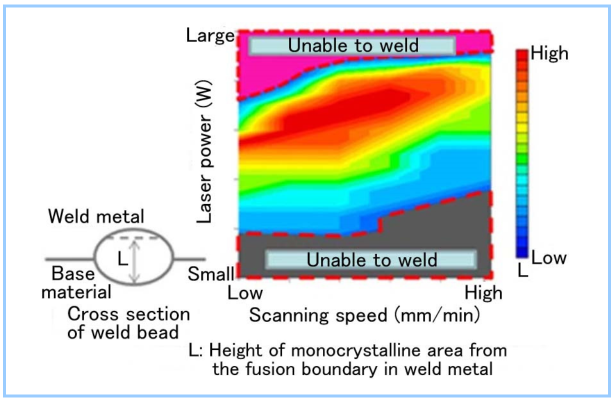

Figure 18 Relationship between the LMD condition and range of monocrystalline growth

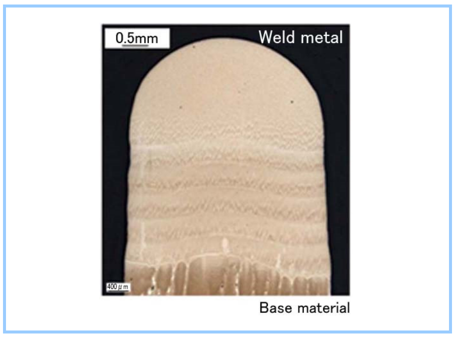

Figure 19 Cross section of the weld bead microstructure

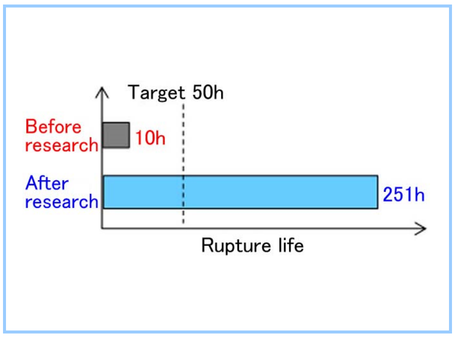

Figure 20 High-temperature creep rupture test results

(2) Additive manufacturing technology for hot parts

With the aim of improving the performance of the gas turbine by the reduction of the cooling air volume of the gas turbine hot parts (blade, vane, ring segment), we developed additive manufacturing technology for complex cooling structures through which the existing processing technologies cannot be manufactured. To ensure the material strength of additive manufactured products, which is one of the problems, we adjusted the material composition and optimized the building conditions and heat treatment processes. As a result, we ensured the required strength of the additive manufactured products in a high-temperature environment (Figure 20). We plan to develop high-precision building technologies for hot parts with complex cooling structures in the future.

(3) Turbine blade material and casting technology[1, 9]

We developed a super heat-resistant material for single crystal blades in collaboration research with the National Institute for Materials Science (NIMS). The new single crystal alloy named MGA1700 has excellent creep strength and dwell thermo-mechanical fatigue strength (Figure 21). MGA1700 is a superior alloy in terms of its good mechanical properties without the expensive element rhenium.

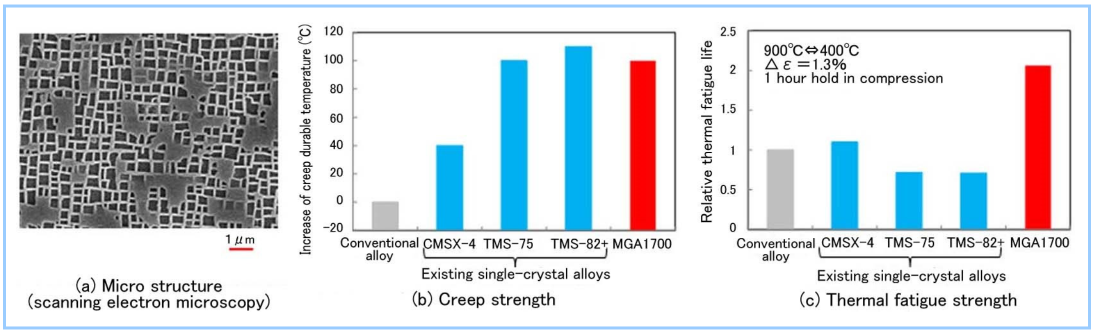

Figure 21 Micro structure and high-temperature mechanical properties of the developed alloy

In addition to the material development, we developed various simulation technologies for casting processes of directionally solidified blades (include uni-directionally solidified blades and single crystal blades) (Figure 22). By using these simulation technologies, we can predict not only casting defect generation, but also phenomena in each casting process, such as the plastic flow behavior in the core injection molding process. As a result, the condition optimization of the overall casting process and the improvement of casting quality were realized.

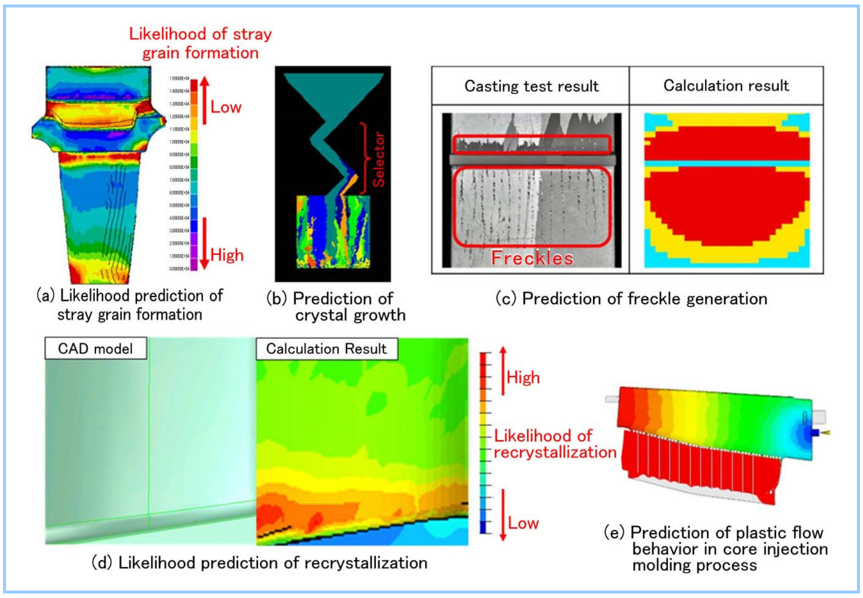

Figure 22 Simulation (calculation) results for each casting process

2.8 High-precision/high-functionality inspection technologies

(1) Wireless power supply technology on wireless sensing

Strain data is wirelessly transmitted to measure the vibration of the moving blade which is rotating at high speed. We developed a module that can wirelessly receive the electric power required for the measurement/transmission (**Figure 23**). High-frequency electric power is received from the antenna on the front face, and DC voltage is supplied to the strain measuring amplifier and the data transmitter in the same module. Changing batteries becomes unnecessary, and continuous measurement becomes possible. This method has the advantage that the high-frequency power transmission enables power transmission over longer distances compared to the electromagnetic induced method.

(2) Blade inside surface defect detection technology[10]

In gas turbine blade defect inspection, technology for the detection of defects at invisible positions such as the cooling passage face side is important in terms of ensuring the reliability of the turbine blade. Therefore, the matrix array UT probe, which has an improved focusing property of the ultrasonic beam, was developed as a tool for accurately inspecting any defects of the blade inner surface from the blade outer surface side (**Figure 24**). In an inspection of an actual blade, the UT probe is attached to a 3D scanner and the blade face is scanned, allowing the rapid defect inspection of the inner surface side (**Figure 25**).

Figure 23 Appearance of the wireless power supply type transmission module

Figure 24 Appearance of the matrix array UT probe

Figure 25 Blade surface scanning state

3. Conclusion

This article describes part of the high-efficiency gas turbine technology demonstration project (the development of ultra-high efficiency 1700°C-class gas turbines) which is under implementation as a project subsidized by New Energy and Industrial Technology Development Organization (NEDO), and we are developing technologies to be applied to the actual equipment toward the development and demonstration of key technologies required for actual use. Various technologies for the improvement of performance and technologies for an increase in reliability under severe conditions such as high temperature/high pressure and for manufacturing and inspection are under development. Some of the latest technologies, for which the effectiveness was recognized through technical studies and verifications, have been applied to the development of the 1600°C-class J-series gas turbine and next-generation high-efficiency gas turbines. At the same time, the obtained long-term operation data is reflected in research to improve the reliability of the developed technologies. Through the diffusion of the latest combined cycle power generation technologies, we would like to greatly contribute to the reduction of CO_2 emissions at thermal power generation plants.

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