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Development of Metal AM technology for gas turbine components

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Abstract

Mitsubishi Heavy Industries, Ltd. (MHI) Group has been developing additive manufacturing (AM) as a method that can manufacture parts with complex shapes and considering its application to manufacturing processes. In combustor components, application of AM process to rapid prototyping and multi-cluster nozzles for hydrogen or ammonia gas fuel is being considered. In turbine parts, with the aim of improving performance by reducing the amount of cooling air, the adoption of a complex internal cooling structure, which cannot be made with conventional manufacturing methods but can only be made by AM, is being considered. This paper describes design for AM technology for gas turbine components and metal AM process technology such as building simulation based high stiffness support design and pre-set distortion, microstructure control by laser scanning conditions, quality control through in-process monitoring tools and application of AM technology to gas Turbine Components.

Introduction

While the popularization of the renewable energy advances, the importance of the gas turbine which covers the instability of the power supply increases (Toyoaki 2013). Mitsubishi Heavy Industries, Ltd. (MHI) Group has been releasing gas turbines to the market since 1962 (See Figure 1). As shown in the Figure 1, turbine inlet temperature is increasing year by year. Increasing of turbine inlet temperature of gas turbine is indispensable for improvement of power generation efficiency. To operate in such a high temperature environment, high-strength heat-resistant alloys and cooling technology are applied to hot parts such as turbine blades and combustors. Commercial operation of a state-of-the-art 1,650 Celsius degree class gas turbine has been started since 2020. Our next challenge is to develop CO_2 zero power generation technology (See Figure 2). As shown in the Figure 2, high efficiency natural gas-fired gas turbine, Ammonia Biomass Co-firing Boiler, CO_2 capture, hydrogen and ammonia gas turbine will be developed in sequence. AM process is a promising manufacturing technology to realize high efficiency gas turbine with advanced cooling design for hot parts and hydrogen or ammonia gas-fired gas turbine with advanced combustion structures.

LPBF (Laser Powder Bed Fusion), which is one of the building methods for metal AM, is a process built layer by layer with laser beam and metal powder. This method can build complex internal structures

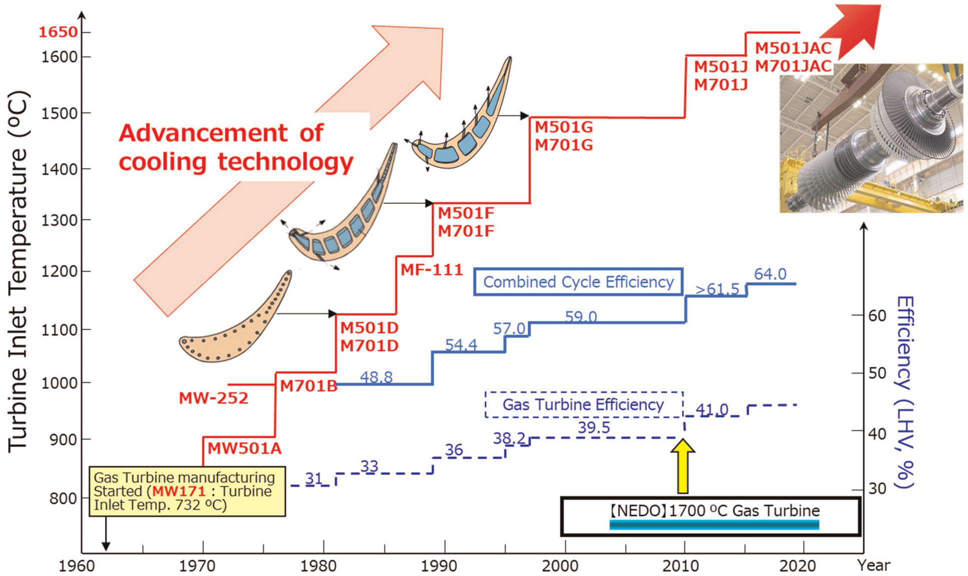

Figure 1. History of Mitsubishi gas turbine.

and is expected to be applied to innovative structural design parts. In recent years, with the increasing size of equipment, the increasing of building speed through multi-laser scanning, and the decreasing price of equipment, more parts are expected to be applicable to the AM process. MHI group has been considering the application of metal AM to various products since fiscal 2013 (Takashi et al., 2018). We are considering the adoption of a complex internal cooling structure for gas turbine components, which cannot be made with conventional manufacturing methods but can only be made by AM, with the aim of improving performance by reducing the amount of cooling air. We are also promoting the application of metal AM for realizing rapid prototyping of combustor parts to shorten the development lead time and to replace the conventional manufacturing method (integrated building of weld-assembling parts) to reduce cost. On the other hand, there are several difficulties in

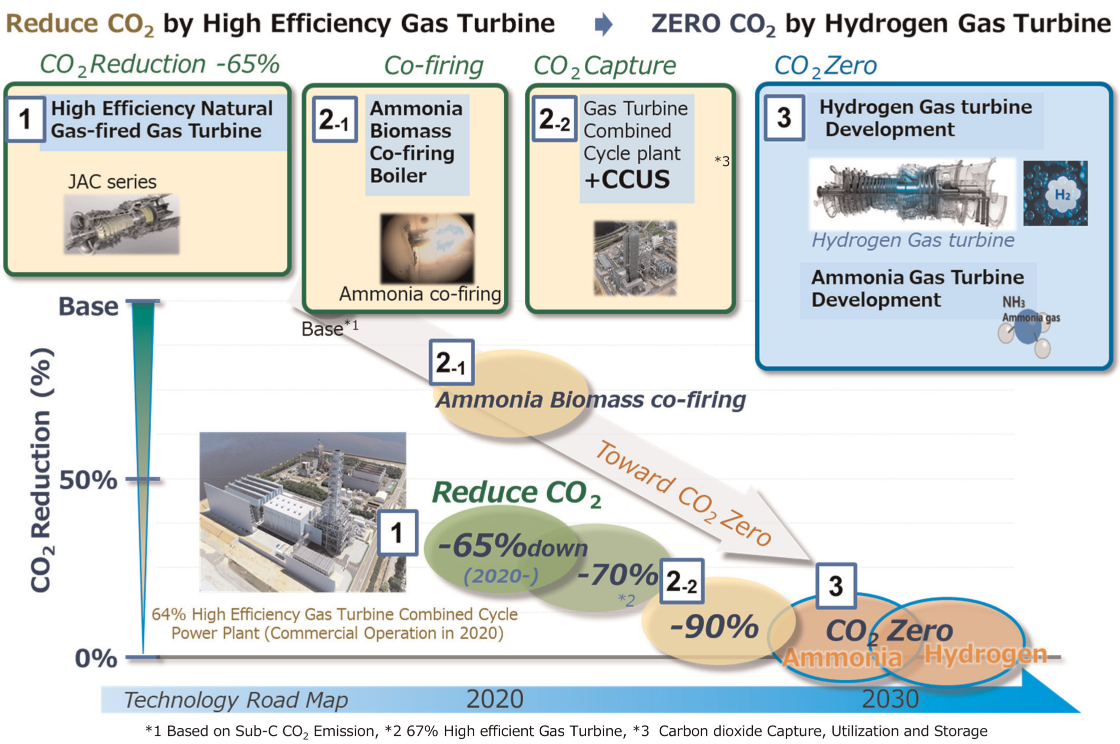

Figure 2. CO_2 zero power generation technology roadmap.

applying the metal AM process. Specifically, an innovative design concept (Adamos et al., 2021) based on the characteristics and restrictions of building objects is required. In addition, the development of AM building process such as the suppression of building distortion (Vastola et al., 2022), assurance of the material properties required for hot parts (Ashutosh et al., 2022) and quality assurance (Yavari et al., 2021) is required. This paper presents the development status of metal AM technology about design for AM and AM process for gas turbine components.

Scope for AM in GT component design

The advantages of AM are lead time reduction and complicated cooling scheme manufacturing. Lead time is reduced for any AM process, but in case of gas turbine components, it is necessary to demonstrate the applicability of AM components.

Design for AM combustor

In the AM Combustor, the development of the process cycle of AM design, building and demonstration is progressing with the aim of lead time reduction (Kota et al., 2022). Figure 3 shows gas turbine combustor AM component prototyping and Figure 4 shows combustor development cycle. In new gas turbine combustor development, such as for the low-emission and the hydrogen firing, are developed through a process of combustion test before applying actual gas turbine engine. However, it takes a couple months to manufacture prototypes because many combustor components are manufactured by sheet metal processing or welding. Therefore, utilizing the AM technology for combustor development, shortening of prototype manufacturing lead time was realized.

Design for AM turbine parts

The development of additive manufacturing technology has widely been promoted as a technique capable of manufacturing the complex shapes which could not be produced by the conventional method. To enhance the cooling efficiency of hot gas path parts is effective for performance improvement of gas turbine, and it may be realized by incorporating the advanced cooling structure using additive manufacturing technology (Julius et al., 2016). This section describes the development of additively manufactured ring segment (AM ring segment) for gas turbine applying the complex cooling structure unique to additive manufacturing.

Figure 5 shows the ring segment of gas turbine. The ring segment is a stationary component arranged annularly to surround the turbine rotor blade. It is divided in the circumferential direction to reduce thermal distortion and stress and is fixed to the blade ring on the outer circumference side. Since the inner surface of the ring segment is exposed to hot gas flow, a cooling structure is incorporated inside the ring segment, which is cooled by cooling air. Because the use of cooling air causes a decrease in gas turbine efficiency, a highly efficient cooling structure that can cool with a small amount of air is required.

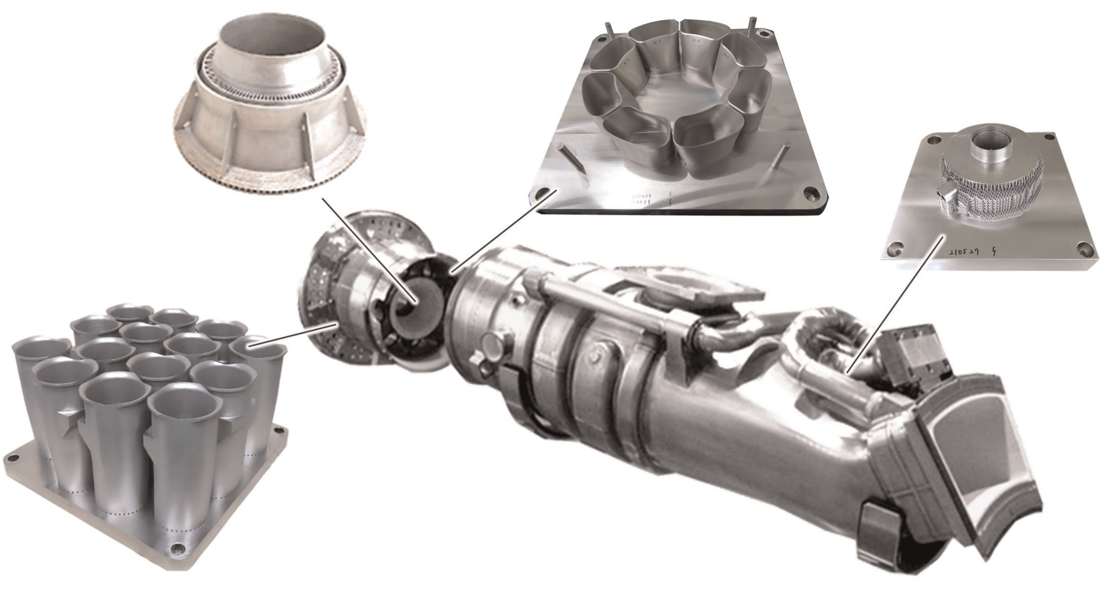

Figure 3. AM combustor for rapid prototyping.

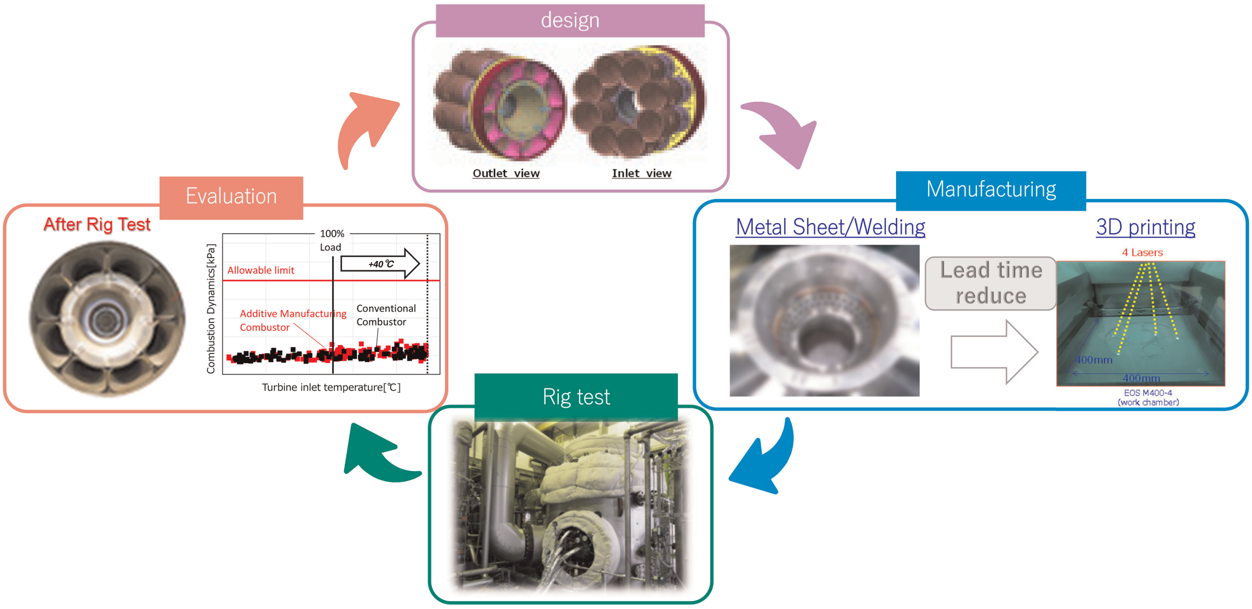

Figure 4. Gas turbine combustor development cycle with AM prototyping.

Therefore, an advanced cooling structure unique to AM was designed for the ring segment to enhance cooling efficiency. An example of the cooling structure is shown in Figure 6. By applying a complex fine cooling structure including branching and merging, which is difficult to manufacture by conventional methods, the variation of metal temperature distribution on the gas path surface was reduced and cooling performance was improved compared with conventional cooling structure. Several AM ring segments were built using metal AM process technology described in the following section.

Methodology of AM process

High-precision building technology

In the metal AM process, thermal distortion such as shrinkage, warpage and bending occurs during building (See Figure 7). Shrinkage deformation is caused by thermal shrinkage at the confluence of separately built parts. Warping up causes deformation that warps in the Z direction when heat is applied to the surface layer of parts

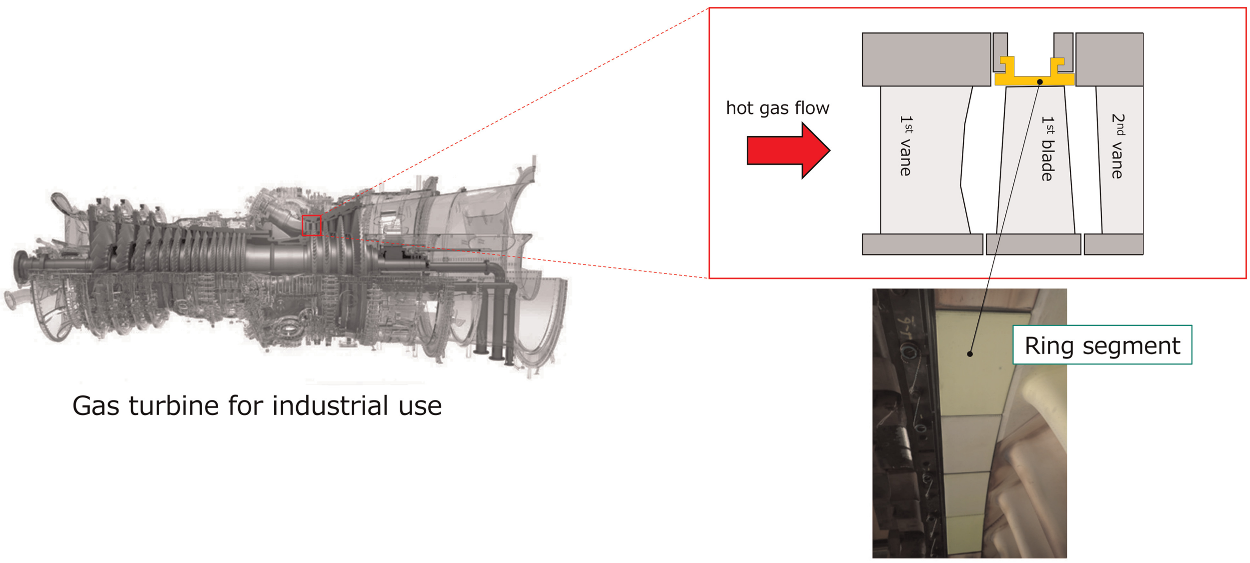

Figure 5. Ring segment of gas turbine.

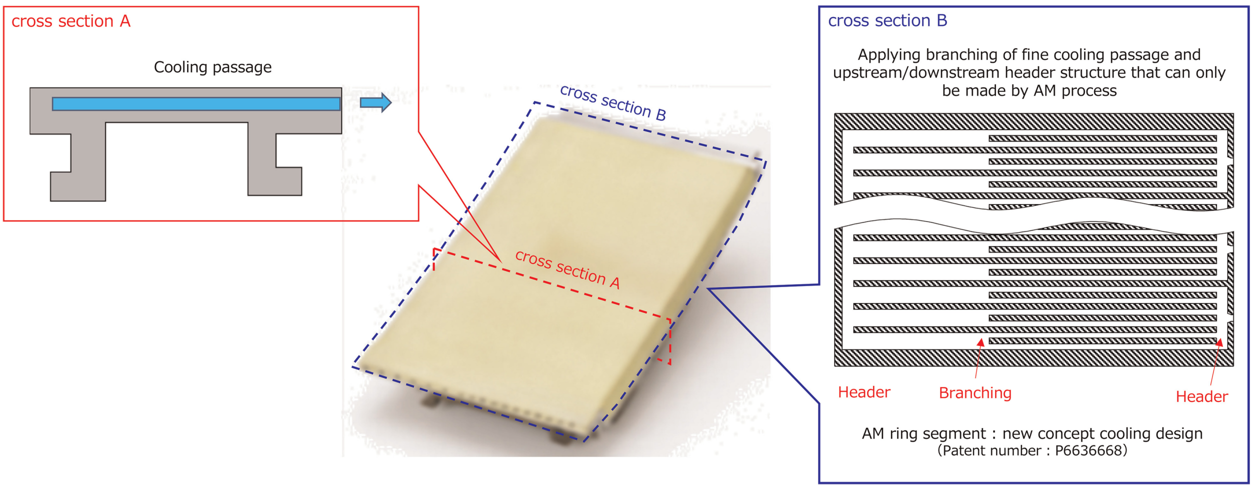

Figure 6. Advanced cooling structure example of AM ring segment.

with weakly constrained overhangs such as cantilevers. Bending occurs under the influence of thermal shrinkage when the laser scanning area (heat input range) increases rapidly, especially in areas with weak constraints such as overhang areas. Therefore, high precision building technology is required. In the case of simple shapes such as a cylinder, the building accuracy can be improved by uniformly offsetting the model according to the amount of heat shrinkage. On the other hand, in the case of a three-dimensional complex shape models, various distortion modes occur in multiple directions. Therefore, the uniform offset model described above does not work.

So, we developed methods distortion prediction by building simulation based on earlier trials, restraint support design and model offset correction (Shuji et al., 2022) corresponding to each distortion (See Figure 8). The distortion is suppressed by setting a restraint support with a highly rigid shape suitable for the distortion direction. The accuracy of distortion simulation can be enhanced by reducing the distortion beforehand. Also, distortion can be further suppressed by offsetting the design model in the opposite direction of distortion based on the results of simulation (Shukri et al., 2021).

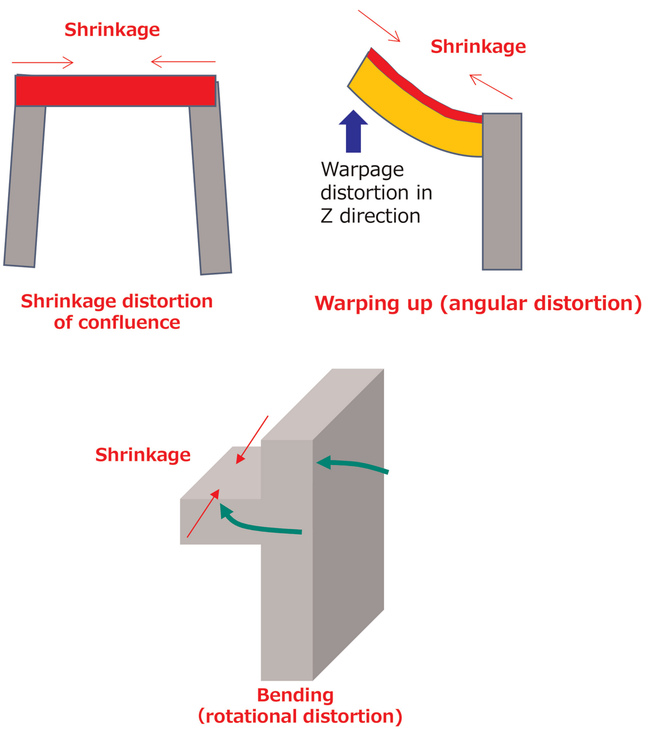

Figure 7. Distortion mode in AM process.

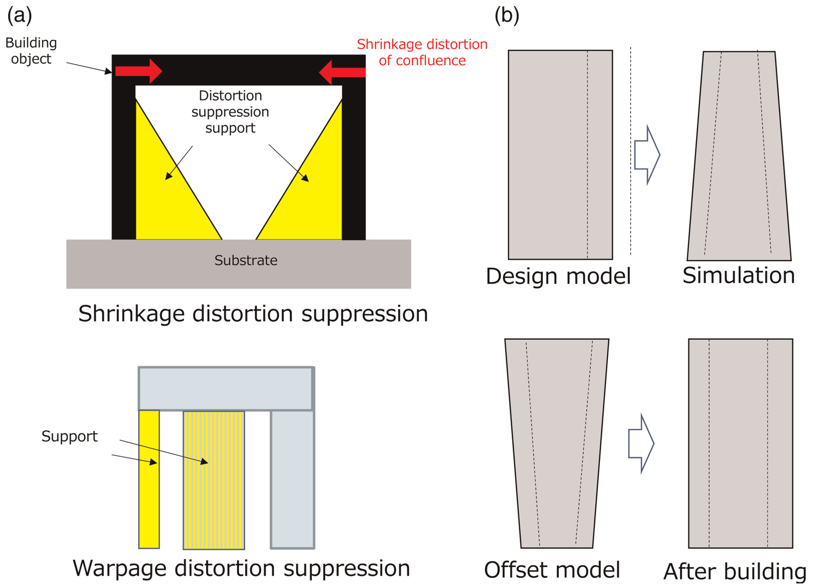

Figure 8. Distortion suppression method. (a) Restraint support (b) Model offset correction.

Improvement of material properties of AM objects

For hot parts of gas turbine, forged and cast nickel-based superalloys with high temperature strength are mainly used. Fabrication of these parts by the additive manufacturing is expected to provide significant advantages in realizing complex cooling structures and simplifying the manufacturing process. On the other hand, high material strength is required for these parts used in harsh environments, and there are many problems to be solved to satisfy the required strength for materials manufactured by the additive manufacturing. Although LPBF-type additive manufacturing technology is suitable for accurately building fine complex structures, it is essentially inevitable to include small defects in the material because it is formed by stacking small molten beads. Since the size and number of defects are greatly affected by the building conditions, it is very important to adjust the conditions properly. Figure 9 shows an example of the effect of building conditions on the generation of defects in a material. The energy density in laser irradiation varies depending on the building conditions, and if the density is too small, defects due to insufficient melting occur. On the other hand, if the energy density is too large, defects due to overheating occur. Therefore, it is necessary to control the building conditions in the appropriate range.

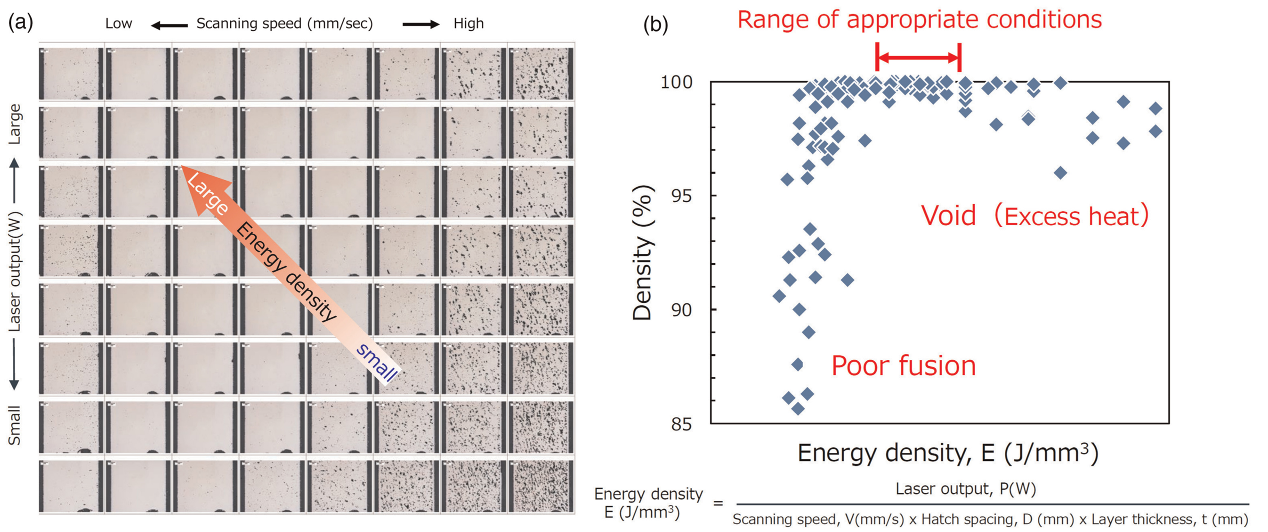

Figure 9. Effect of building conditions on generation of defect in materials. (a) Cross-sectional microstructure for each building condition (b) Relationship between energy density and density of the building.

A major issue in the application of additive manufacturing to Ni-based high strength alloys is the compatibility of material strength and crack suppression in building. Although strengthening by gamma-prime phases is the most effective for the alloys, addition of Al or Ti to increase the amount of the gamma-prime phase greatly reduces weldability. Figure 10 shows the weldability of various conventional Ni-based alloys (Amrita et al., 2017). The alloys located at the upper left in the Figure 10a have higher strength but more difficult weldability. That is, cracks are more likely to occur during building. As shown in Figure 10b, cracks occur along grain boundaries. We had developed the MGA2400 alloy as a weldable high-strength alloy and have been investigating the application of additive manufacturing technology to the alloy, including Hastelloy X equivalent alloys.

Quality monitoring technique

Building process takes tens of hours to complete. So, if some detects are detected in a non-destructive inspection such as RT or X-ray CT after building, it will take a lot of cost and time to build again. Therefore, with the aim of preventing re-building and ensuring traceability, we are developing in-process monitoring technique and a quality judgment method for the state of the laser irradiation area (light emission from the molten pool) to understand the operating state during building. Figure 11 shows an example of AM quality assurance. On the

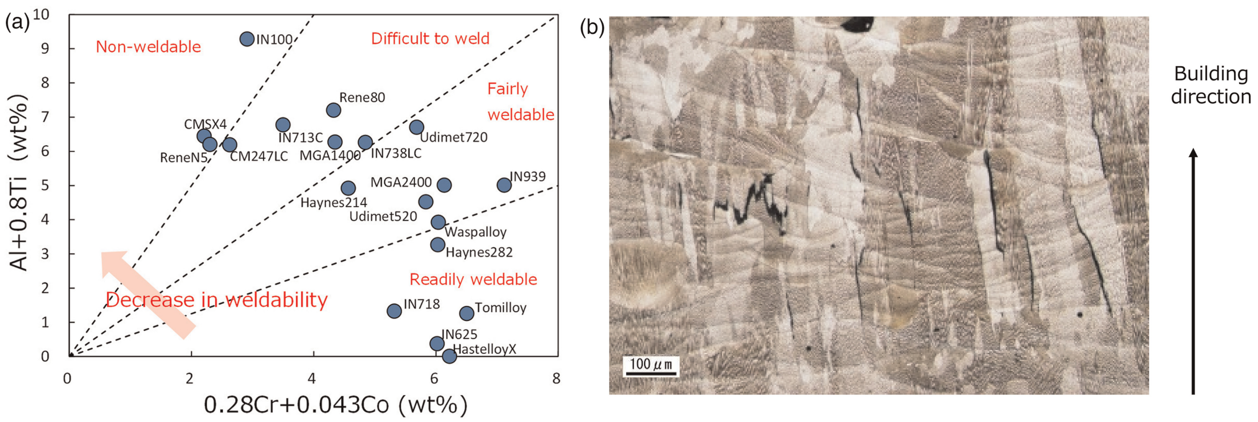

Figure 10. Weldability of various conventional Ni-based alloys and generation of cracks in additive manufacturing. (a) Relationship between Additive Elements and Weldability of Nickel Alloys (b) Cross-sectional structure and cracks in the building.

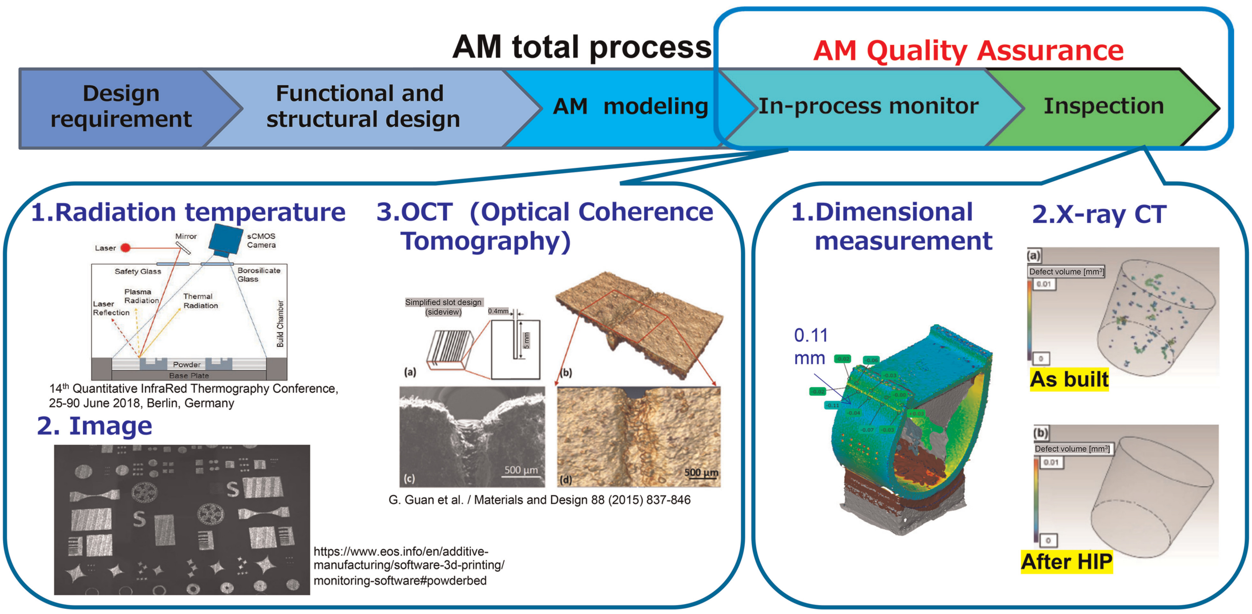

Figure 11. AM quality assurance method.

left side of the Figure 11, radiation temperature measurement, OT (Optical Tomography) and OCT (Optical Coherence Tomography; technique for measuring irregularities in ophthalmic fundus examination, Guan et al., 2015) are shown as examples of in-process monitoring. The right side of the Figure 11 shows dimensional inspection and X-ray CT as examples of non-destructive inspection.

This paper describes the consideration status of applying fringe projection for surface shape measurement and OT for process monitoring.

Results and discussion

Performance test results of AM combustor and AM ring segment and results obtained in each AM process technology development are described.

Design for AM combustor

Figure 12 shows a comparison of the lead time for a combustor prototype verification between the conventional process and additive manufacturing process. We reduced the prototype verification to one month by the AM, whereas it took several months by the conventional process. As shown in Figure 13, the prototype combustor manufactured by AM had a little rough surface compared to the conventional process and caused a slightly decrease in surface velocity. The effect of slow flow velocity was verified by high pressure rig test. As a result, there are the same combustion dynamic characteristics between AM and conventional process as shown in Figure 14. These results make it possible to manufacture combustor prototypes by AM.

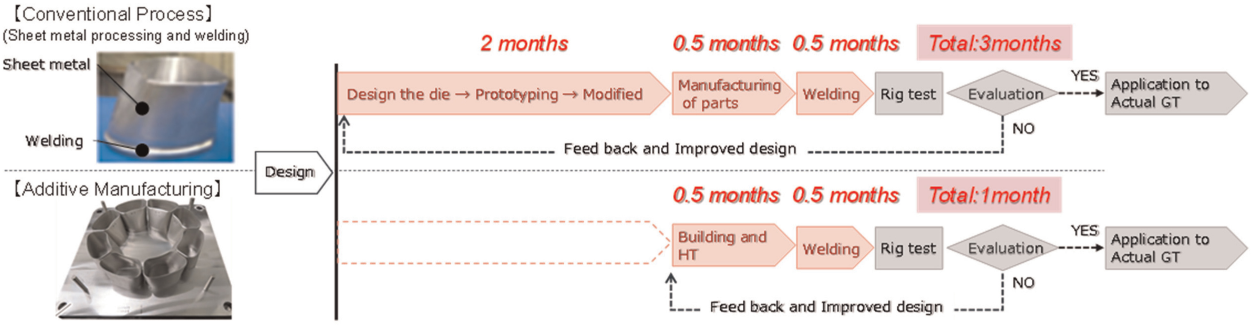

Figure 12. Comparison of the lead time for a combustor prototype verification.

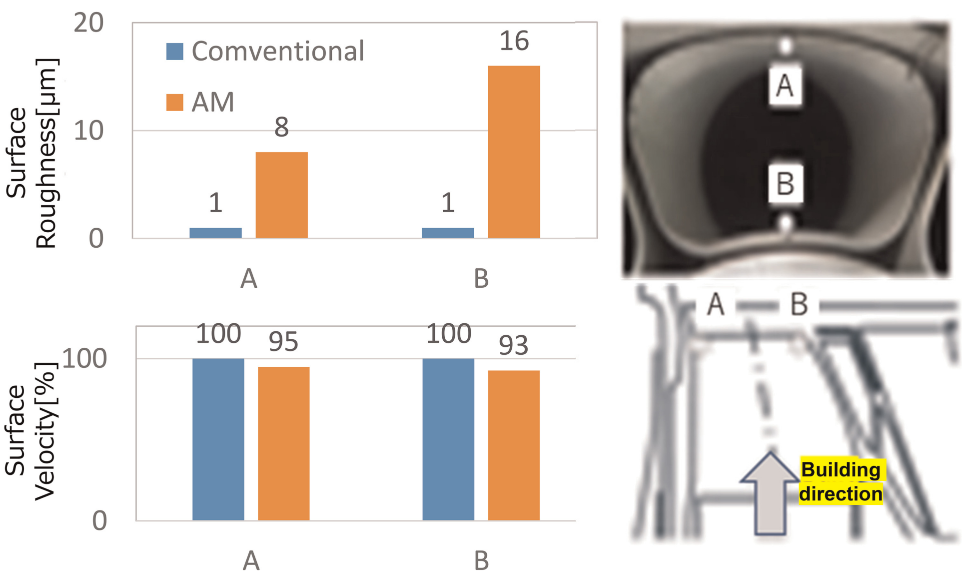

Figure 13. Comparison of the surface roughness and velocity.

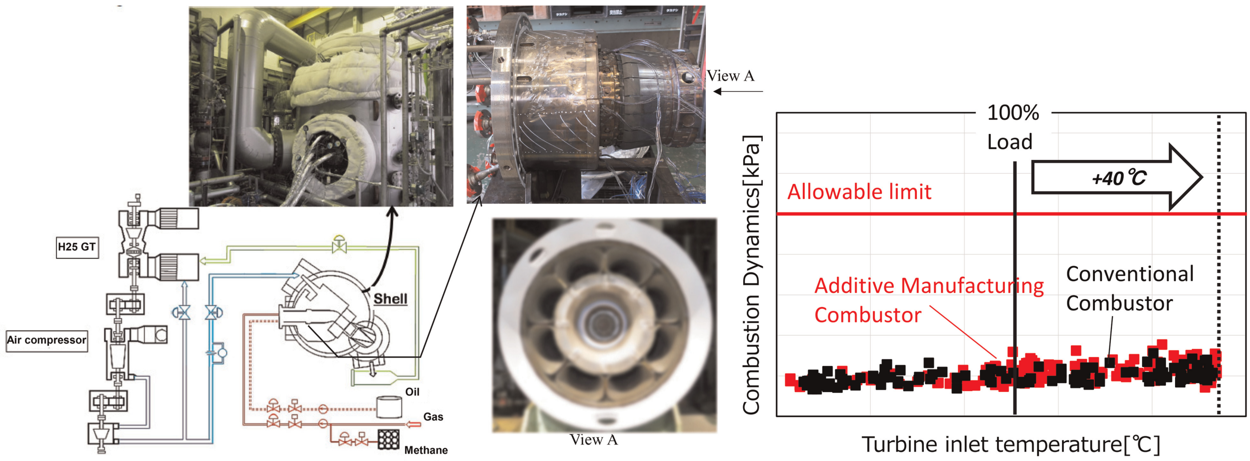

Figure 14. High pressure rig test and results of the combustion dynamics.

Design for AM turbine parts

AM ring segments with an advanced cooling structure unique to AM were built and post-processed. This section describes results about the cooling performance of AM ring segment. The manufacturing results such as accuracy and material strength are shown in the following sections.

Firstly, the shape of cooling channel inside AM ring segment was inspected with a pin gauge, a borescope, and X-ray CT scan. The pin gauge inspection ensured the minimum size of cooling channels which is an indicator of clogging characteristics. The borescope inspection provides a direct view into the cooling passage, allowing for the identification of minor defects on the surface. X-ray CT scan can identify anomalies such as powder residue throughout the cooling structure, including areas inaccessible by pin gauges and borescopes. These tests confirmed that there was no problem with the shape of the cooling passage, which determines cooling performance.

Secondly, the cooling performance test using a lamp heater and an IR camera were carried out to ensure the quality of AM ring segment with complex fine cooling structures including branching and merging. The schematic and results are shown in Figure 15. A given amount of cooling air was supplied to AM ring segment and it was heated by the lamp heater. After it reached steady state, the surface temperature was taken by the IR camera. If there was an anomaly such as a partial blockage of the cooling passage, the temperature would rise locally, but such anomalies were not found in the AM ring segment manufactured in this time.

Finally, AM ring segment was put into the power plant demonstration facility (See Figure 16) in our company, and cooling performance was verified under the real machine condition. Figure 17 shows the metal temperature distribution on gas path surface of the AM ring segment in the real machine condition. It was confirmed that the metal temperature measured by the thermocouples attached on the AM ring segment almost agreed with the predicted value and had the expected cooling performance.

The AM ring segment was then operated for about a year at the power plant demonstration facility. During this time, the metal temperature on AM ring segment were constantly monitored, and no outliers were indicated. Figure 18 shows an appearance of the AM ring segment after 1 year demonstration. There was no noticeable damage, and the reliability of AM ring segment was confirmed in the real machine condition.

High-precision building technology

The effect of model offset was confirmed using element models of portal shape and thin plate circular shape (See Figure 19). In a portal shape, shrinkage distortion occurs at the joints of parts. Shrinkage distortion was reduced from 0.77 mm to 0.23 mm with model offset correction. In a thin plate circular shape, bending distortion occurs in the direction of increasing radius. Similarly, bending distortion was reduced from 0.89 to 0.18 mm with model offset correction.

Procedure of model offset correction was as follows. First, building simulation was performed. Next, some restraint support was installed based on the building simulation results, and the first trial building was performed. After shape measurement of the building object, make corrections so that the simulation results match the shape measurement results. Specifically, the inherent strain distribution was adjusted based on our original calculation

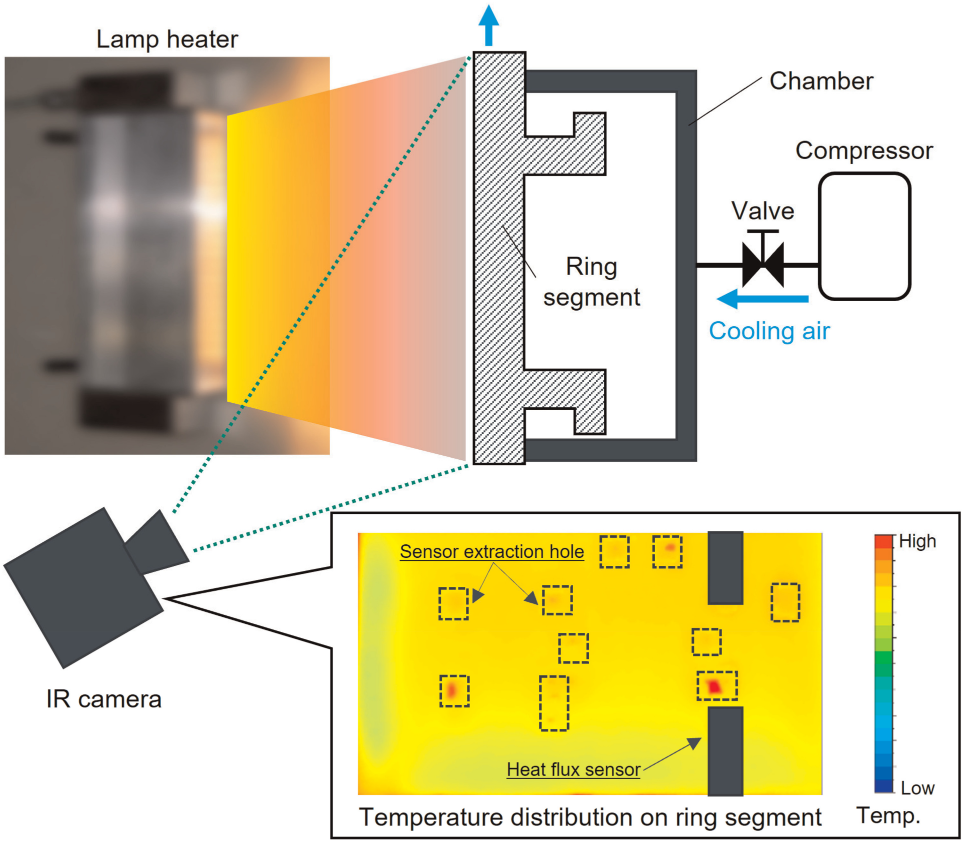

Figure 15. Cooling performance test for AM ring segment.

method. After that, the second trial building was performed. As a result, the building accuracy was greatly improved.

Three-dimensional complex shape models of combustors and turbine vanes were built (See Figure 20). In the combustor model, mainly shrinkage distortion occurred. On the other hand, in turbine vane model, warpage and shrinkage distortion occurred. Shape accuracy was 0.3 mm by restraint support and model offset correction for either model.

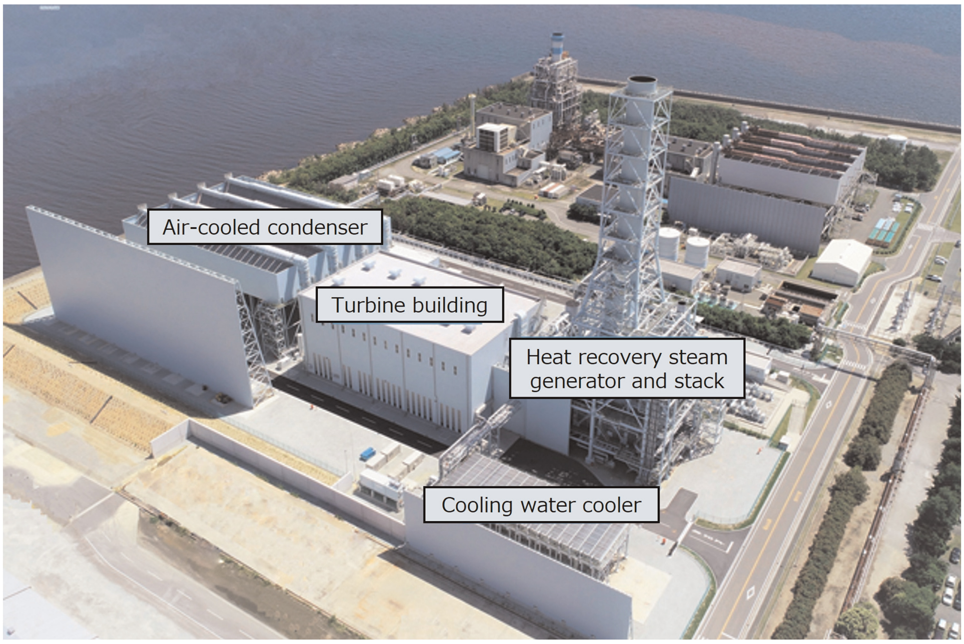

Figure 16. T-point 2 power plant demonstration facility (Hyogo, JAPAN).

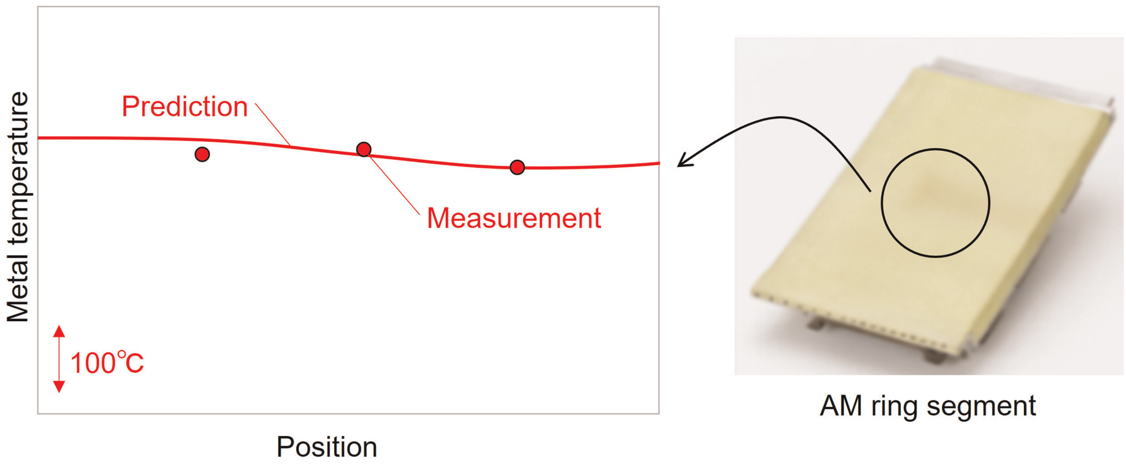

Figure 17. Metal temperature distribution on AM ring segment.

Improvement of material properties of AM objects

The generation of defects and cracks in building was important problems to be solved, but it could be minimized by optimizing the building conditions including modification of the building machine. On the other hand, the microstructure of the materials built by additive manufacturing is much more different than that of conventional cast materials. In additive manufacturing, the solidification rate after melting is so fast that the crystal grains

Figure 18. AM ring segment after demonstration test.

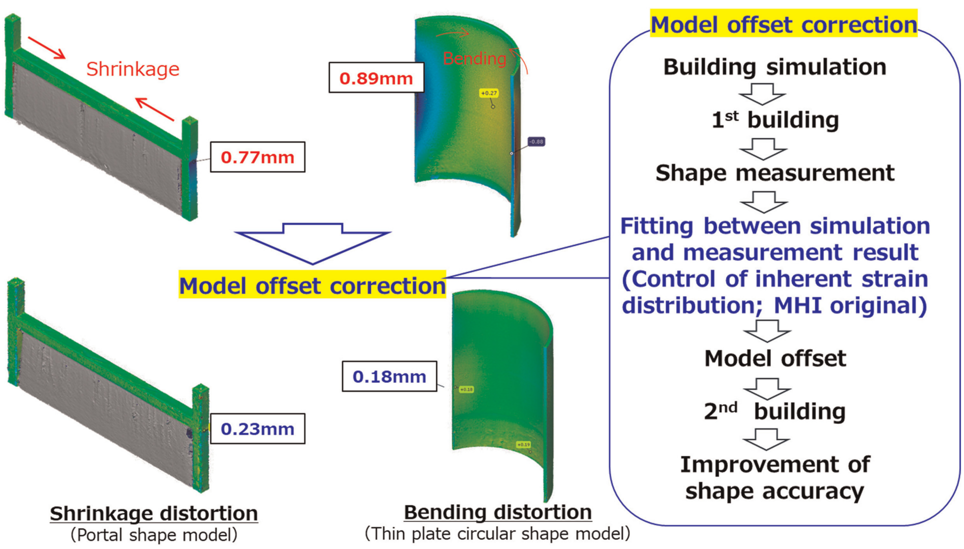

Figure 19. Improvement of shape accuracy by model offset correction.

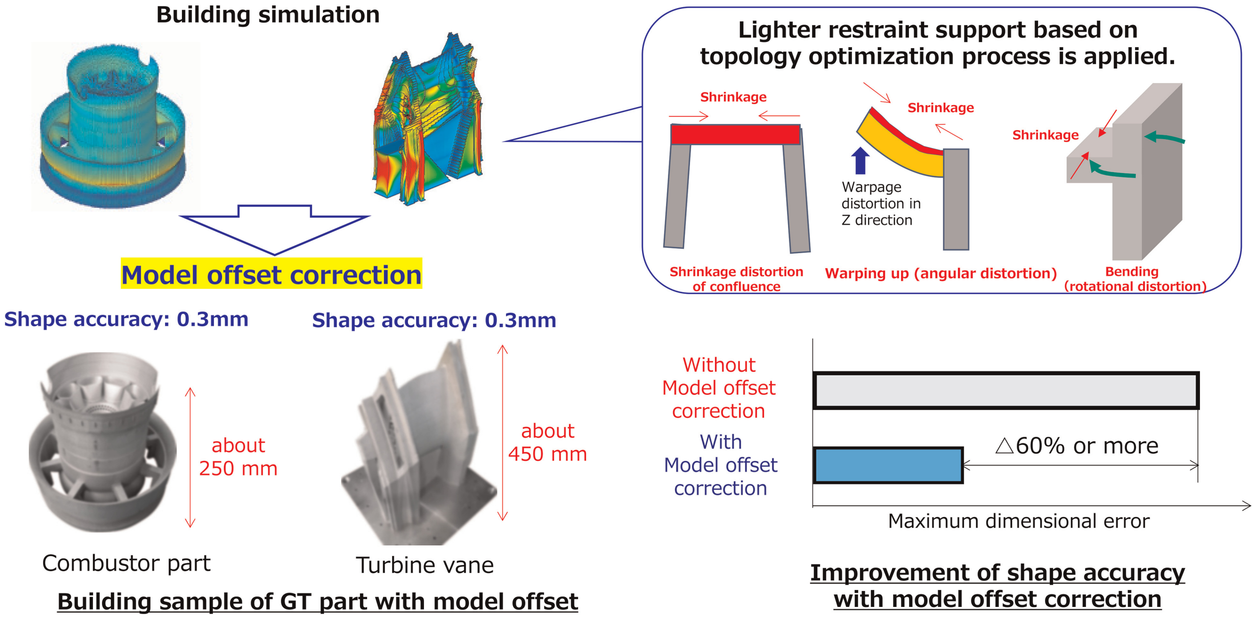

Figure 20. Shape accuracy of AM combustor and turbine vane.

become very fine (Patcharapit et al., 2017). Figure 21 shows the results of microstructure observation of cast and additive manufacturing materials by optical microscopy. Due to the slow solidification rate of the cast material, the dendritic structure can be clearly observed even with an optical microscope, but the additive manufacturing material is too fine to be observed. The size and distribution of carbides in additive manufacturing materials are also different from that in conventional materials. The coarse MC-type carbides in cast material are sparsely distributed, while carbides in additive manufacturing material are too small to be observed with an optical

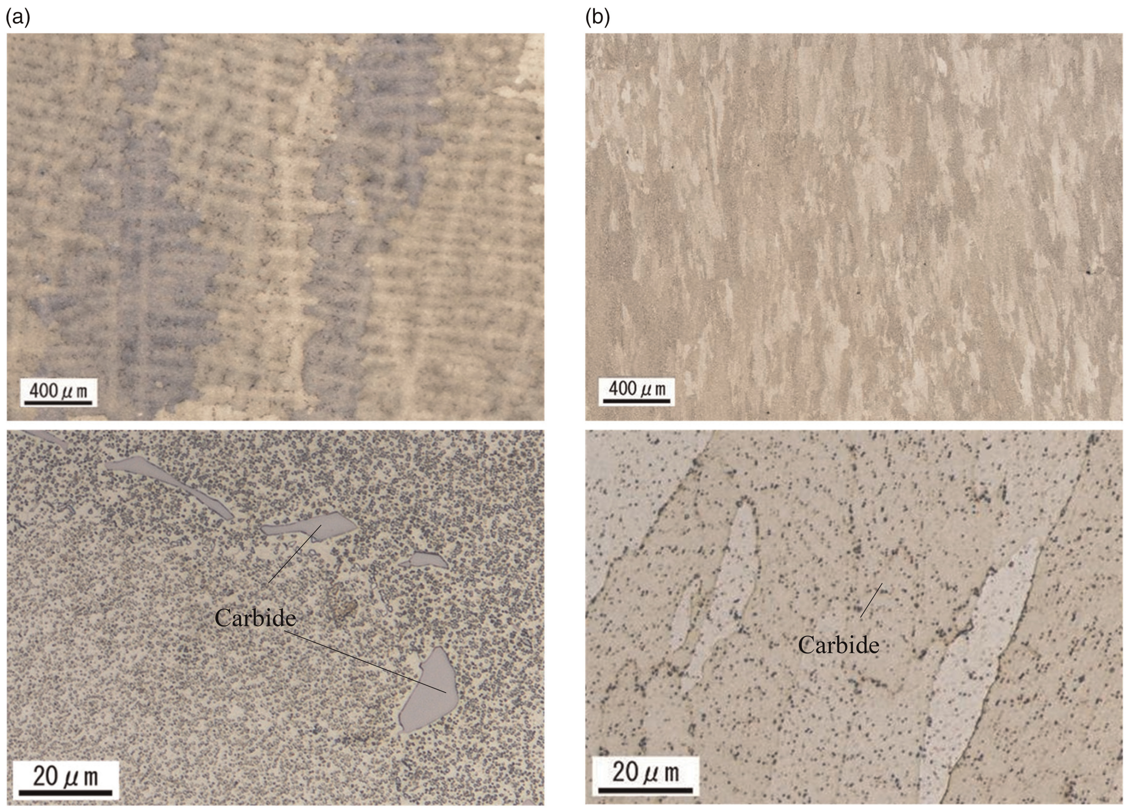

Figure 21. Difference in microstructure and carbides between cast and additive manufacturing materials. (a) Cast (b) AM.

microscope (Masaki et al., 2021). Because of this large difference in the microstructure, microstructure control suitable for additive manufacturing materials is quite important to ensure material properties.

Based on knowledge of the characteristics of cast and forged materials obtained so far, we have been adjusting parameters such as material components, building conditions and heat treatment conditions while utilizing material calculation technology in consideration of the effect of rapid solidification peculiar to additive manufacturing materials. As an example, Figure 22 gives the results of EBSD (Electron Back Scatter Diffraction) analysis of grain morphological changes and residual strain (KAM (Kernel Average Misorientation) value) before and after heat treatment. By adjusting the heat treatment conditions to eliminate fine columnar grains and high residual strain after building, relatively equiaxed grains could be obtained and the anisotropy of strength was greatly reduced. Such microstructure control brought about great improvement of the high-temperature strength properties of the additive manufacturing materials as shown in Figure 23. In particular, the improvement of high-temperature ductility is important for ensure fatigue strength and creep strength. Based on various investigations, we have been able to develop material and manufacturing technologies to satisfy the required strength for actual use.

These results were obtained using machined specimens. The internal structural part that cannot be machined is the surface roughness as built. Also, surface roughness varies depending on the angle of inclination to the building direction. Surface roughness affects fatigue strength (Esmaeil et al., 2023) and pressure loss of fluids (Lokesh et al., 2020) such as cooling air. In the future, we will develop technologies to reduce surface roughness by improving the building process and applying surface treatment to internal passages, as well as design technologies that consider the effect of surface roughness.

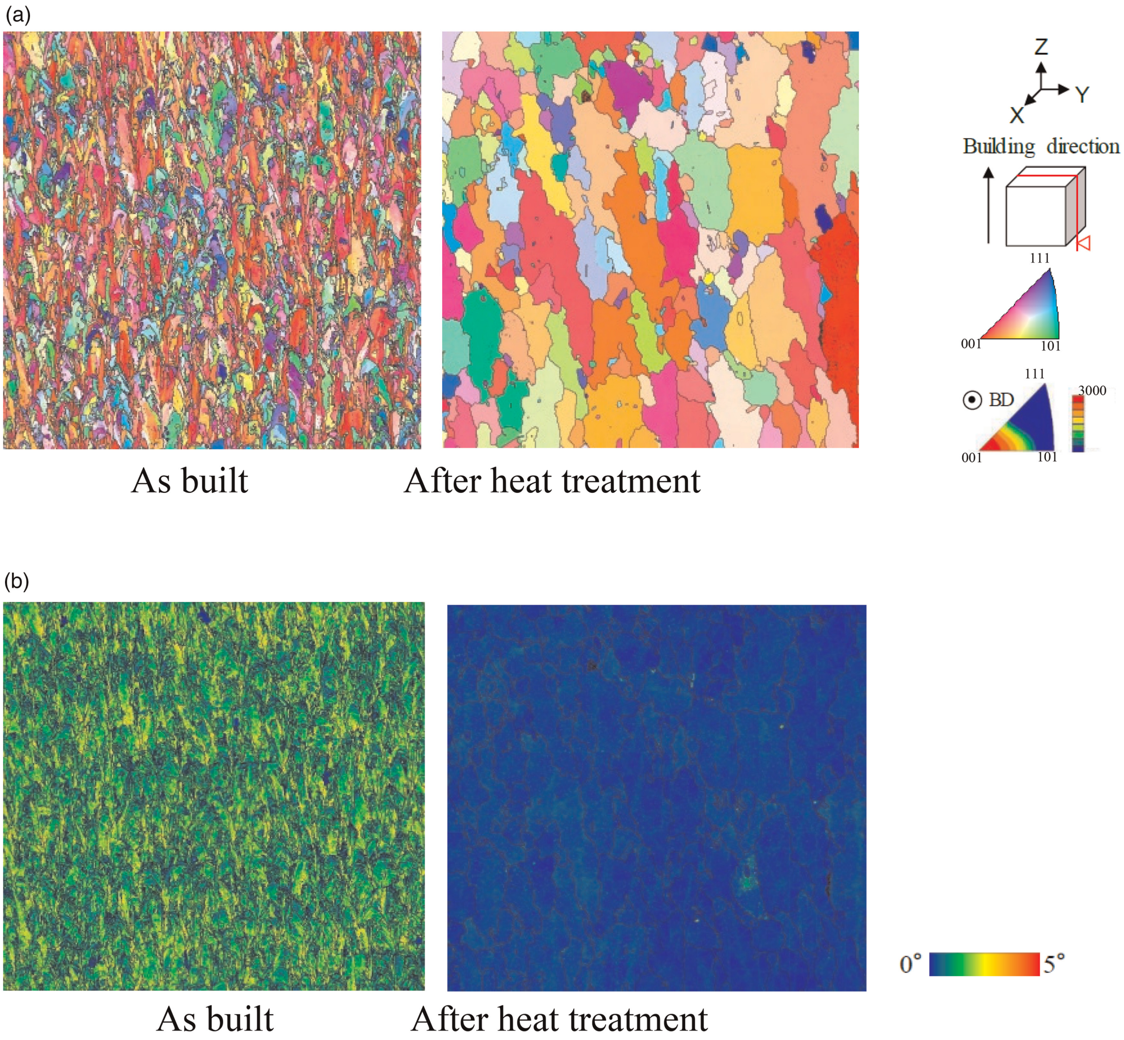

Figure 22. Reduction of microstructure anisotropy and residual strain by heat treatment. (a) IPF map (Z direction) (b) KAM map.

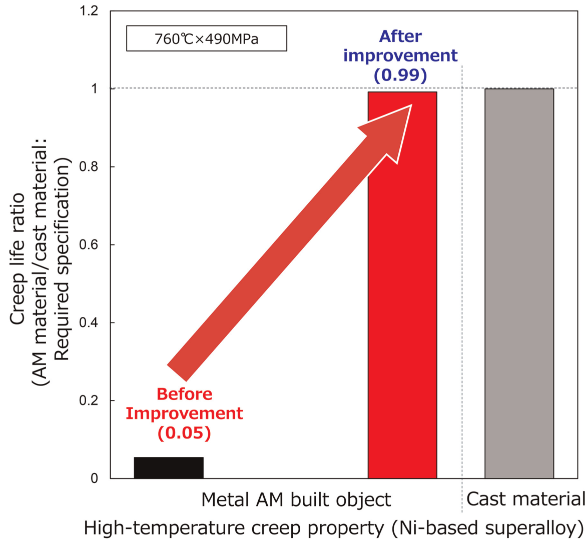

Figure 23. Improvement of high-temperature creep property of additive manufacturing material.

Quality monitoring technique

Fringe projection technology is a method that can detect surface defects with an accuracy of tens of microns in-process. It is also possible to evaluate the stability of layer thickness and to prevent contact with the powder laying blade due to warping distortion of the building objects. As shown in Figure 24, the fringe projection detector can be mounted in the building chamber. It has been confirmed that it is possible to measure the unevenness of the layer thickness and the surface of the building object. In the future, we plan to develop an in-process correction method for anomaly detection points.

OT is a technology to capture the emission intensity from the molten pool of the laser irradiation area during building by using a CMOS camera with a certain exposure time and use the integrated value and maximum value thereof to detect process abnormalities (scattering of laser beam due to fluctuations in laser power and strain on the protective glass) and opening defects near the building surface.

Figure 25 shows light emission images captured by OT and the integrated average of the emission intensity with the energy density changed in various ways (the parameters of laser power, scanning speed and hatch distance were changed). The integrated average of the emission intensity changes not only by the energy density, but also by the temperature and shape of the building object. In the future, we will utilize the monitoring technology as quality control of AM by increasing the acquired data, improving the detection accuracy of process abnormality and seeking the criteria of emission intensity to ensure the quality (filling ratio) of the AM objects, etc.

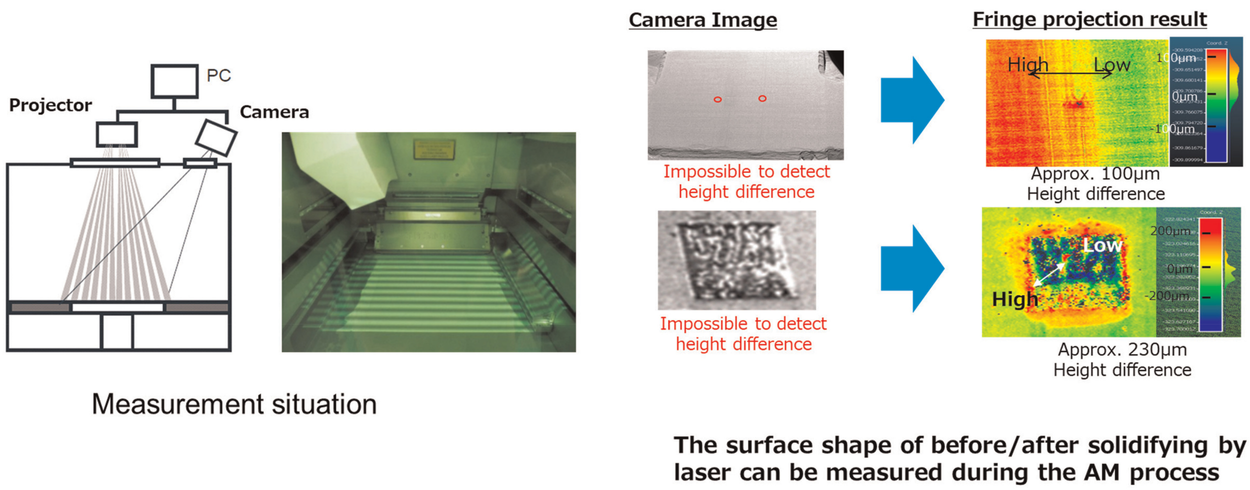

Figure 24. Result of fringe projection measurement.

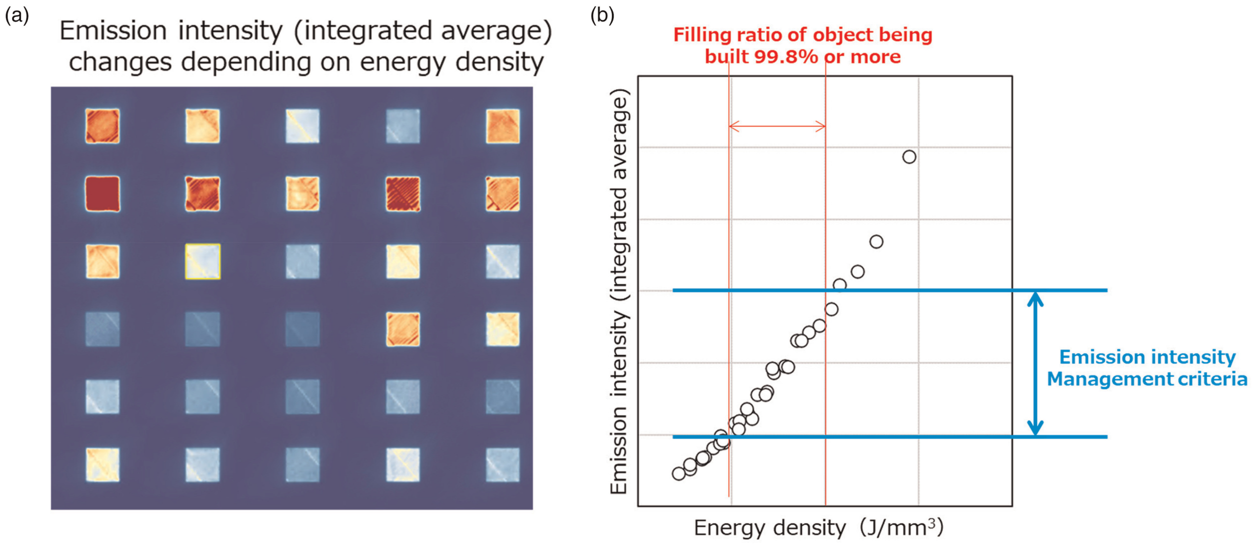

Figure 25. Result of OT measurement. (a) OT measurement image (b) Relationship between energy density and emission intensity (integrated average).

Status of applying AM to gas turbine components

Since we started using AM Technology in 2014, we have been working on the development of new GT technology and the expansion of mass production by applying the results, and now we are applying AM to various parts (See Figure 26).

Also, since we started to apply AM technology for first part mass production in 2017, more than 50,000 parts has been already shipped so far and its application is increasing year by year (See Figure 27).

Conclusions

This paper presented design for AM technology for gas turbine components and metal AM process technology such as building simulation with high stiffness support design and pre-set distortion, microstructure control by laser scanning conditions, quality control through in-process monitoring tools and application of AM technology to gas turbine components.

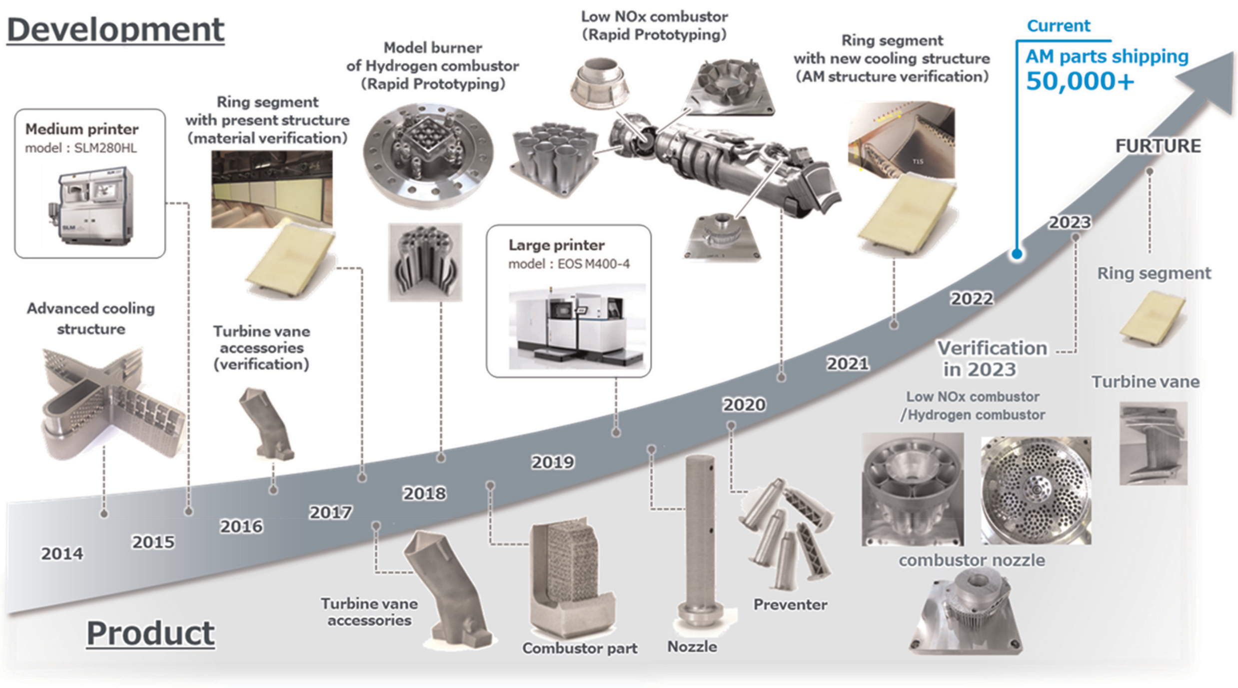

Figure 26. MHI Additive Journey in GT.

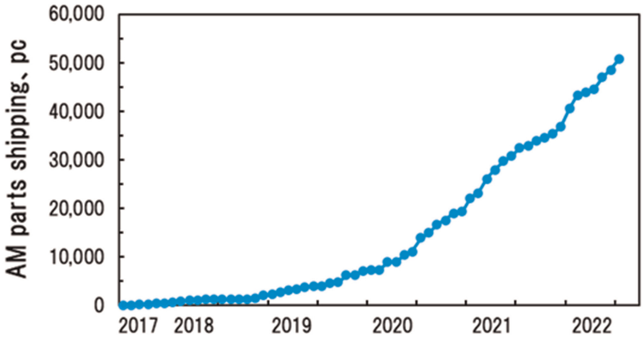

Figure 27. AM parts shipping for gas turbine components.

AM process is a promising manufacturing technology to realize high efficiency gas turbine with advanced cooling design for hot parts and hydrogen or ammonia gas-fired gas turbine with advanced combustion structures. We have already started manufacturing several parts in AM process to realize the above, and plan to verify them at the power plant demonstration facility. On the other hand, because turbine blades and combustor components are used in a harsh environment, there are development issues for mass production applications, such as development of design rules to maximize benefits while considering AM constraints, acquisition of AM material data, mass production management methods, and quality inspection methods. We will continue to monitor the development of external research institutes and equipment manufacturers, as well as trends in the establishment of international standards, to incorporate the latest technologies, and to work on the development of AM processes within our company.

We are working to eventually achieve CO_2 zero power generation by providing feedback on the verification results and making improvements.

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Competing interests

Masahito Kataoka declares that he has no conflict of interest. Shuji Tanigawa declares that he has no conflict of interest. Masaki Taneike declares that he has no conflict of interest. Ryuta Ito declares that he has no conflict of interest. Takanao Komaki declares that he has no conflict of interest. Norihiko Motoyama declares that he has no conflict of interest.

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