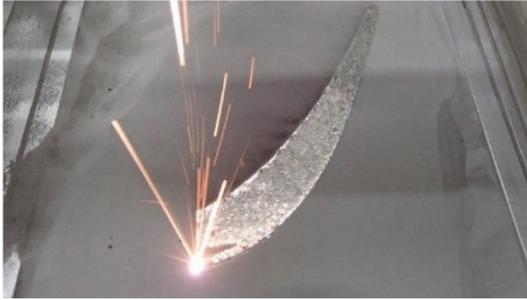


High-Accuracy Hybrid Printing on Large Structures Enabled by Chamber-Free PBF

SHUJI TANIGAWA*¹TAKASHI ARAI*²MASAKI TANEIKE*³KIMIHISA SAKIMA*⁴YOSHINAO KOMATSU*⁵TARO TOKUTAKE*⁶

If complex-shaped components can be directly printed onto products or other components using the Powder Bed Fusion process, an additive manufacturing method, creation of a wider range of applications can be expected. However, the conventional Powder Bed Fusion process is limited in its applications because building on curved surfaces or large components that do not fit inside a build chamber is difficult. Therefore, Mitsubishi Heavy Industries, Ltd. has been working on the development of a chamber-free Powder Bed Fusion process that enables additive manufacturing on large structural components outside a chamber, and has evaluated its practicality by assessing build accuracy and material properties, in addition to conducting build verification on components that simulate actual machine parts.

1. Introduction

The Powder Bed Fusion (hereinafter referred to as PBF) process, an additive manufacturing (hereinafter referred to as AM) method for metallic materials, creates layers by melting metal powder deposited on a substrate with a laser, enabling building of complex internal structures. Application of this process to innovative structural design components is expected. Further expansion of applications is expected due to advancements in recent years, such as increased build size of PBF systems, improved processing speeds through multi-laser scanning, and lower system costs. Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) Group has been investigating the application of metal AM to various products since fiscal 2013 ⁽¹⁾⁻⁽⁵⁾, and has already applied this method to mass-produced parts for large power-generation gas turbines ⁽¹⁾ and rocket engines.

While building onto a substrate (base plate) is common in the PBF process, if components with complex shapes can be directly built onto the product or other components, creation of a wider range of applications can be expected. However, the conventional PBF process is limited in its applications because building on curved surfaces or large components that do not fit inside a build chamber is difficult.

MHI has been working on the development of a chamber-free PBF process that enables AM of different materials and microstructures on the curved surface of a large component outside of a chamber as shown in **Figure 1**. This report describes the progress of process development and examples of fabricated structures.

*1 Research Manager, Factory Innovation Center, Research & Innovation Center

*2 Project Manager, Factory Innovation Center, Research & Innovation Center

*3 Research Manager, Strength Research Department, Research & Innovation Center

*4 Strength Research Department, Research & Innovation Center

*5 Manager, Fluid Dynamics Research Department, Research & Innovation Center

*6 Fluid Dynamics Research Department, Research & Innovation Center

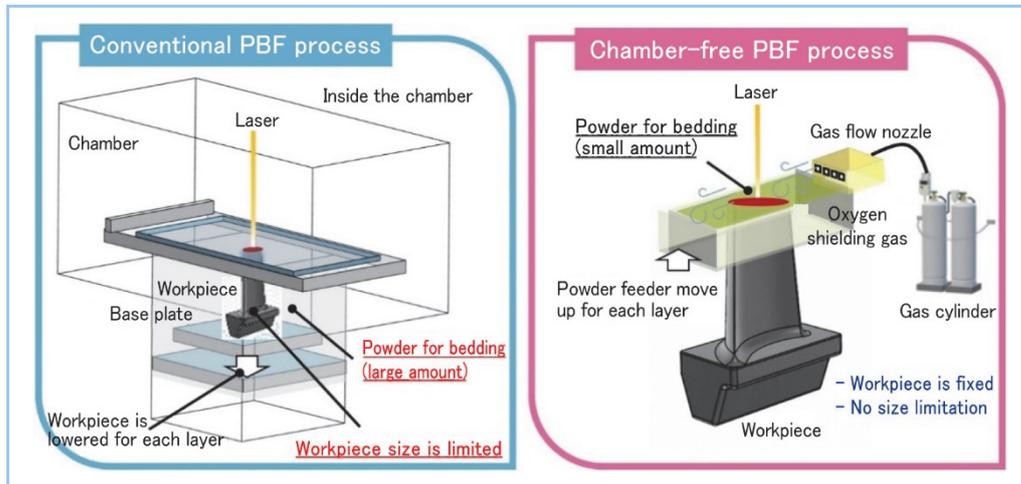


Figure 1 Schematic drawing of chamber-free PBF process

2. Characteristics of the chamber-free PBF process

2.1 Correction of the build model

Since tolerances, etc., are included in the manufacturing process for the components (workpieces), shape errors between the component and the built object occur if building is performed exactly according to the design CAD model. Therefore, the area around the build part of the component is measured in 3D in advance, and a build CAD model, in which the external shape and the position of the internal structure of the design CAD model are corrected according to the measurement results, is used.

2.2 Movable powder feeder

As shown in Figure 1, the powder feeder unit moves up and down for each layer (layer height: 30 μm to 60 μm), eliminating the need to change the height of heavy objects such as large parts as required by the conventional PBF process.

2.3 Gas flow nozzle

As shown in Figure 2, a gas flow nozzle was developed to ensure shielding (exclusion) of oxygen gas near the AM surface and removal of metal fumes generated during building, in an environment outside of the chamber. Specifically, the gas flow nozzle was first designed so that argon gas supplied from a gas cylinder via piping flows uniformly within the build area, and then manufactured using a resin AM process. As a result, metal fumes could be removed using the developed gas flow nozzle, while ensuring oxygen gas shielding (5 ppm or less) within the build area (140 mm square).



Figure 2 Gas flow nozzle for chamber-free PBF

2.4 Procedures of the chamber-free PBF process

As an example of building on a workpiece using the chamber-free PBF process, the repair procedure for a damaged blade section is shown in Figure 3. By applying the technologies described above, high-quality and high-precision building is achieved.

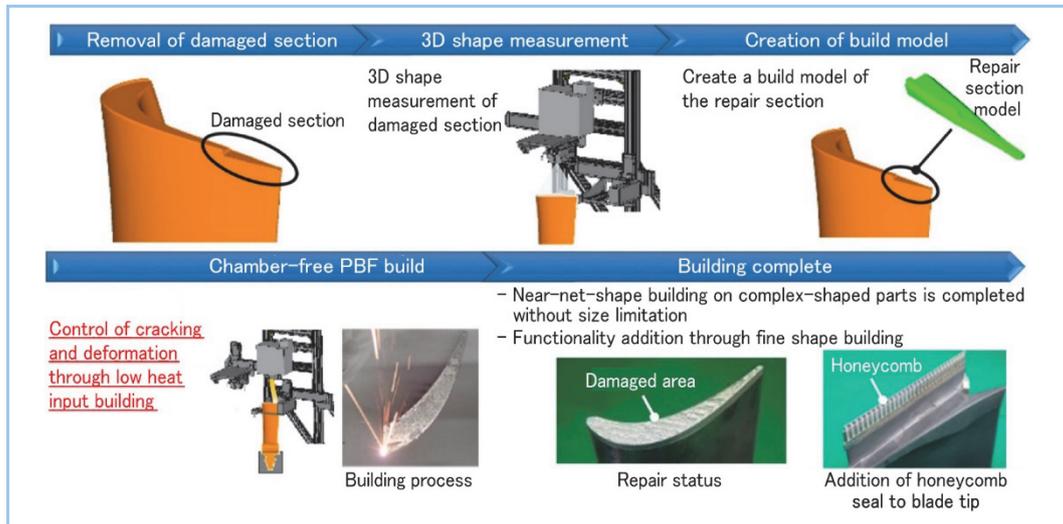


Figure 3 Building procedure of chamber-free PBF process

3. Powder bedding technology on curved surfaces

To bed the powder onto a curved surface, automatic powder bedding technology was developed. A container filled with powder and equipped with a metallic mesh over the outlet is vibrated by air pulses or ultrasonic waves to discharge the powder while scanning over the curved surface. Specifically, the shape of the container and the placement of vibration points were optimized in consideration of powder fluidity and vibration propagation characteristics, respectively.

While this method has the advantage of being less susceptible to the effects of surface undulations and roughness on the build surface, consistency of the powder bedding thickness is an issue. Therefore, thickness of the deposited powder and height of the layer were measured after building, using sensors such as laser displacement meters, and the thickness of the deposited powder and height of the layer were adjusted by applying the feedback to the scanning speed of the container (powder feeding amount).

Results of bedding metal powder (Inconel 718) on a groove test sample (depth: 2 mm, 30° taper) are shown in Figure 4. As shown in the figure, thickness after depositing five layers of powder was 0.15 mm to 0.25 mm, which is equivalent to 0.03 mm to 0.05 mm per layer. Therefore, thickness within the range building is possible using the PBF process was confirmed.

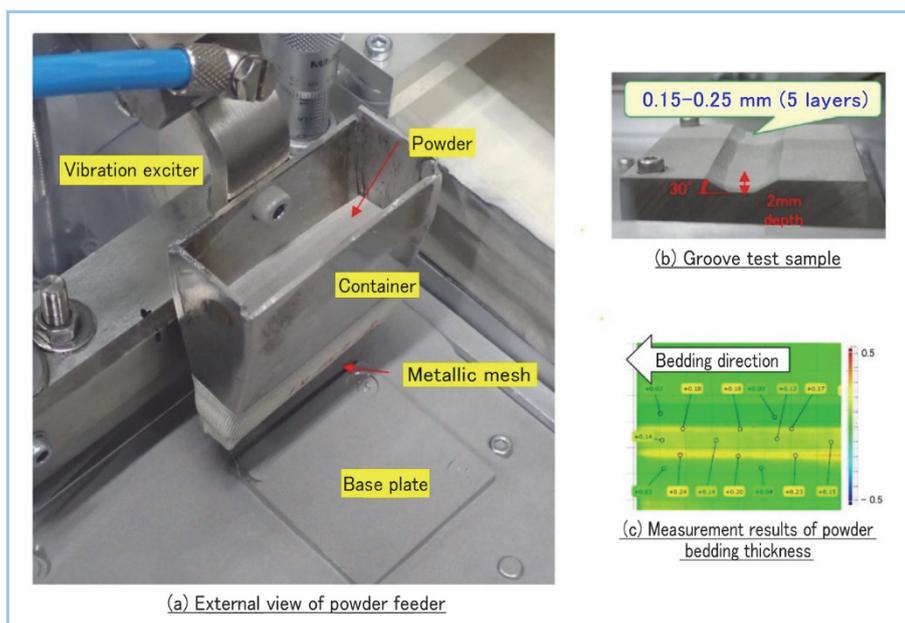


Figure 4 Powder spreading unit for curved surfaces

4. Building verification

4.1 Elemental testing

Challenges to the chamber-free PBF process include ensuring relative density of the build objects, positioning accuracy of the build interface, and interface strength. Therefore, cylindrical models with the same cross-sectional shape were built onto cylindrical test samples (25 pieces in total) arranged within the build area, and observation of the cross-sectional microstructure (measurement of relative density) and positioning accuracy of the interface (measurement of steps) of the build objects were evaluated. Specifically, using build position and gas pressure near the gas flow nozzle (0.02 MPa, 0.04 MPa) as error factors, cylindrical models (SUS316L material) with the same cross-sectional shape, expanded by 0.8% to suppress steps, were built onto cylindrical test samples (SUS316L material) using the chamber-free PBF process. Before building, the laser irradiation position for each cylindrical model was verified using a guide laser and a coaxial camera, and any deviations in the irradiation position were corrected. Being able to easily correct the laser irradiation position in this manner is one advantage of the chamber-free PBF process. After building, cross-sectional microstructure observation and shape measurement of the cylindrical sections were performed. Relative density was calculated using image processing (binarization).

As a result, relative density of all built objects within the build area (25 pieces in total) was 99.95% and higher, and the measured step at the build interface averaged 0.037 mm (standard deviation: 0.024 mm) as shown in **Figures 5** and **6**. High-quality and high-precision AM was confirmed to be possible with the chamber-free PBF process, similar to the conventional PBF process. As shown in **Figure 7**, the possibility of building on thin-walled cylinders and thin-plate components at a similar high precision as conventional PBF was also confirmed.

Next, in order to evaluate tensile strength of the build interface, test samples were prepared by building Inconel 625 material onto a Ni-based alloy substrate (equivalent to Inconel 738) using the chamber-free PBF process so that the build interface was the evaluation section, and tensile tests were conducted at room temperature. As a result, as shown in **Figure 8**, yield strength, tensile strength, and elongation was confirmed to satisfy ASTM standard values, and the tensile test samples did not fracture at the build interface, ensuring sufficient interface strength.

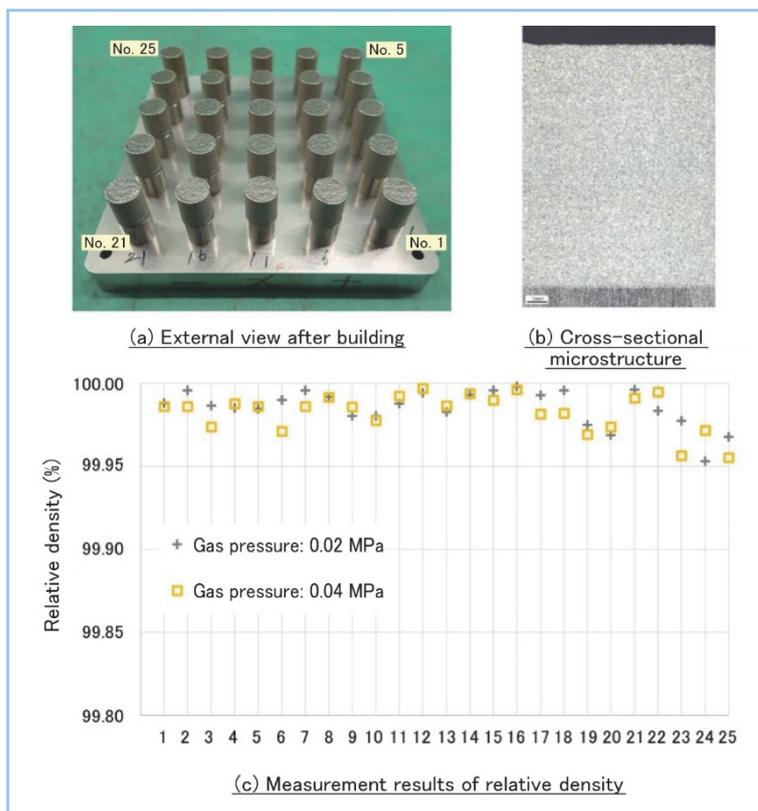


Figure 5 Measurement results of relative density for cylindrical test samples

4.2 Build on precision internal passages

For casting components containing precision internal passages that simulated damage to turbine blade tips, repair sections (material equivalent to Inconel 939) were additive manufactured using the chamber-free PBF process. Specifically, the substrate was measured by a 3D scanner, and the build model was finely adjusted to follow the contours, including internal passages, while the laser irradiation position was corrected using a coaxial camera. The fine passages were masked before building to bed the powder on. Masking material was removed after building by heat treatment or a finishing process. As a result, high-precision building of fine internal passages could be achieved as shown in **Figure 9**.

Furthermore, with the aim of improving product performance, MHI has been working on developing technology for the localized building of structures equipped with fine internal cooling passages on the surface of components, using the chamber-free PBF process. As shown in **Figure 10**, formation of fine internal cooling passages using this process was confirmed possible.

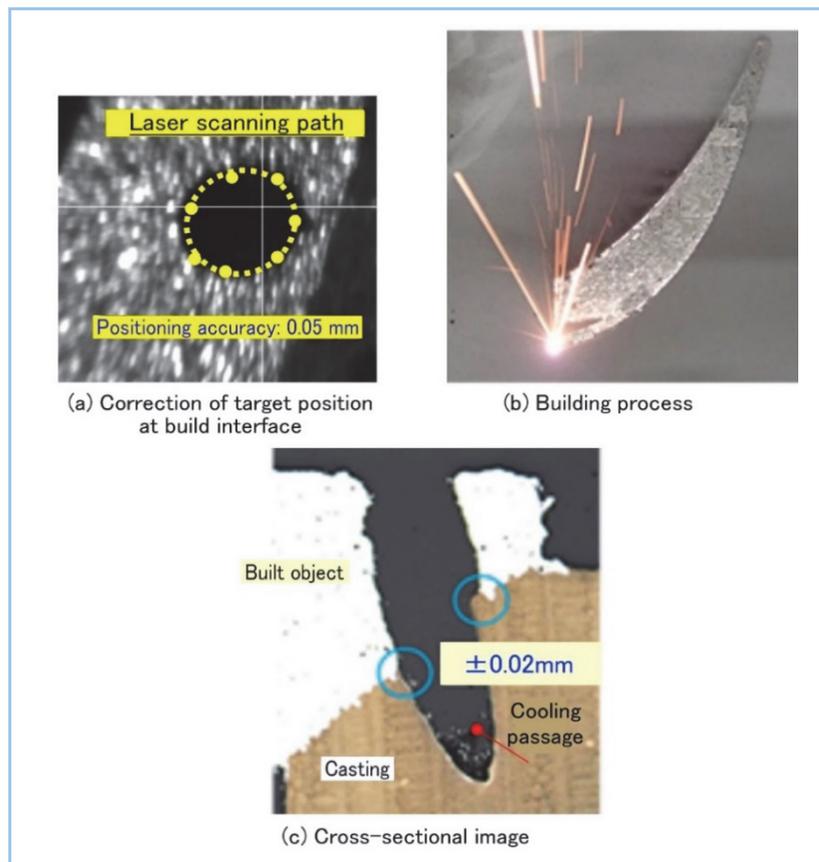


Figure 9 Building fine passages on simulated turbine blade parts

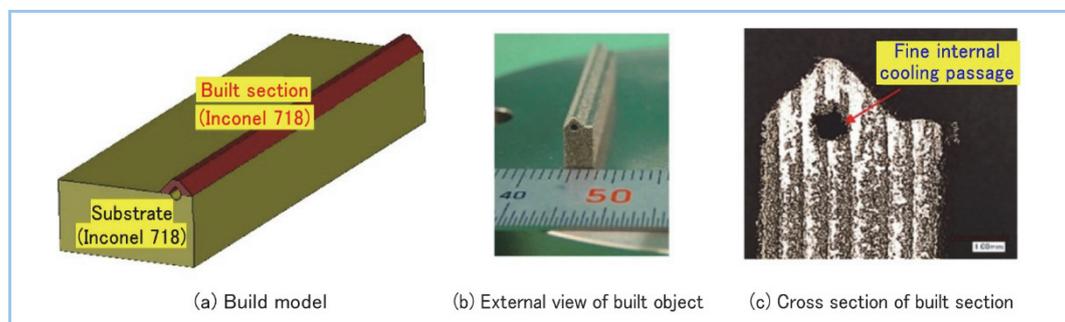


Figure 10 Building of fine internal cooling passages using chamber-free PBF

4.3 Honeycomb building on thin-walled sections

Honeycomb seals made of thin plates (plate thickness: 0.2 mm, material equivalent to Inconel 625) were built onto a thin plate that simulated a turbine blade tip using the chamber-free PBF process. As shown in **Figure 11**, high-precision building was confirmed possible even on thin-walled components.

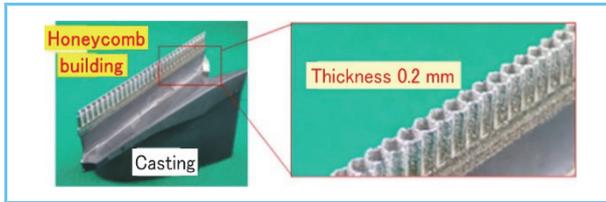


Figure 11 Honeycomb seal building on thin plate using chamber-free PBF

4.4 Build inside grooves

Localized repair of cracks and defects in components was simulated, and building was performed inside a groove after removing a crack. Specifically, a groove was machined into a Ni-based alloy casting component (material equivalent to Inconel 738), and a build model to fill inside the groove was created based on the results of the 3D shape measurements of the formed groove. The build model was given a 0.5 mm allowance to prevent insufficient fusion on the sloped sections of the groove and to ensure the machining allowance for the built-up area. Regarding powder deposition inside the groove, technology to bed the powder on a curved surface as described in Chapter 3 was applied, and the inside of the groove was additive manufactured with material equivalent to Inconel 738 using the chamber-free PBF process. As a result, building inside the groove could be performed with high relative density and without any fusion defect on the sloped sections, as shown in **Figure 12**.

Subsequently, strength test samples of Ni-based alloy (material equivalent to Inconel 738) were built using the chamber-free PBF process. After heat-treatment under the same conditions as the casting, high-temperature tensile tests were carried out. As indicated by the test results, tensile strength was equivalent to or higher than that of the casting, as shown in **Figure 13**. Additionally, the tensile test samples were confirmed to not fracture at the build interface, ensuring sufficient interface strength.

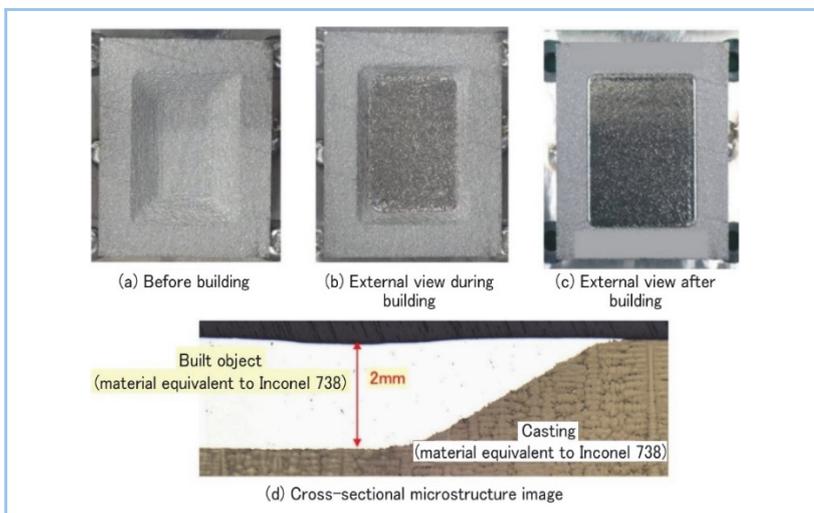


Figure 12 Building within groove using chamber-free PBF

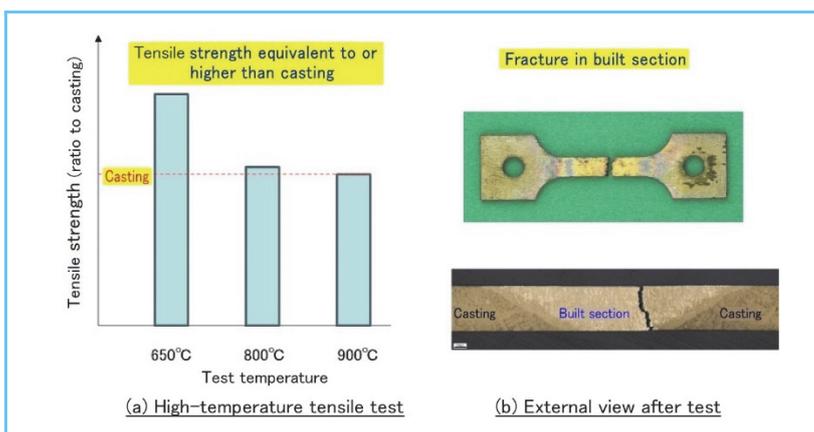


Figure 13 High-temperature tensile test results of AM built section within groove

4.5 Built on test samples

Reducing the size of samples used for material testing is necessary, particularly when obtaining a sample from the actual product is difficult or the number of samples are limited. Therefore, we attempted to build tab sections onto small-sized samples using the chamber-free PBF process to produce standard-sized test samples. Since the chamber-free PBF is an ultra-low heat input process with an extremely small heat-affected zone (HAZ), material degradation and deformation of the samples can be suppressed.

Specifically, the built sections were built onto low-alloy steel samples (SQV2A material) to produce Charpy impact test samples, according to the procedure shown in **Figure 14**. The cross-sectional microstructure observation results and Vickers hardness test results for the sample section and the built section of the Charpy impact test sample are shown in **Figure 15**. As shown in the figure, the HAZ was confirmed to be extremely small at 0.1 mm. Charpy impact test results are shown in **Figure 16**. The absorbed energy was confirmed to be equivalent to that of a standard test sample, and from the appearance after the test, the fracture was shown to occur in the sample section rather than the additive manufactured section. Having confirmed applicability of this process, MHI will consider verification for practical application in the future.

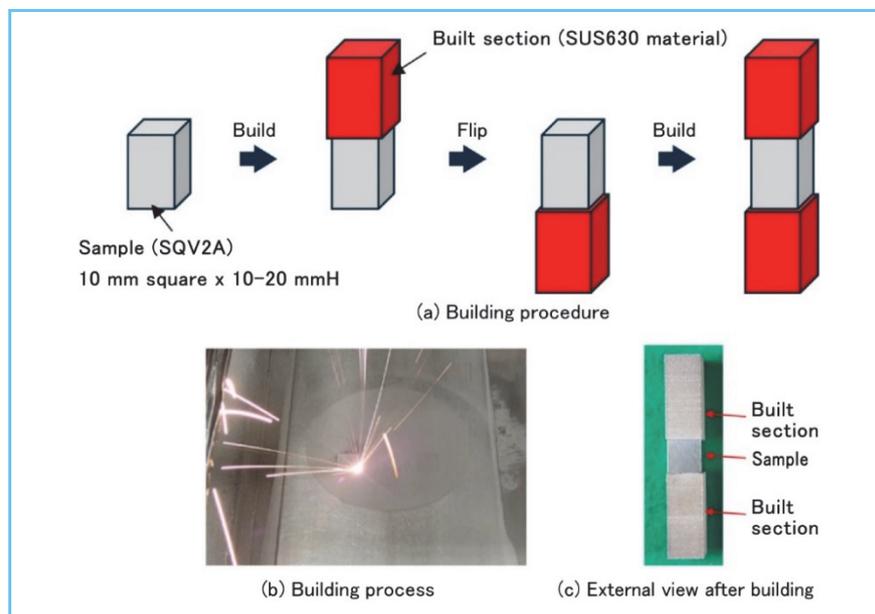


Figure 14 Regenerative building of sample gripper section using chamber-free PBF

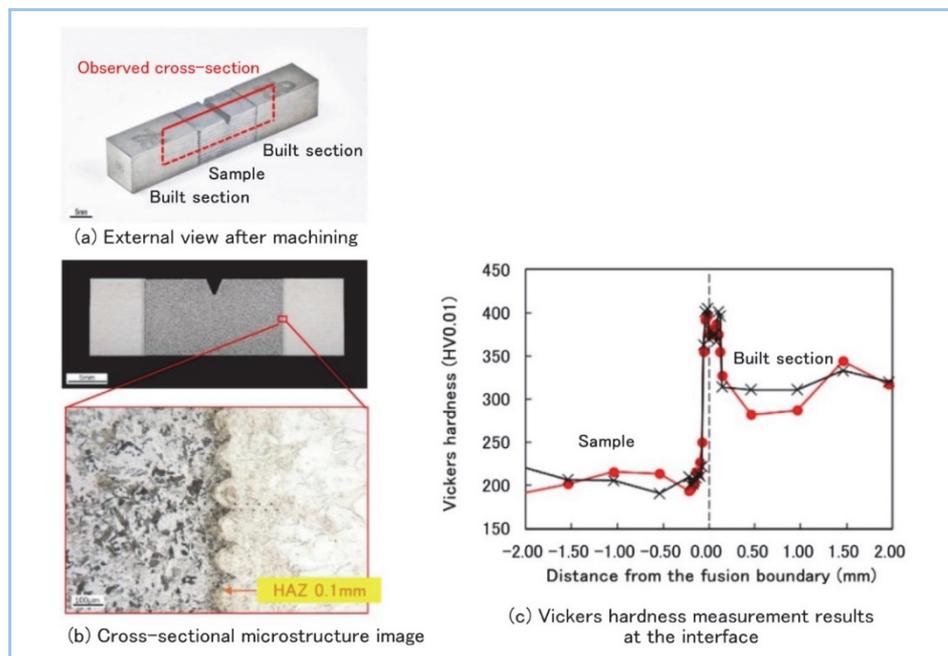


Figure 15 Cross-sectional microstructure and Vickers hardness test results at the interface between the sample and built section

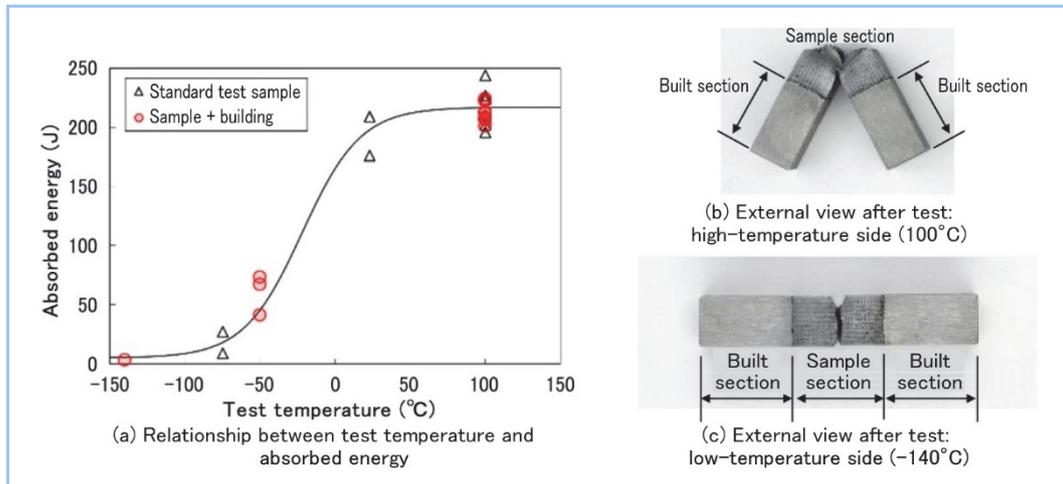


Figure 16 Charpy impact test results

5. Conclusion

As part of MHI Group's initiatives in metal AM technology development, this report described the progress of development of direct AM technology on large components and curved surfaces using the chamber-free PBF process and examples of fabrication using it. Future challenges include establishing related technologies for automation and mass production applications of this process, with focus on achieving early practical implementation by development that targets candidate components for actual machine applications. In addition, not limited to this process, MHI will seek to develop AM technologies in general, in order to improve the quality, cost, and delivery of the MHI products.

References

- (1) M. Kataoka et al., DEVELOPMENT OF METAL AM TECHNOLOGY FOR GAS TURBINE COMPONENTS, *J. Glob. Power Propuls., Soc.* 2023: 49-65
- (2) T. Ishide et al., Development of Additive Manufacturing Technology toward Practical Utilization, *Mitsubishi Heavy Industries Technical Review*, Vol.55 No.2 (2018)
- (3) T. Takahashi et al., Development of AM Technology for Aircraft Application, *Mitsubishi Heavy Industries Technical Review*, Vol.58 No.4 (2021)
- (4) S. Tanigawa et al., Development of Metal AM Technology for Gas Turbine Components, *Mitsubishi Heavy Industries Technical Review*, Vol.59 No.1 (2022)
- (5) H. Nakaharai et al., Development of Compact and High-performance Heat Exchangers Using Metal Additive Manufacturing, *Mitsubishi Heavy Industries Technical Review*, Vol.60 No.1 (2023)