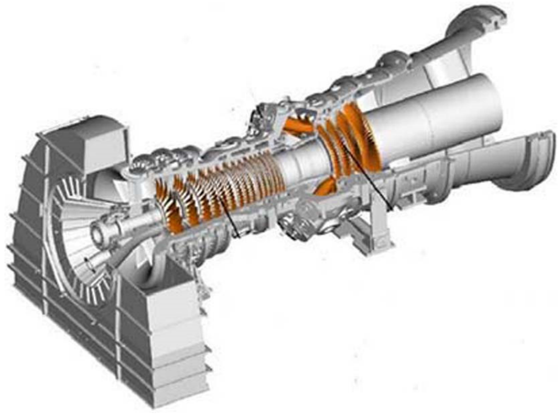
Development of Advanced Materials and Manufacturing Technologies for High-efficiency Gas Turbines



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The market for gas turbine combined cycle (GTCC) power generation is expected to grow on a long-term basis as the cleanest and most economic thermal power generating system that can coexist with renewable energy. To further achieve further efficiency, it is essential to improve the properties of turbine component materials and develop manufacturing technologies for building the complicated structures required by advanced blade design. This report presents the development of technologies including alloy design and casting, coating, welding repair, and cooling-hole drilling processes, as material and manufacturing technologies for the higher-temperature application of gas turbines.

1. Introduction

In recent years global energy demand is increasing markedly, especially in Asian countries such as China and India. It is predicted that global energy consumption in 2035 will reach a level approximately 1.5 times higher than that of 2010. In Japan, the energy self-sufficiency rate is less than 10% and it is an issue of urgency to improve energy use efficiency and reduce environmental load. In particular, thermal power generation, which is currently responsible for nearly 90% of the electricity production in Japan, should be made more efficient. Power generation efficiency is significantly affected by the firing temperature of gas turbine (the main component of the system). Because the thermal cycle efficiency can be improved as the temperature rises, Mitsubishi Hitachi Power Systems, Ltd. (MHPS) has developed advanced systems with higher temperatures/ better efficiency and larger capacities since the early 1980s.

As shown in **Figure 1**[1], the turbine inlet temperatures started with a 1,100°C-class in 1984 (Type D), followed by a 1,350°C-class in 1989 (Type F) and a 1,500°C-class in 1997 (Type G). Further in 2011, 1,600°C-class gas turbines (Type J) were launched.[2] The national project "Elemental Technology Development for 1,700°C-class Gas Turbine" started in fiscal 2004. In developing the Type J gas turbines, the project results such as advanced thermal barrier coating (TBC) and cooling/aerodynamic technologies were also utilized (**Figure 2**).

To further elevate the gas turbine temperature, it is critical to design a new material that can withstand such high temperatures, improve the properties of turbine components and invent manufacturing technologies for building complicated structures required by advanced blade design. This report introduces these technologies that MHPS is developing with Mitsubishi Heavy Industries, Ltd. (MHI) Research & Innovation Center.

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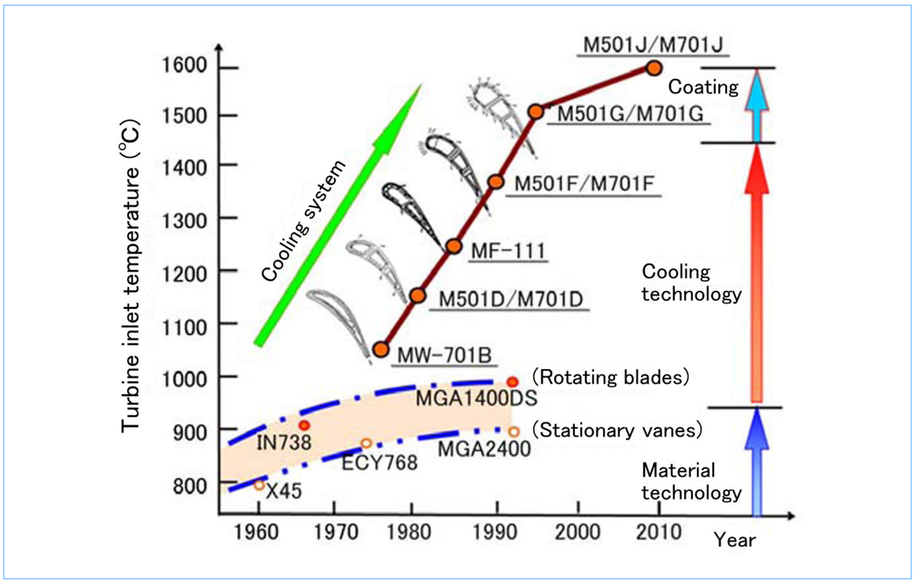


Figure 1 Increase in the turbine inlet temperature and transition of applied materials and technologies

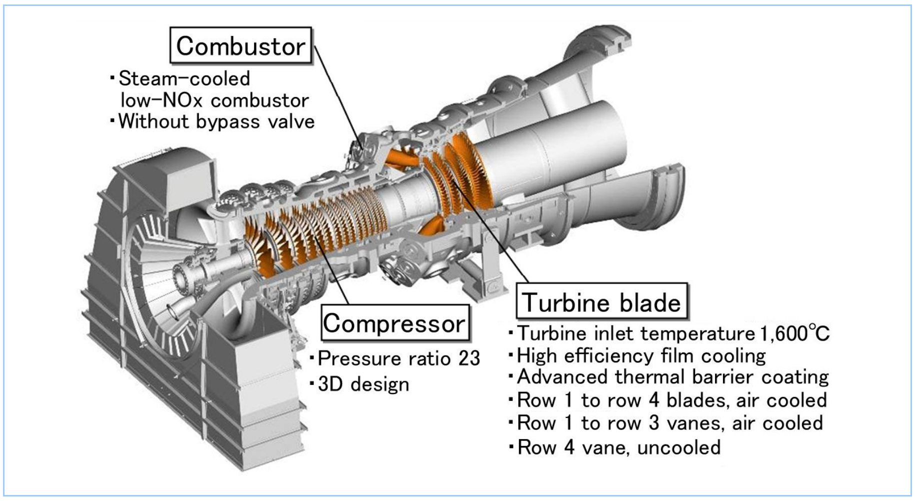


Figure 2 Characteristics of the M501J gas turbine

2. Turbine blade material and casting technology

2.1 Design of turbine blade materials

MHPS and MHI have developed MGA1400, MGA1400DS and MGA2400 as high-strength Ni-base superalloys that are durable enough to be used in high-temperature environments and applied them for their products. Generally, depending on the casting method, superalloys used in turbine blades are classified as one of the following: conventional cast alloys, directionally solidified alloys, and single crystal alloys. Of these three types, MGA1400 and MGA2400 fall under the category of conventional cast alloys, whereas MGA1400DS is a directionally solidified alloy.[3] The single crystal alloy is the strongest because there are no grain boundaries (their presence is disadvantageous in terms of material strength) and the alloy composition can be optimized without considering grain-boundary strengthening. However, as casting defects produced in the casting process can greatly lower the strength, the establishment of manufacturing technology is important. As industrial gas turbine blades are larger in size, they are more difficult to manufacture than those for aircraft engines.

With a view to building 1700°C-class gas turbines, MHI Research & Innovation Center conducted joint research with the National Institute for Materials Science (NIMS) to develop highly heat-resistant materials for single-crystal blades. It is essential to not only verify the material strength at high temperatures, but also develop a casting technology to obtain a good monocrystalline structure with no defects. The new material should also be satisfactory in terms of economy including raw material and casting costs. It also needs to exhibit all the required material properties at high temperatures (e.g., creep strength, thermal fatigue strength and oxidation resistance). Especially challenging was the development of technology to realize the coexistence of creep strength and thermal fatigue strength. While examining a test alloy with a composition that was determined by the NIMS alloy design program, MHI and NIMS collected data mainly on thermal fatigue strength to augment the database for property prediction. Such efforts enabled the development of MGA1700, which is a single-crystal alloy with excellent properties of both creep strength and thermal fatigue strength (**Figure 3**). Unlike other single-crystal alloys with high strength, which usually contain expensive rare metals such as rhenium, MGA1700 is a groundbreaking alloy that realizes high strength without containing rhenium.

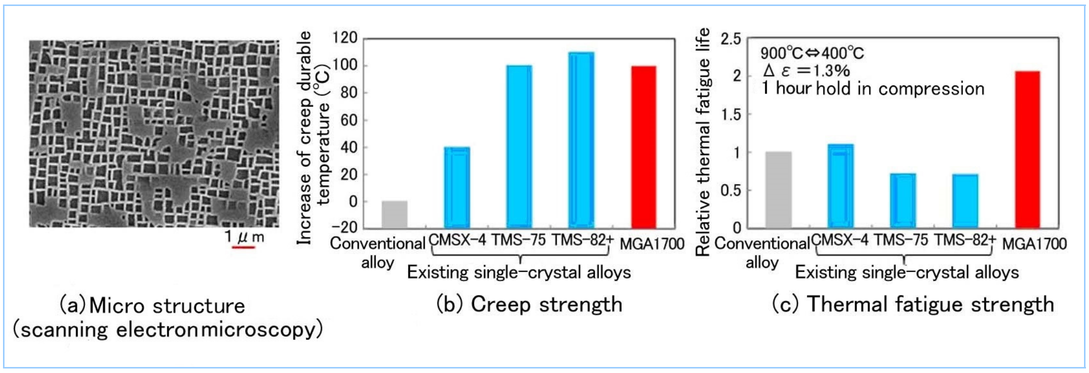


Figure 3 Micro structure and high-temperature strength property of the designed alloy

2.2 Casting technology

In addition to the material design, MHI has undertaken research on casting simulation technology to predict the formation of casting defects in directionally-solidified blades (unidirectionally-solidified and single-crystal blades), in order to optimize casting conditions and improve quality (**Figure 4** &**5**).

(a) Likelihood prediction of stray grain formation

A stray grain is produced as a result of new crystalline nucleation and its growth in the solidification process when a crystal, which has formed at the bottom of the cast, grows straight upward. The formation of stray grains occurs when the balance between cast solidification speed and temperature gradient during solidification is disrupted. Therefore, it can be predicted by examining these parameters based on solidification heat transfer analysis.

(b) Prediction of crystal growth

For single-crystal blades, casting conditions need to be determined in detail to allow crystals to properly form/grow at the bottom of a mold and let the right grain selection take place in the selector. Such crystallization can also be calculated for prediction.

(c) Prediction of freckle formation

Likewise, the formation of freckles, a type of casting defect in directionally-solidified blades, is initiated when the normal crystal growth is inhibited because of the convection resulting from the local deviation of the specific gravity of molten alloy, caused by concentration fluctuations during solidification. The likelihood of freckle formation can be predicted by assessing factors such as changes in the molten alloy density during solidification and the spacing of dendrites that can prevent molten alloy convection.

(d) Likelihood prediction of recrystallization

When residual strain, produced in the course of cast solidification/cooling, exceeds the limit, it can induce recrystallization in the later stage of the process (i.e., during thermal treatment), lowering the strength of the affected area. FEM elasto-plastic analysis at the time of casting was conducted on the mold, the cast and other mold-support structures. Based on the calculation results of the post-casting residual plastic strain, MHI developed a technology to predict the likelihood of recrystallization.

Making full use of these simulation technologies, MHI designed the mold shape, determined casting conditions and built a large single-crystal test blade using MGA1700 alloy (**Figure 6**). As there was no noticeable distortion of crystals or casting defects, the ability of casting unblemished single-crystal blades was successfully demonstrated.

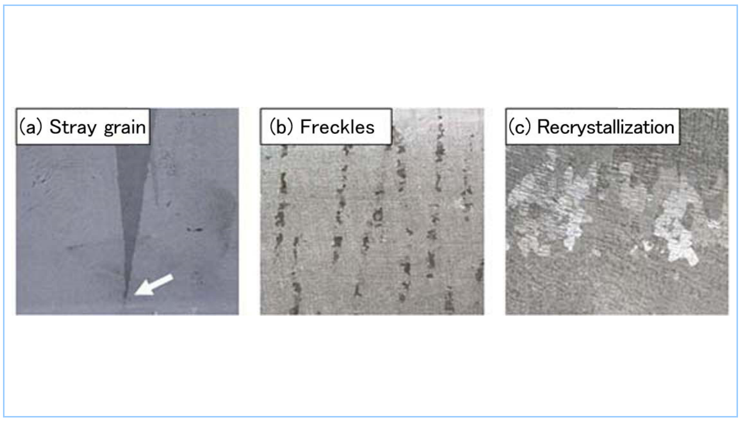


Figure 4 Casting defects in directionally-solidified or single-crystal blades

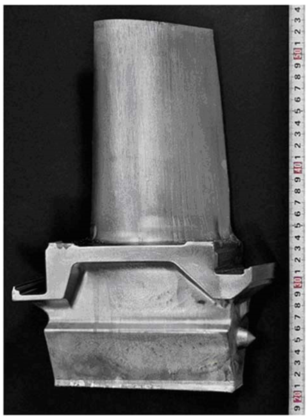


Figure 6 Large single-crystal trial cast blade

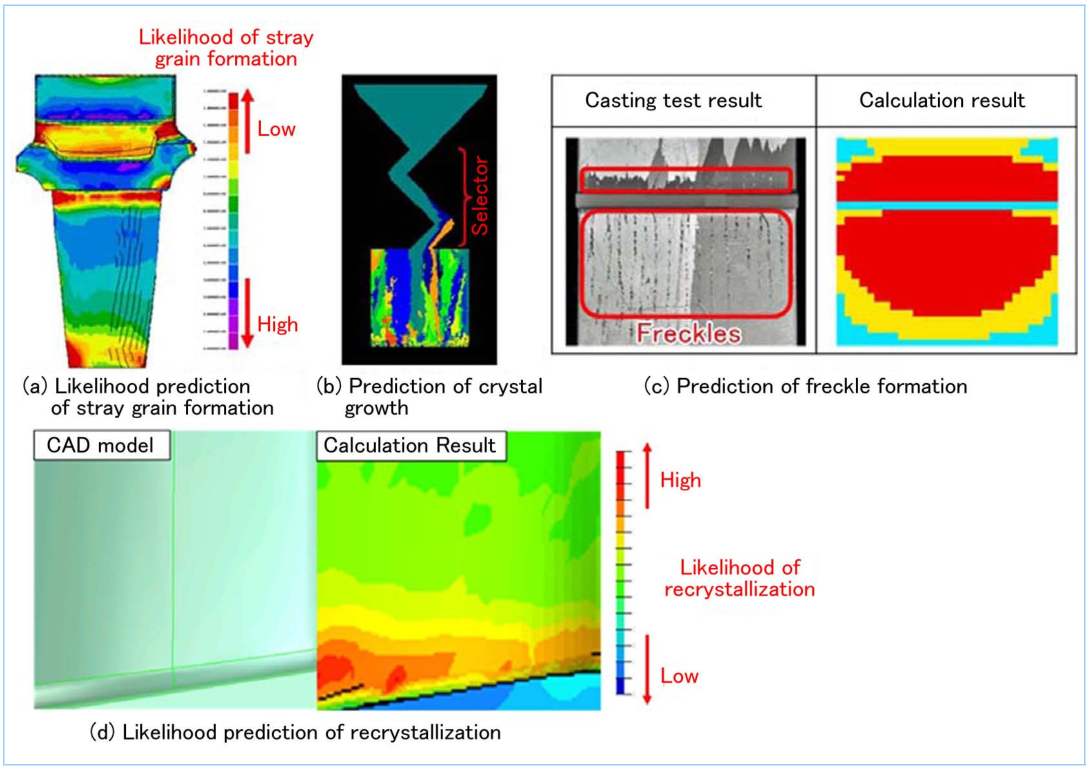


Figure 5 Casting simulation (calculation) results

3. Thermal barrier coating technology

As shown in Figure 1, the increase rate of the gas turbine inlet temperature is far greater than that of the upper temperature limit of superalloys. This rapid increase in inlet temperature has been managed by improving cooling and coating technologies. The latest 1600°C-class Type J gas turbines have adopted the advanced TBC, which was developed as part of the national project as mentioned earlier. Given below are the material design for advanced TBC and its application technologies.

3.1 Material design for advanced TBC

In designing the material composition, MHI's material calculation system based on electron structures was used to determine possible materials that can exhibit high temperature stability, low thermal conductivity. Sintered bodies with the selected material composition were prepared, and their thermal conductivity and high-temperature stability were examined. MHI and MHPS succeeded in identifying the best possible material that has a lower thermal conductivity than the conventional one (i.e., yttria partially stabilized zirconia). When it comes to stability at high temperatures, it can prevent the formation of undesired monoclinic phase even in high-temperature environments (**Figure 7**).

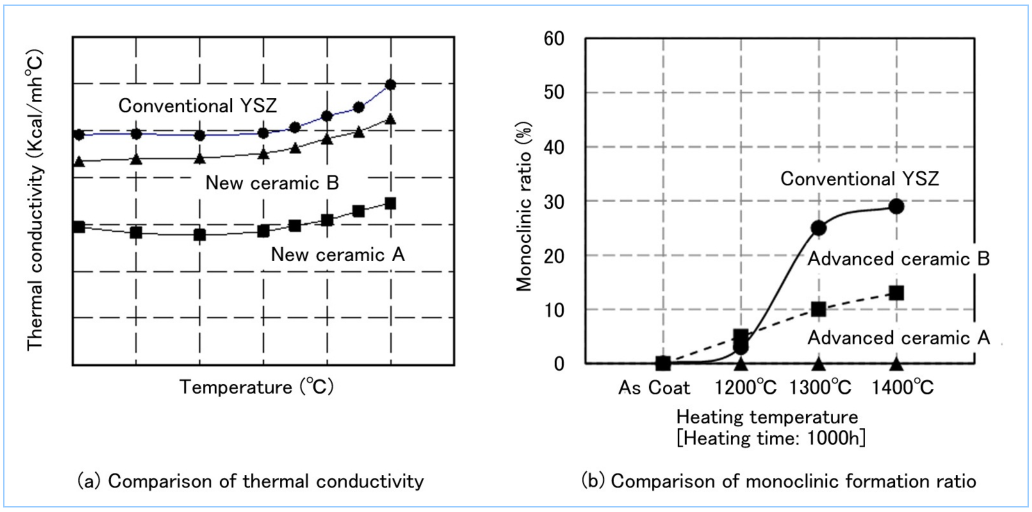


Figure 7 Measurement results of high-temperature stability and thermal conductivity of top coat materials (sintered bodies)

TBC is applied by thermal spraying. The introduction of micro scale pores in the coatings enables the formation of coatings with a lower thermal conductivity than sintered bodies. However, the presence of too many pores can induce abrasion due to erosion or cause early coating spallation under the actual operating conditions of high temperature and high flow rate, which in itself may lead to the loss of thermal barrier effectiveness. The next issue is therefore the development of a coating technology including the optimization of thermal spraying conditions. As shown in **Figure 8** (a), the thermal cycle resistance of coatings is examined by the laser thermal cycle test and with the simultaneous measurement of temperature, thermal conductivity is also evaluated. MHI developed high-temperature erosion test rig by which erodent particles can impinge on the coating under simulated operating conditions of high temperature and high flow rate (Figure 8 (b)). The coating erosion property is thus evaluated. With the use of such equipment, the material design for TBC was conducted while optimizing the thermal spraying conditions (which is described in the next section). The obtained coatings satisfy the required criteria of reliability and thermal barrier effectiveness.

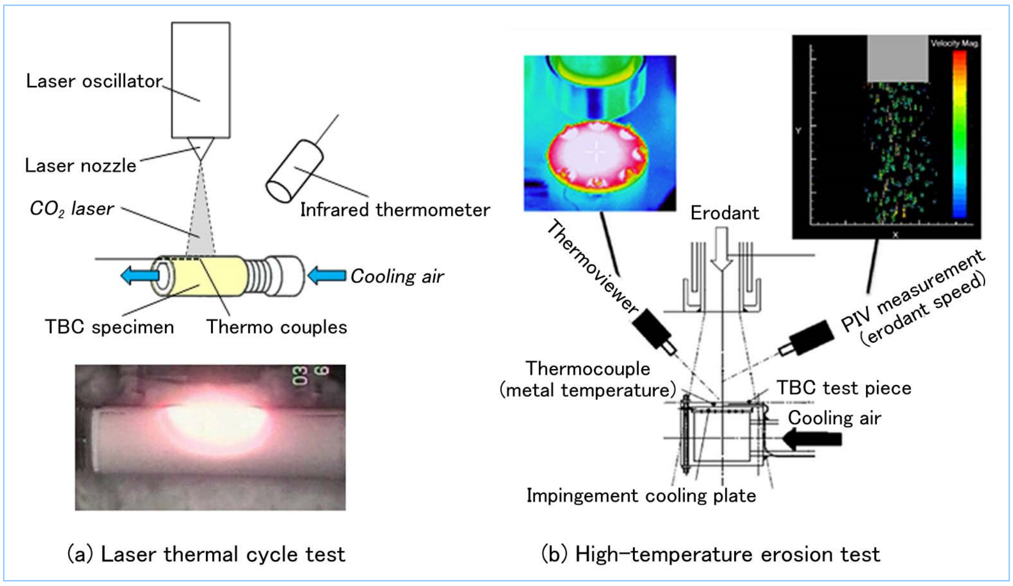


Figure 8 Evaluation test of thermal sprayed coatings

3.2 Application technology

As described earlier, changes in the thermal spraying conditions can change the micro structure of the coating, which can greatly affect the thermal barrier effectiveness and reliability of the coating. Therefore, using high-speed cameras, MHI observed how the plasma flame changed under various thermal-spraying conditions and how thermal sprayed particles impinged on the substrate and were flattened. The thermal spraying conditions have thus been optimized to prevent excess particle splashing and defect formation in the coating (**Figure 9**).

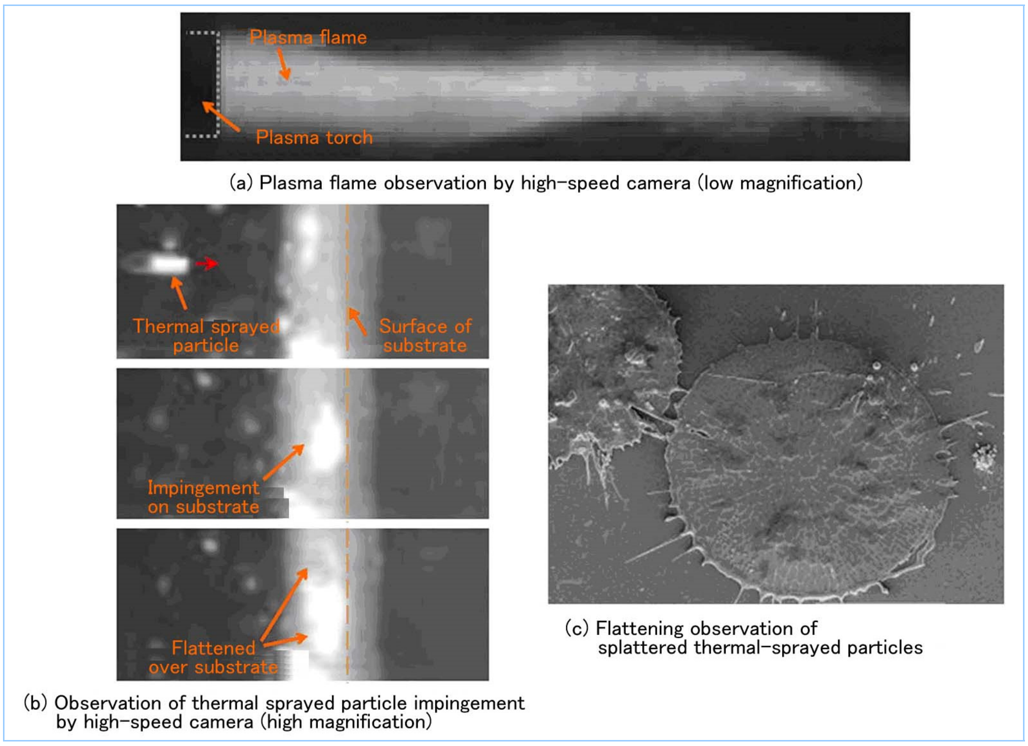


Figure 9 Observation of dispersal and flattening of thermal sprayed particles

The coatings formed in accordance with the determined thermal-spraying conditions exhibit excellent properties. However, this is the case only with objects with a simple shape such as test pieces. Turbine blades have end walls and the contour is three-dimensional. It is not easy to produce an ideal uniform coating all over the surface, as with the test pieces. To make it possible, it is necessary to execute the application technique under the same condition as the test pieces, while synchronizing the robot arm with a thermal spray gun and the turn table with a turbine blade fixed on it to stop them from interfering with each other. CAD-based robot simulation technology is used to program such complicated robotic operations (**Figure 10**).

After advanced TBC was applied to a real blade using the robot programming, a test piece from the blade was used to verify the soundness of the coating on the blade through a thermal cycle test and blade cutting inspection. The advanced TBC technology was thus completed and was applied to Type J gas turbines, which have been in operation for approximately 130000 hours (at the end of October, 2015) with excellent operational results.

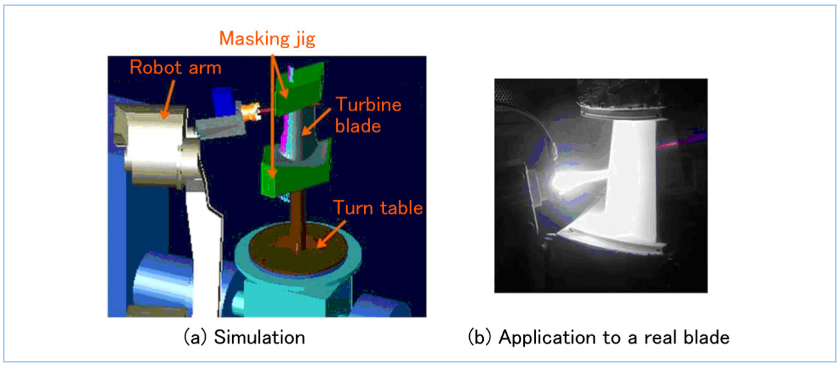


Figure 10 An example of thermal spraying programming simulation

4. Welding repair technology for components subject to high temperatures

Whenever the turbine blades are damaged during operation, they are repaired for continuous use until the end of their lifetime. It is vital to establish a repair technology for the assurance of effective gas turbine operation. As with the currently-used conventional cast alloys and directionally solidified alloys, this is also the case with our newly-developed single-crystal alloy MGA1700. From the viewpoint of maintaining the superior high-temperature strength of single-crystal alloys after repair, the structure of the repaired area should also be monocrystalline. However, when applying a widely-used repair technique (welding), it is difficult to cause the weld metal to take a monocrystalline structure and, when stray crystals are formed, they should be processed for removal.[4] 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 monocrystalline structure within the bead.

The type of welding that was employed was laser metal deposition (LMD), in which dilution with the base material is easily controllable, and the analysis was conducted using general-purpose thermal fluid analysis software (Flow-3D). **Figure 11** gives a schematic diagram of LMD. The weld material used was a powder with the same composition as the base material (MGA1700 alloy). The weld bead geometry was first predicted by analysis, and the result was compared with the actual bead geometry formed by LMD to assess the validity of the analysis. **Figure 12** gives the analytical model and a typical result of the analysis. The analysis is based on the LMD process in which the weld material is supplied to the designated site for laser irradiation and weld beads are formed by moving the laser. The blue color in the analysis results indicates the area of unmolten base material, while the red shows that the base material is completely fused. Partial fusion is represented by the transition colors between red and blue. **Figure 13** is a cross-sectional comparison between the analysis results and LMD weld beads, which shows a good correspondence with each other.

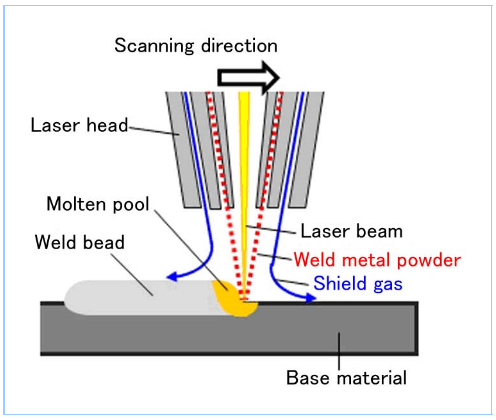


Figure 11 Schematic diagram of LMD

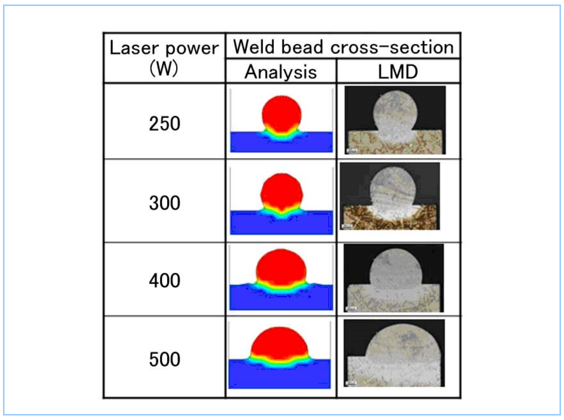


Figure 13 Cross-sectional comparison of weld beads between analysis results and LMD application

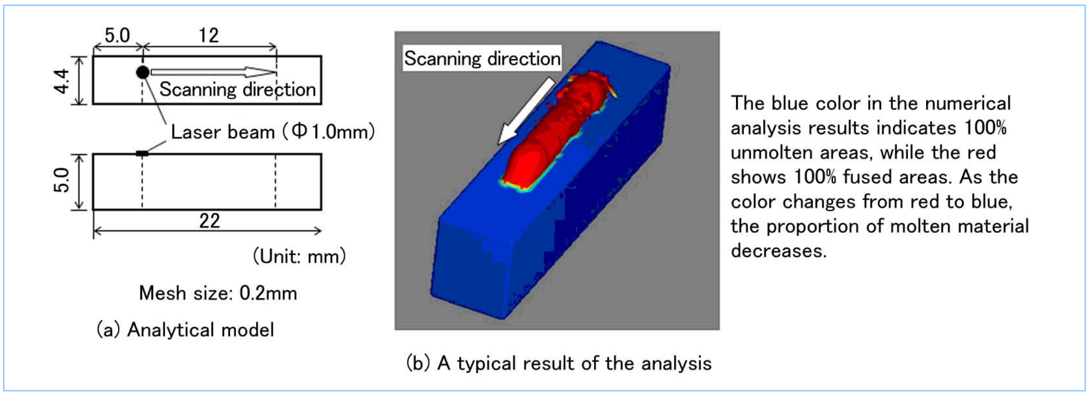


Figure 12 Analytical model and a typical result of the analysis

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 fused boundary and result in a large G/R value during solidification. The analysis was conducted to estimate G and R values in the designated areas under various LMD conditions. Specifically, based on G/R values, the areas in which monocrystalline crystals (formed on the fused boundary with the base material) can grow normally are predicted. **Figure 14** shows the results of the predicted height of normal growth under various welding conditions. The bottom right of the figure represents the application condition in which welding heat input is too small, while the upper left is the application condition in which heat input is too large, and are areas where welding could not be performed. The results indicate that, to expand the formation range of the weld metal with the same crystal orientation as the base material (i.e., monocrystalline), the laser power should be increased and the welding speed should be decreased.

LMD was applied under the appropriate conditions determined by the analysis. **Figure 15** is a cross-sectional image of the weld bead structure. It shows the normal monocrystalline structure of the weld metal, confirming that the desirable results have been obtained.

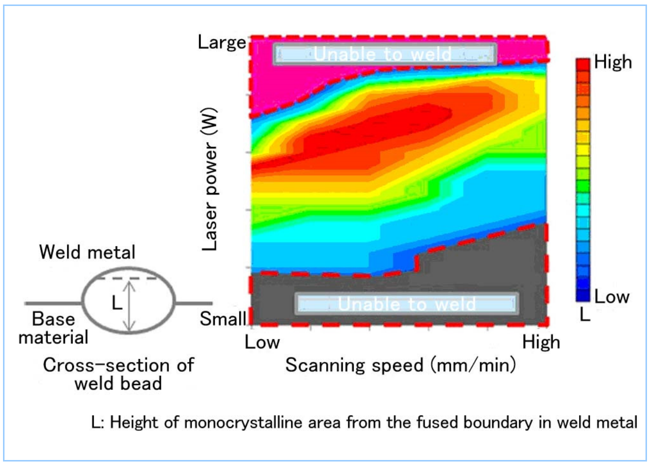


Figure 14 Relationship between LMD condition and range of monocrystalline growth

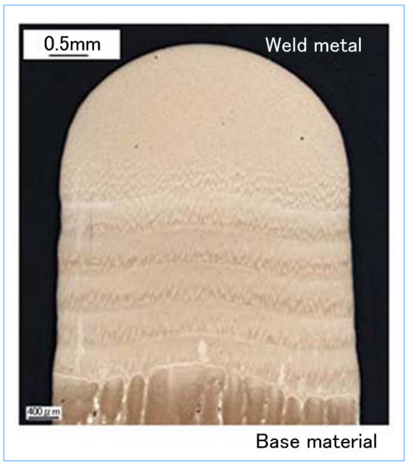


Figure 15 Cross section of the weld bead microstructure

5. Drilling technology for components subject to high temperatures

5.1 Current drilling process

Because of the durability required for high-temperature environments, TBC is applied on the surface of turbine blades, which are made of Ni-base superalloy with high strength. To create cooling holes in turbine blades (circles and shaped holes), the currently-used Ni-base superalloy is drilled through using processes such as electrical discharge machining, before the coating is thermal sprayed. Afterward, the coating is machined to drill a hole. Therefore, different drilling methods were employed for the Ni-base superalloy and TBC. This is because the coatings are non-conductive and difficult to process by electrical discharge machining. To further improve GTCC efficiency, the coating is expected to become thicker for better high-temperature resistance and the diameter of cooling holes will become smaller for better cooling efficiency. With the current process, however, difficulties in manufacturing are predicted because of problems such as the blocking of cooling holes during TBC thermal spraying. To solve these problems, it is necessary to develop a drilling technique by which the coating can be thermal sprayed on the Ni-base superalloy before drilling them together in a continuous process.

There are mainly two types of cooling-hole shapes: round holes and shaped holes. In developing a continuous process of drilling the TBC-sprayed Ni-base superalloy using lasers, MHPS and MHI used round holes (which were simpler in shape) for the verification of this component technology. The drilling verification test was conducted using a thin sheet (Ni-base superalloy: roughly 1 mm in thickness) as a test material for demonstration.

5.2 Two-stage processing by short-pulse/fiber lasers

Laser processing is applicable to both the Ni-base superalloy and TBC (non-conductive) and thus is suitable as a process for treating both types of materials.[5] In thermal processing with high output lasers such as fiber lasers, energy is concentrated in a micro area to cause the target area of the work piece to melt and evaporate. It is advantageous in terms of processing speed, but can cause difficulty in maintaining sufficient processing quality in some types of work pieces because of its high energy density. As TBC is vulnerable to heat, it is difficult to maintain the processing quality when these coatings are thermally processed by fiber lasers.[6] On the other hand, short-pulse lasers have a pulse width ranging from femtoseconds to several hundred nanoseconds, which is significantly shorter than that of high output lasers (milliseconds to continuous waves). Therefore, in contrast to high output lasers being used for thermal processing, short-pulse lasers excel at non-thermal processing with the minimized thermal impact and high quality, but the output is lower than thermal processing lasers and sufficient processing speed is difficult to attain.

Table 1 gives the characteristics of short-pulse lasers and fiber lasers. Making use of the advantageous features of each laser oscillator, MHI have developed a two-stage processing method in which the coatings are drilled through using short-pulse lasers (i.e., high quality by non-thermal processing) and the Ni-base superalloy is drilled through using fiber lasers (high speed processing). The optical system in two-stage processing consists of the prism rotator, which is MHI's proprietary technology suitable for high-speed, high-quality processing (**Figure 16**).[7]

Table 1 Characteristics of short-pulse lasers and fiber lasers

		Short-pulse laser	Fiber laser
Processing quality		Good (Non-thermal processing)	Acceptable Thermal processing
Processing speed		Acceptable (Insufficient power)	Good (High power)
Object to process	TBC	Good (High-quality processing)	Bad (Thermal damage)
	Ni-base superalloy	Bad (Slow processing speed)	Good (Satisfactory quality and high processing speed)

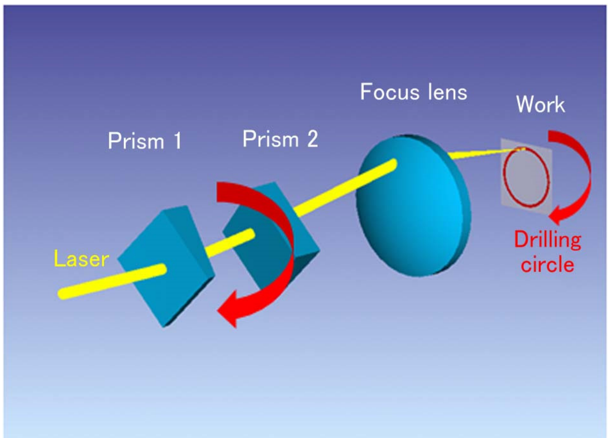


Figure 16 Prism rotator suitable for high-speed, high-quality processing

In developing this method, a processing test was conducted to drill simple round holes as the verification of two-stage processing effectiveness. **Figure 17** illustrates the mechanism of two-stage processing for the TBC-sprayed Ni-base superalloy. In Step 1, a short-pulse laser beam is radiated to the coating while rotating the beam in a circle, thereby creating a hole outlined by the red ring hatch and allowing the Ni-base superalloy underneath (which is the substrate) to be exposed. In Step 2, the Ni-base superalloy is irradiated by rotating a fiber laser beam in a circle, creating a hole outlined by the yellow hatch. The drilling process for the TBC-sprayed Ni-base superalloy is thus completed.

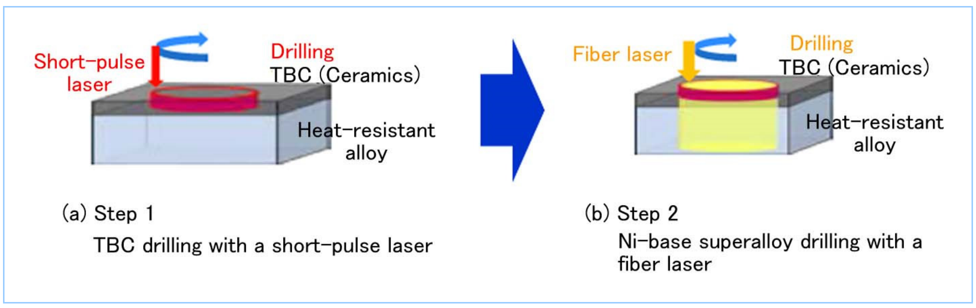
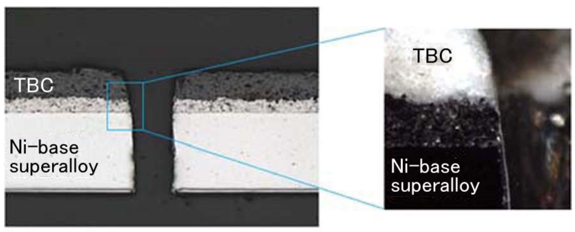


Figure 17 Processing method for two-stage drilling

5.3 Verification

Two-stage processing was applied to the TBC-sprayed Ni-base superalloy. The drilled holes are perpendicular to the surface of the substrate. **Figure 18** gives the optical-microscopic cross-sectional images of a drilled hole, which indicate that the round hole is drilled through the TBC-sprayed Ni-base superalloy. None of the defects such as cracks are seen even in the coating, which is vulnerable to heat. High-quality processing has thus been enabled.

The cooling holes in gas turbine blades are angled to achieve better cooling efficiency. When two-stage processing was applied for drilling angled round holes, the obtained results were similar to those of vertical round holes, confirming the ability of executing high-quality processing without causing thermal damage to the coating. In this verification test of the component technology (i.e., the continuous processing of the TBC-sprayed Ni-base superalloy), a simple, round hole was drilled using two-stage processing with short-pulse/fiber lasers. To create holes with complicated shapes, MHPS and MHI will develop a drilling technology with a continuous process for the TBC-sprayed Ni-base superalloy using the parts constituting the actual unit, thus further contributing to the improvement of GTCC efficiency.



(a) Whole image (b) Enlarged image

Figure 18 Microscopic cross-sectional images of a drilled hole

6. Conclusion

To deal with the increase in temperature applied to gas turbines, it is crucial to develop new materials durable enough to resist high-temperature environments, improve turbine component properties and invent manufacturing technologies to build complicated structures required by advanced blade design. This report introduced our progress in such technological development. MHPS and MHI verified the usability and effectiveness of the developed material and manufacturing technologies. Some of the latest technologies have already been used in our gas turbines. MHPS and MHI will continue to develop technologies that can improve the performance and reliability of our gas turbines and satisfy the needs of our clients, while enabling the further effective use of energy and a reduction in environmental load.

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