Development of Metal AM Technology for Gas Turbine Components

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Mitsubishi Heavy Industries, Ltd. (MHI) Group has been developing additive manufacturing (AM) as a method that can manufacture parts with complicated shapes and is considering its application to manufacturing processes. For large frame gas turbines, with the aim of improving performance by reducing the amount of cooling air for hot parts, the adoption of a complicated internal cooling structure, which cannot be made with conventional manufacturing methods but can only be made by AM, is being considered. AM is not a method that can build a practical part immediately when 3D CAD data is input to the building equipment, but a method that requires an innovative design concept based on the characteristics and restrictions of building objects, in addition to technological development for the optimization of building and post-processing conditions, quality assurance by in-process monitoring, etc. This report describes the development of metal AM technology for gas turbine components.

1. Introduction

LPBF (Laser Powder Bed Fusion), which is one of the building methods for metal AM, is a process built layer by layer from a metal powder bed with a laser. This method can build complex internal structures and is expected to be applied to innovative structural design parts. In recent years, the buildable size of LPBF equipment has been increasing, multi-laser scanning has made building speed faster and its price has been reduced, so it is expected that metal AM will be applied to a wider range of parts. MHI group has been considering the application of metal AM to various products since fiscal 2013[(4)]. For example, we are considering the adoption of a complicated internal cooling structure for large frame gas turbine hot parts, 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) in order to reduce cost.

On the other hand, there are issues that need to be considered for the application of metal AM. Specifically, an innovative design concept based on the characteristics and restrictions of building objects is required in addition to technological development for the suppression of distortion during building, assurance of the material properties required for hot parts, quality assurance, etc. This report presents the development status of metal AM technology for gas turbine components.

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2. High-precision building technology

Metal AM causes thermal distortion during building, so technology for building the shape exactly according to the design model is required. In the case of a simple shape such as a cylinder, the building accuracy can be improved by uniformly offsetting the model by the amount of shrinkage caused by thermal distortion (adjusting the shrinkage rate). In the case of a three-dimensionally shaped part with a complex structure, however, various distortion modes (shrinkage, warpage and bending) occur locally in multiple directions (**Figure 1**), so the aforementioned adjustment with a uniform shrinkage rate cannot be used. Therefore, we established a technique to predict distortion during building by building simulation and then offsetting and correcting the building model in the direction to counteract the distortion, as well as a technique to install a support for suppressing distortion (**Figure 2**). Specifically, the calculation formulas and input values of a commercially available building simulation were customized according to the size and material of the object being built to improve the analysis accuracy and a support with a shape that offered high rigidity against the deforming direction of steep distortion at a building confluence—the prediction of which was difficult with building analysis—was installed (**Figure 3**). By applying these techniques, we realized high-precision building of various parts including the gas turbine components described later (**Figure 4**).

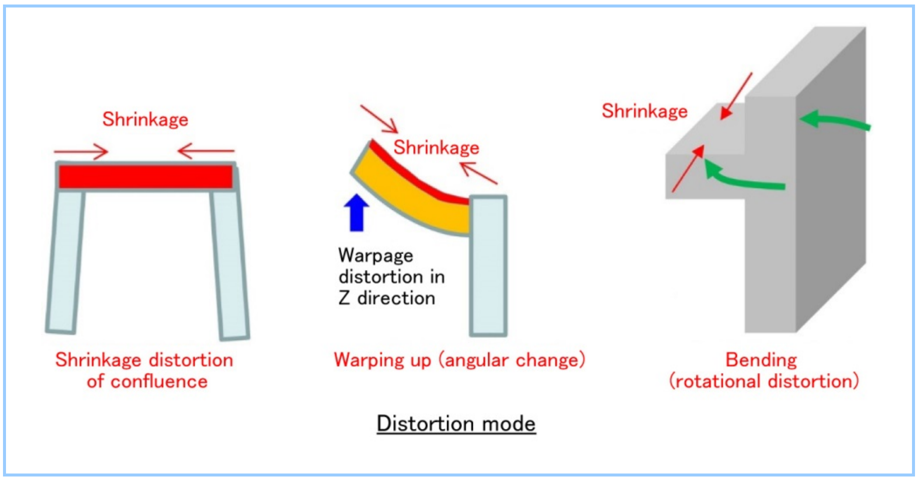

Figure 1 Distortion mode

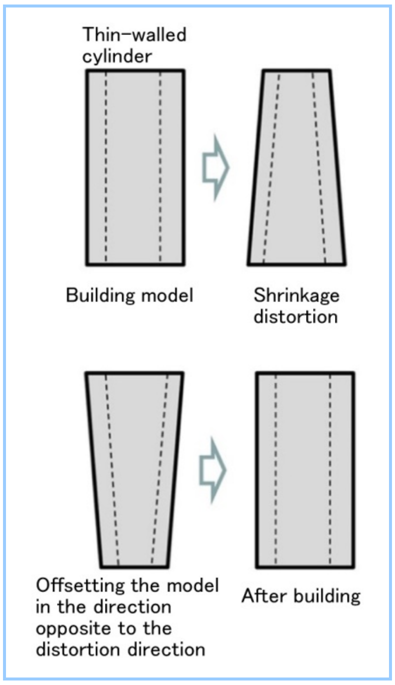

Figure 2 Offset correction of building model

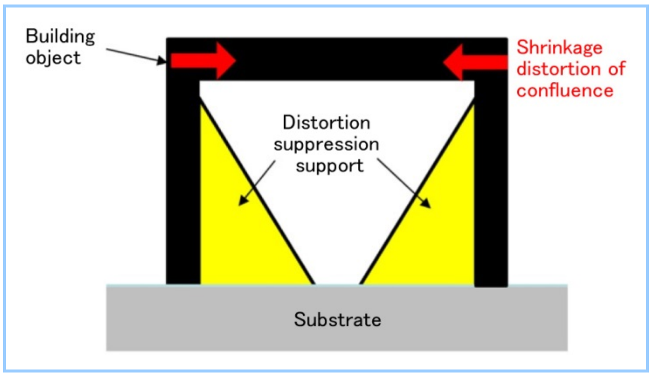

Figure 3 Installation of distortion suppression support

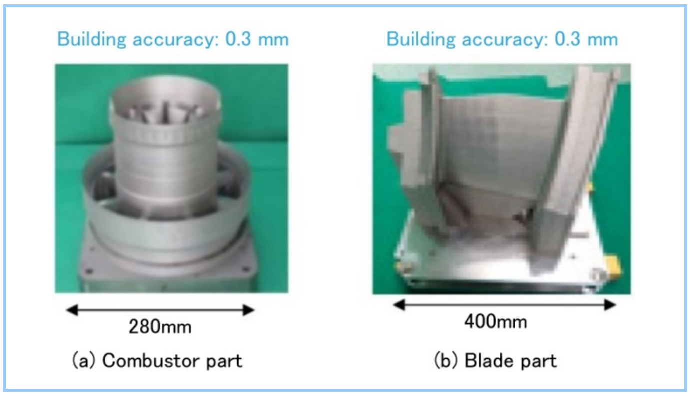

Figure 4 Example of high-precision building

3. Improvement of material properties of AM objects

For hot parts of gas turbines, forged and cast nickel-based superalloys with high-temperature strength are mainly used. AM materials built by the LPBF process using the powder of these alloys have a significantly different microstructure from the conventional materials since the cooling rate during melting and solidification in building is extremely high compared to the conventional manufacturing method and their grain size and precipitates tend to be finer (**Figure 5**). If the grain size of a part used at high temperature is too fine, the material strength will often be adversely affected by high-temperature creep, etc. In addition, since the microstructure of the material after building becomes fine columnar grains extending in the building direction, strong anisotropy occurs in the material properties as a result, so the strength may be significantly reduced depending on the stress loading direction[6]. Therefore, it is important to control the microstructure with an understanding of the characteristics of these AM materials.

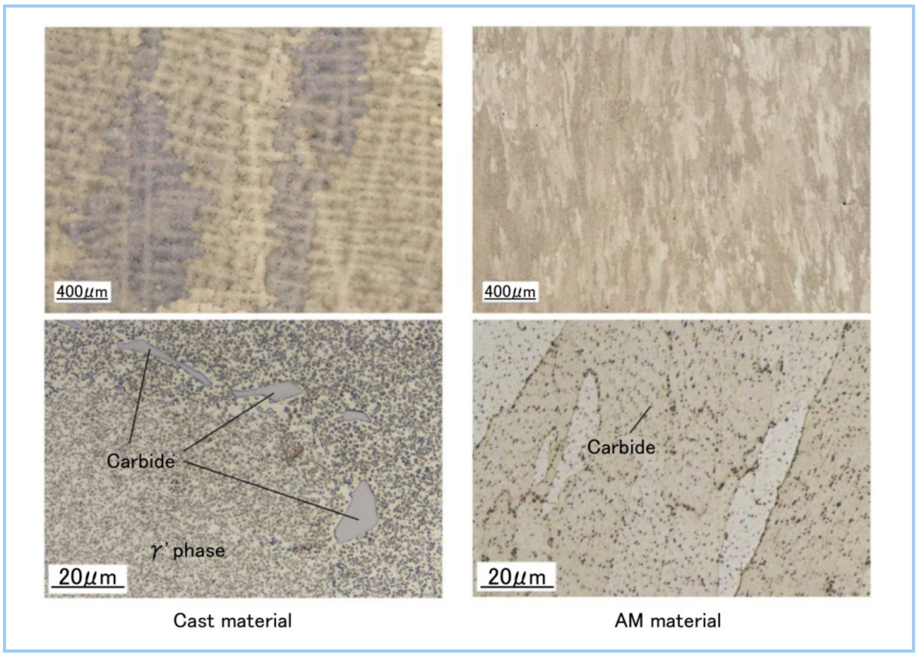

Figure 5 Difference in micro structure and precipitate between cast and AM materials

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 AM materials. As an example, **Figure 6** 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. At the same time, the same property as the conventional cast materials in terms of high-temperature creep life was obtained (**Figure 7**). This finding has been applied not only to the ring segments used in the verification test, but also to various nickel-based AM materials, to acquire material strength data in sequence[7].

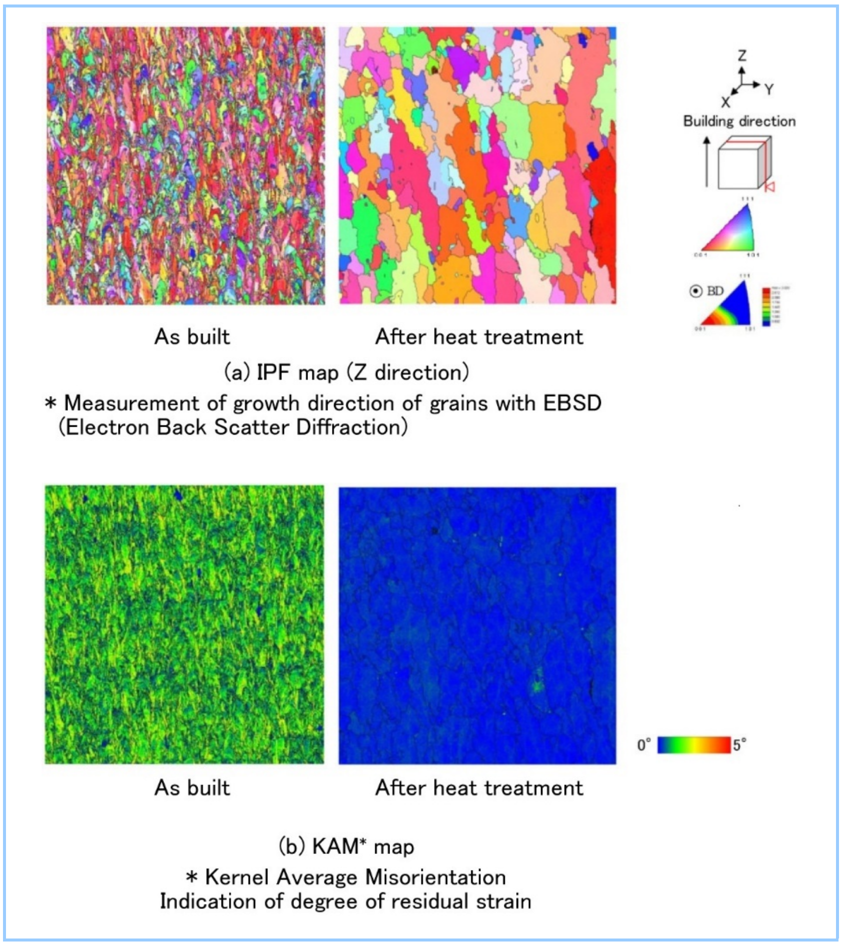

Figure 6 Reduction of microstructure anisotropy and residual strain by heat treatment

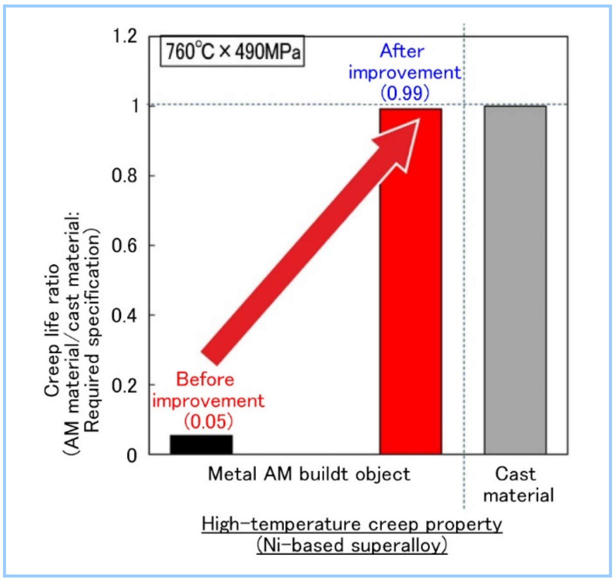

Figure 7 Improvement of high-temperature creep property by AM conditions and heat treatment conditions

4. Quality monitoring technique

Metal building takes several dozen hours to complete building, so if the quality inspection after the building fails, it means a big rework. Therefore, with the aim of preventing rework and ensuring traceability, we are developing a 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[4]. This report describes the consideration status of applying OT (Optical Tomography) as a building process monitoring technique.

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 8 is 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). It can be seen in this figure that the integrated average of the emission intensity changed according to the energy density. The integrated average of the emission intensity changes not only with the energy density, but also with the temperature and shape of the object being built. 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.

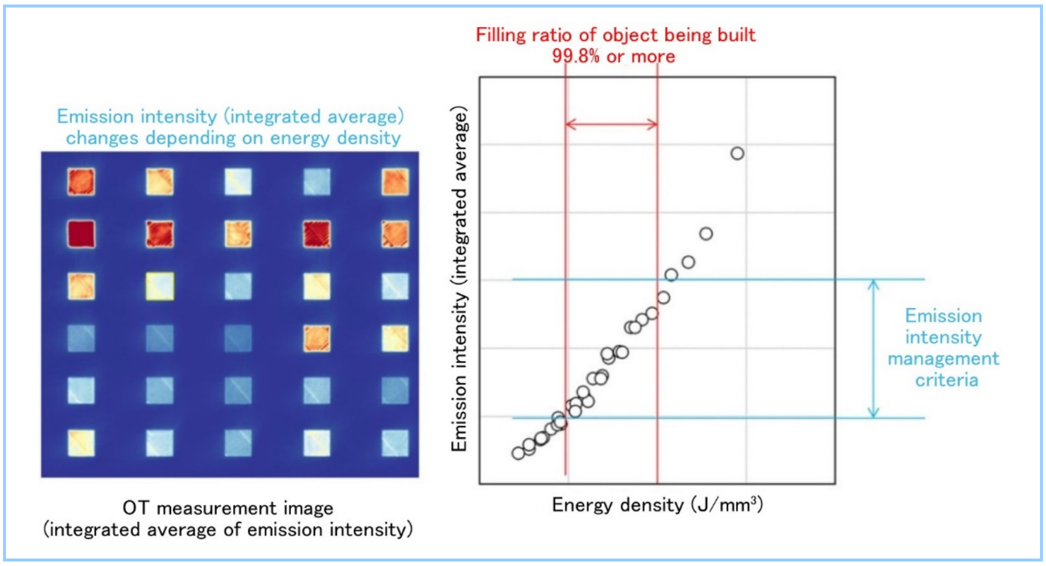

Figure 8 Relationship between energy density and emission intensity (integrated average)

5. Status of applying AM to gas turbine components

Gas turbine combined cycle (GTCC) power generation is a system that can be used to realize the cleanest and most economical thermal power plants that coexist with renewable energy. The GTCC system is expected to continue to lead the power generation market[1] and we have also been developing a new type of GTCC system. This report introduces, among the examples of applying AM to large frame gas turbine components shown in **Figure 9**, the complicated internal cooling structure which can only be made by AM, the reduction of development time with rapid prototyping and cost reduction technology with integrated building of weld-assembling parts, as well as their development statuses.

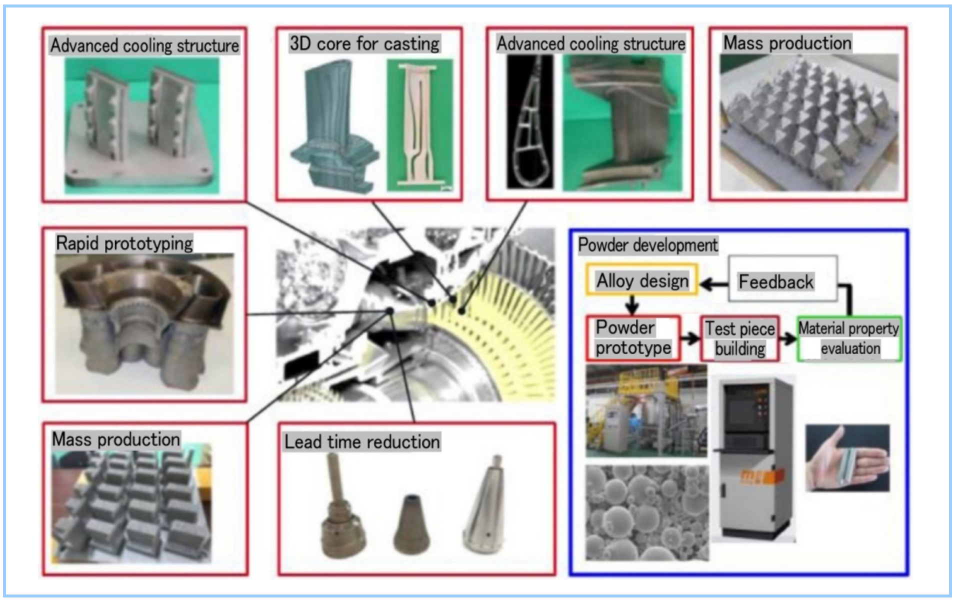

Figure 9 Example of applying metal AM to large frame gas turbine components

(1) Gas turbine ring segment

For a ring segment, which is one of the hot parts, we designed the internal cooling passage that can only be made by AM to reduce the variation in the temperature distribution on the hot gas path surface, resulting in improvement of the amount of cooling performance compared to past methods. In terms of building, we worked on distortion simulation, material composition improvement and the optimization of heat treatment conditions, thereby ensuring the required quality (strength and shape accuracy). We are now conducting a reliability evaluation under the actual equipment environment at our demonstration power generation facility in the Takasago District (**Figure 10**).

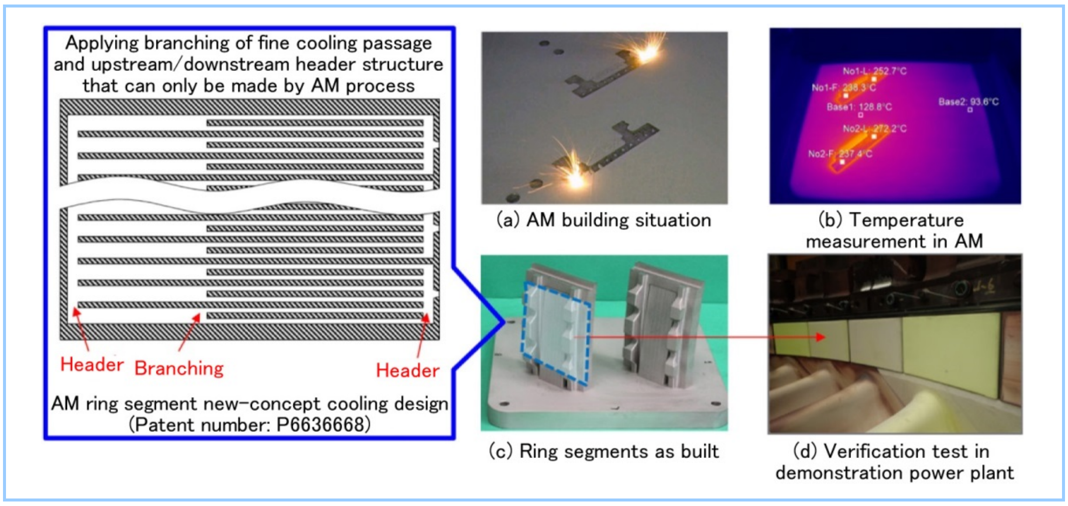

Figure 10 Consideration status of applying AM to gas turbine ring segment

(2) Rapid prototyping of gas turbine combustor components

A gas turbine combustor swirler block is a component that requires sheet metal processing and welding of many parts, so it takes time to manufacture prototypes in its development. Accordingly, we build some of the swirler block components with AM (**Figure 11**) to realize a reduction in the manufacturing cost of test pieces and the shortening of the manufacturing period. It was confirmed in the combustion test that the same performance as the conventional parts was obtained. We plan to utilize AM to shorten the development period of new models in the future.

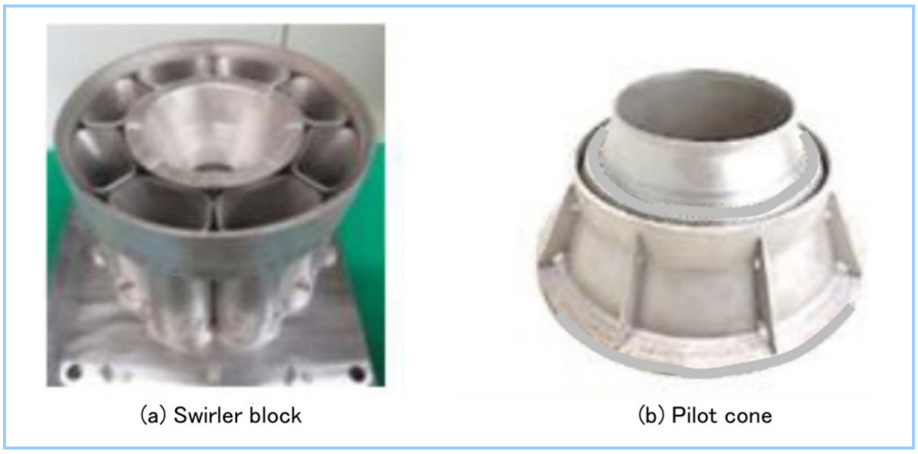

Figure 11 Rapid prototyping of combustor component with AM

(3) Cost reduction of weld-assembling parts

For the utilization of AM, how to determine its added value is important because simply replacing a conventional part does not lead to a cost advantage. There was a gas turbine-related component that was assembled by welding 10 thin sheet metal parts and its manufacturing cost was accounted for mainly by the processing cost. As such, we utilized AM to integrally-build this component to eliminate the weld-assembling process in order to add value and increased the number of components built per batch, etc., to reduce cost. As a result, the cost was successfully reduced by 60% (**Figure 12**). We then started mass production of this component in 2017 after confirming that the quality required for the actual component was satisfied and have already shipped 35000 AM parts in total.

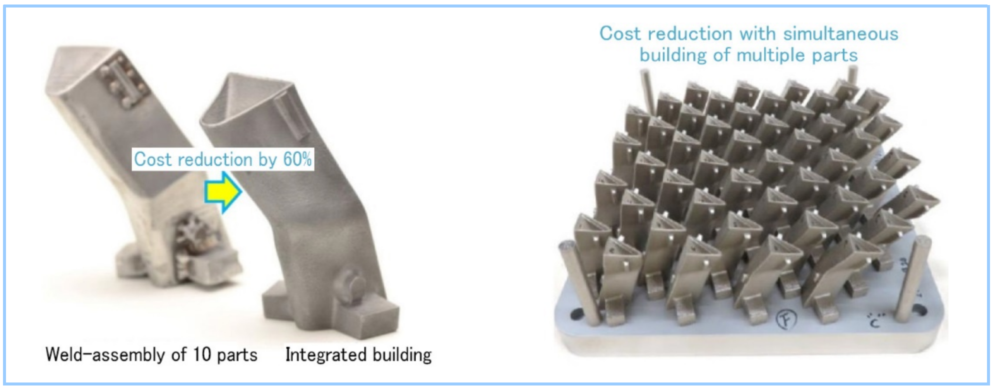

Figure 12 Cost reduction by integrated building of weld-assembling parts

6. Conclusion

This report presented the development status of elemental technology for components of large frame gas turbines as an initiative of MHI Group to develop metal AM technology. We will continue to utilize the AM process to improve the quality, cost and delivery of our products and proceed with technological development to meet the needs of our customers.

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