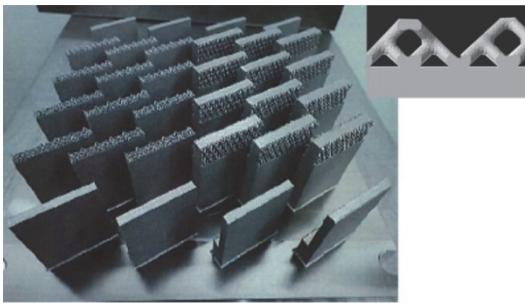


Development of AM Technology for Aircraft Application

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Additive Manufacturing (hereinafter referred to as AM) has undergone a rapid evolution as a new manufacturing technology and its application to products is expected to result in various advantages, such as weight reduction, higher functionality and supply chain innovation. On the other hand, aerospace products require strict quality control and also need to obtain certification of conformity with laws and regulations. Therefore, it is important to establish a process control method that ensures stable quality. Mitsubishi Heavy Industries, Ltd. (MHI) has been making efforts to expand the application of AM technologies to aerospace products by identifying physical phenomena that affect quality and then developing metal and plastic AM fundamental technologies in accordance with applicable products and quality requirements.

1. Introduction

AM is the process of fabricating parts directly from three-dimensional data using powder, wire, etc., as raw materials. AM allows the manufacturing of parts with complex shapes and the integral molding of parts—something that could not be realized by traditional manufacturing processes such as machining and welding—and it is expected to reduce processing/assembly costs and bring about supply chain innovation, leading to lower procurement costs and shorter lead times. As a new manufacturing technique that can become a game changer, AM has been actively researched and developed mainly in the fields of aerospace, energy and medical products all over the world.

MHI has also been developing fundamental technologies of AM and studying their applications to products in a collaborative effort between business domains and the Shared Technology (ST) Framework. Especially in the field of aerospace, although there is a high technical hurdle for its application because of the high quality requirements for aerospace products, AM offers many benefits such as weight reduction, an increase in functionality and the reduction of manufacturing costs and shorten lead times by applying AM-specific design methods.

This report introduces our development of AM technologies for aerospace products, as well as the jigs and tools necessary for manufacturing such products.

2. Development of DED AM process for titanium

2.1 Application of AM to titanium parts for aircraft

Titanium alloys typified by Ti-6Al-4V have a high specific strength and a high corrosion resistance and they are also excellent in terms of compatibility with carbon fiber reinforced plastic (CFRP). Therefore, they are increasingly applied to aircraft. On the other hand, since the material cost is high and the processability is low, the reduction of both manufacturing costs and processing lead times have become challenges. Metal AM technologies are broadly classified into Directed Energy Deposition (hereinafter, DED) and Powder Bed Fusion (hereinafter, PBF). Compared with the PBF process, the DED process offers a faster manufacturing speed and has relatively fewer restrictions in terms of the size of objects to be additive manufactured. Therefore, it is considered to

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be advantageous to apply the DED process to aircraft body structures, which have many large parts. MHI has been developing DED processes using titanium alloy powders as materials (with a laser heating source), aiming at applying them to titanium components for aircraft.

2.2 Concept for development of DED process for titanium

In the application of metal AM technologies to aircraft parts, both the microstructure and the internal quality of the material need to be controlled to satisfy the mechanical properties required for the material. The microstructure and the internal quality change, in principle, depending on physical phenomena such as the melting/solidification and cooling rate of the molten pool. Therefore, it is very important to identify the effects of the main additive manufacturing parameters (key process parameters) in the DED process, such as laser output, scanning rate and beam diameter, on the physical phenomena and set appropriate parameter ranges to obtain a highly reproducible and stable quality. **Figure 1** shows the schematic diagram of the DED process and typical key process parameters. The SAE (Society of Automotive Engineers), which established and has operated the AMS standards (U.S. public standards) applicable to aircraft, set up an AM Committee in 2015, after consultations with the FAA (Federal Aviation Administration), for the purpose of establishing public standards for AM processes and AM powder materials. On the basis of discussions at the regular meetings in which engine/airframe manufacturers, material/equipment manufacturers, government agencies, etc., participate, the AM Committee has been establishing public standards on metal AM by PBF and DED processes and plastic AM. At present, the specifications of powders of Ni-based heat-resistant alloys and titanium alloys and AM processes were established and are currently available. Concerning the key process parameters shown in Figure 1, the kinds and ranges of process parameters have been under study on the basis of the public standard requirements approved by certification authorities.

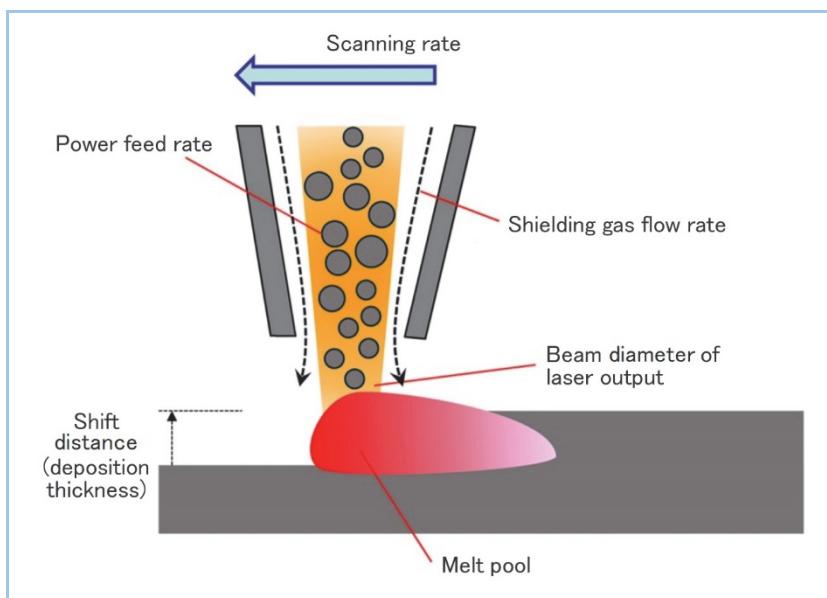


Figure 1 Schematic diagram of DED process and typical key process parameters

2.3 Development of DED process for titanium

MHI started the development of DED processes for titanium in 2018 and has defined the standard additive manufacturing conditions to obtain a good internal quality with fewer internal defects such as a lack of fusion. Ti-6Al-4V is also known to have an $\alpha+\beta$ dual-phase microstructure. It solidifies over the $\alpha-\beta$ transformation temperature (about 995°C) during additive manufacturing by the DED process and as a result, it will have a microstructure with the acicular α -phase deposited inside β - grains. At this time, as previously described, the grain size and the grain morphology will change depending on the heat input and the cooling speed during additive manufacturing. The typical titanium microstructure by DED is shown in **Figure 2**. The relationship between the energy density (=laser output/(scanning rate \times beam diameter)) and the grain size, which was obtained from past research results, is shown in **Figure 3**. It shows that as the energy density increases, the heat input increases, resulting in the trend toward increased grain size. On the other hand, when the energy

density decreases, the risk of internal defects such as a lack of fusion increases, as presented in **Figure 4**. Therefore, it is important to set the ranges of AM parameters so that both the internal quality and the microstructure can satisfy the requirements. The solidification process of the molten pool, which affects the microstructure and the internal quality, involves complicated phenomena that are dependent on not only additive manufacturing parameters, but also powder properties or the shape of the object to be additively manufactured (additive manufacturing path). Therefore, MHI has also been developing DED processes using simulation methods including melting and solidification processes.

The tensile test result of a titanium specimen by DED additive manufacturing with the standard AM parameters is shown in **Figure 5**. It was confirmed that the specimen has tensile strength characteristics equivalent to those of conventional forged titanium materials.

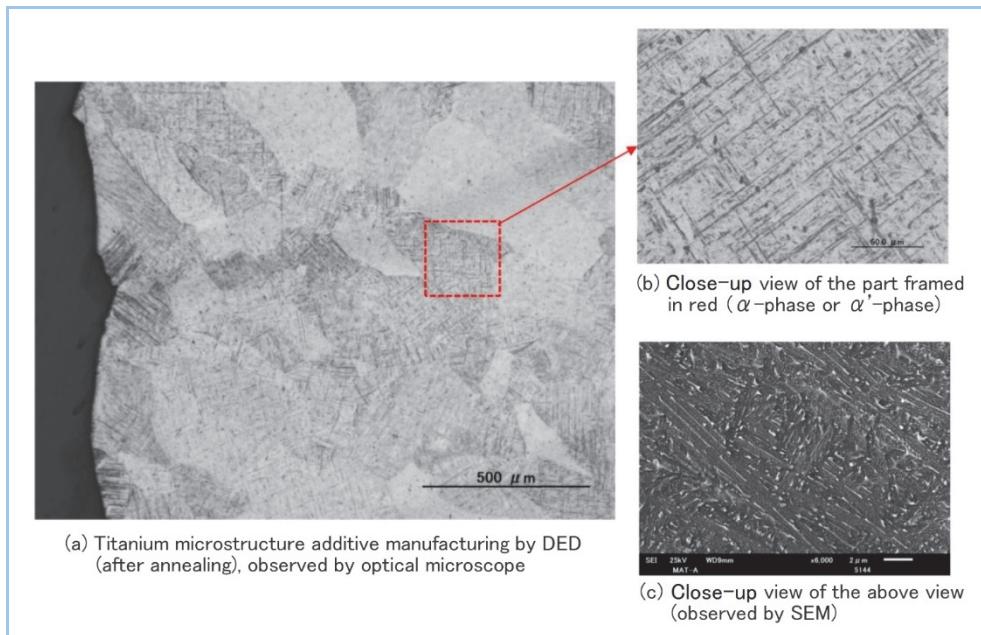


Figure 2 Typical titanium microstructure by DED additive manufacturing

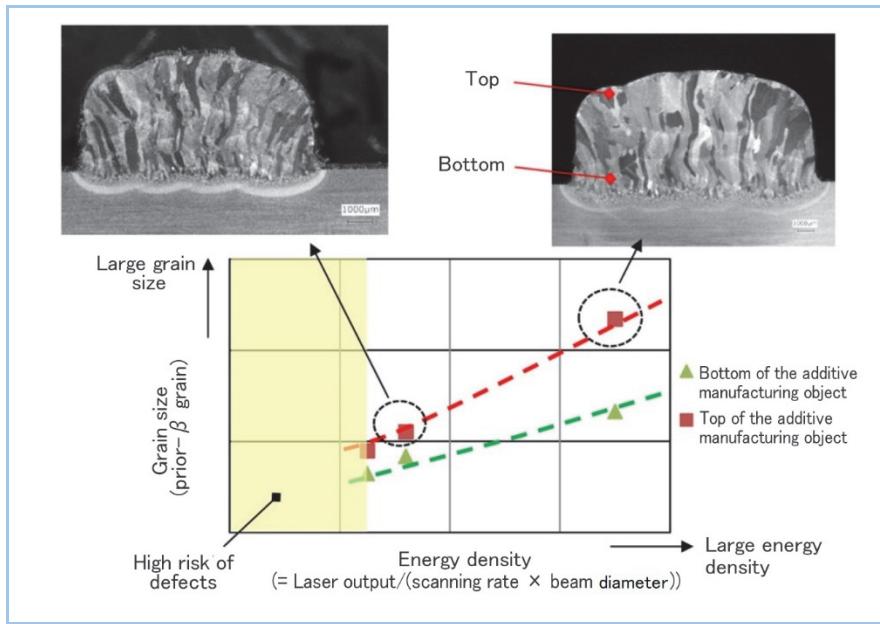


Figure 3 Relationship between energy density and grain size in titanium AM by DED

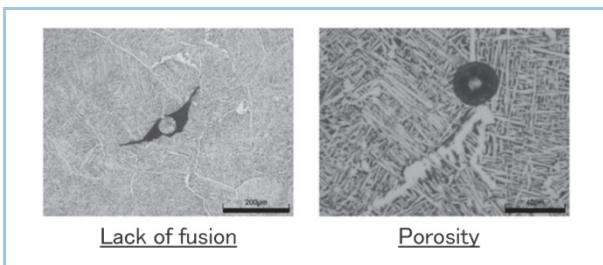


Figure 4 Internal defects in titanium AM by DED

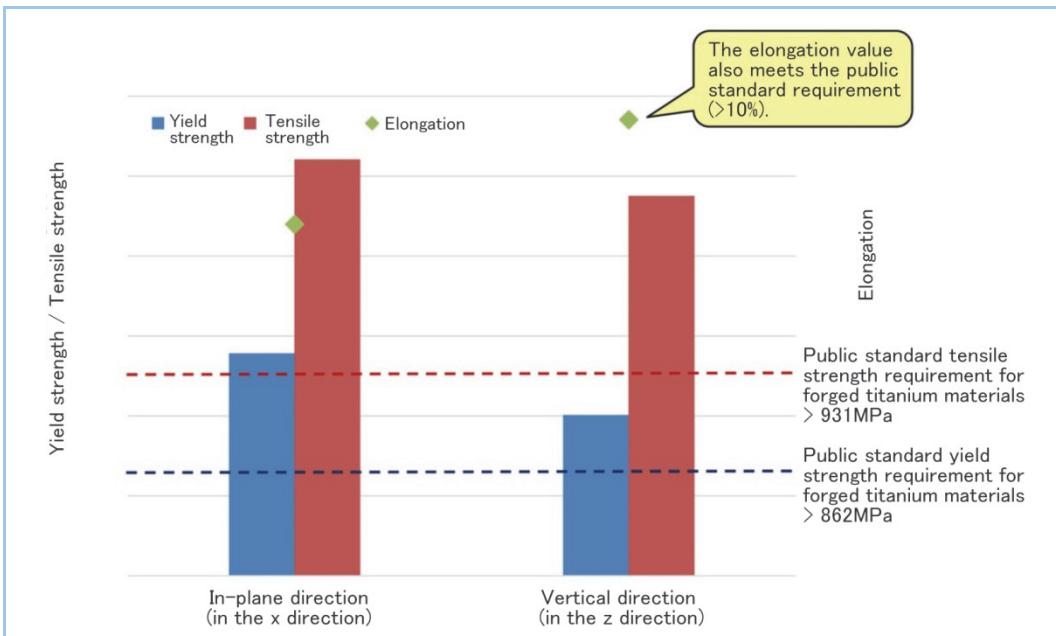


Figure 5 Tensile properties of titanium material additive manufactured by DED (after annealing)

3. Development of AM lattice bonding technology for metal and plastic

In recent years, the need for weight reduction of the transport equipment such as aircraft and automobiles has further increased and the development of methods of manufacturing multi-material structures (integral structures of metal and plastic), in which a part of a metal structure is replaced with plastic material, has been promoted. In a multi-material structure, different materials are bonded. Therefore, the development of metal and plastic bonding technologies is necessary. The methods of bonding metal and plastic with adhesives or by injection molding after special surface treatment of a metal surface have been proposed. But the metal and plastic joining structures obtained by these conventional bonding methods exhibit variations in strength by the interfacial states before bonding or reduced strength due to moisture absorption from the environment during operation. Therefore, at present, such bonding methods are not used for strength members.

MHI has been making efforts to develop highly-reliable, high-strength metal and plastic bonding technologies aiming at applying them to strength members. In particular, AM lattice bonding technology that allows mechanical engagement using the metal AM technology is a promising candidate. AM lattice bonding technology is a technology for manufacturing an integral structure of metal and plastic by making a lattice structure on the metal-side bonding surface, injecting plastic inside the lattice with adhesive or by injection molding and solidifying it. The metal-side material with a lattice structure is fabricated by PBF AM technology. **Figure 6** is the schematic diagram of AM lattice bonding technology and one example of the lattice structure. AM lattice bonding uses mainly a mechanical bonding force by interdigitation, without using the adhesive force of adhesive or plastic which is easily affected by moisture absorption, etc., in the environment. Therefore, AM lattice bonding is considered to be superior in terms of strength and reliability compared with conventional techniques.

To increase the strength of metal and plastic bonded parts manufactured by lattice bonding, it is important to optimize the lattice shapes. We manufactured lattices with shapes that allow plastic to be filled into the inside of the lattice without causing defects or problems during the manufacturing process, while considering the alleviation of heat strain due to load transfer and temperature changes at the bonded parts and repeatedly conducted verification tests of the bonded parts. The appearance of the metal and plastic specimen manufactured by the AM lattice bonding process is given in **Figure 7**. The verification result for static strength and fatigue characteristics showed that the bonded parts obtained by AM lattice bonding technology had a higher strength, maintained the strength even after moisture absorption and showed little variation in strength compared with those obtained by conventional bonding technologies. **Figure 8** shows the tensile strength test result for the bonded part of the injection molded plastic (PEEK-CF30) and the additive manufacturing Ti-6Al-4V alloy. The tensile strength of the bonded part exceeded 70 MPa and rupture occurred on the plastic base. In addition, the fatigue test result for the bonded part is given in **Figure 9**. In the shearing-tension fatigue test, the number of cycles to fracture exceeded 10^6 cycles with a stress of about 20 MPa at maximum (stress ratio: 0.1). The bonded part exhibited an amazingly high bonding strength as a plastic and metal bonded part. It was also observed that fracture occurred on the plastic base regardless of the presence or absence of moisture absorption.

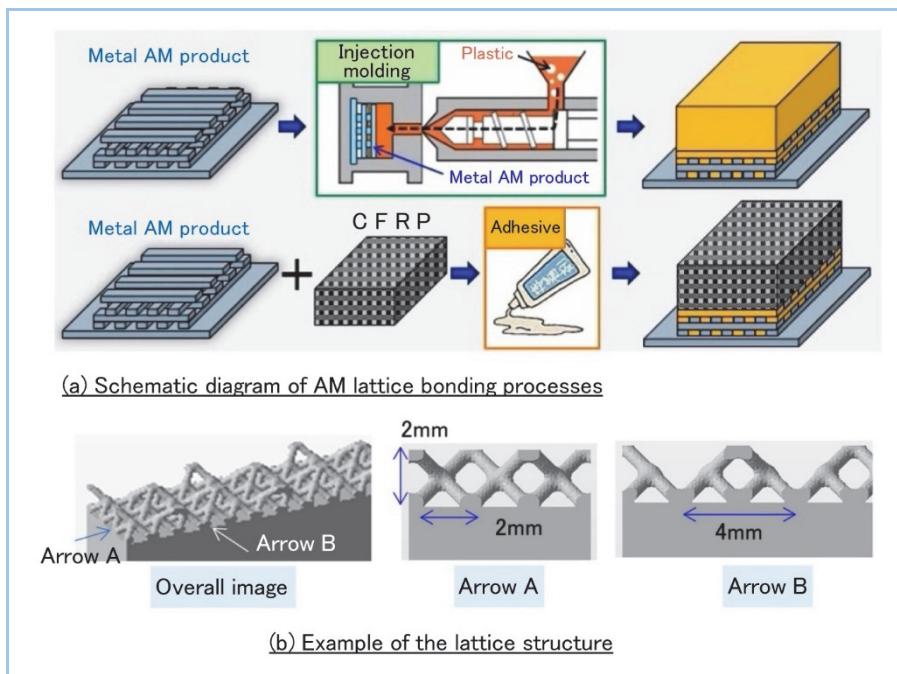


Figure 6 Example of lattice structure and schematic diagram of AM lattice bonding processes

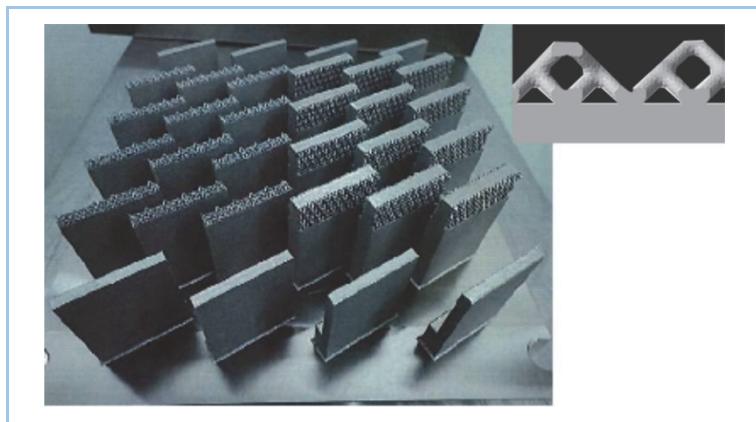


Figure 7 Appearance of metal and plastic specimen manufactured by AM lattice bonding process

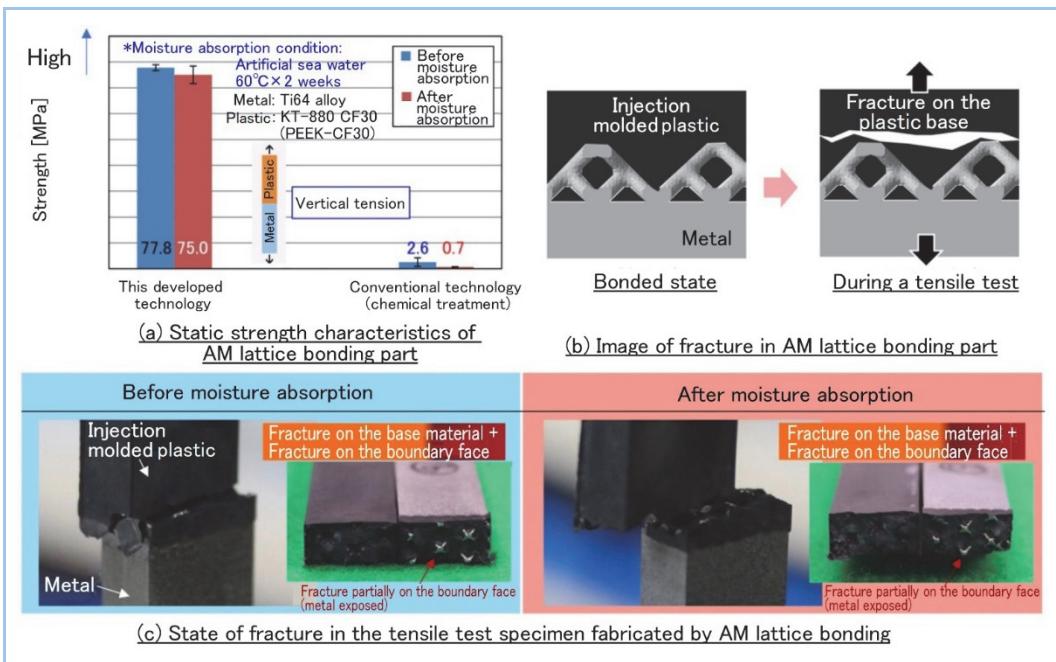


Figure 8 Static strength characteristics of AM lattice bonding part

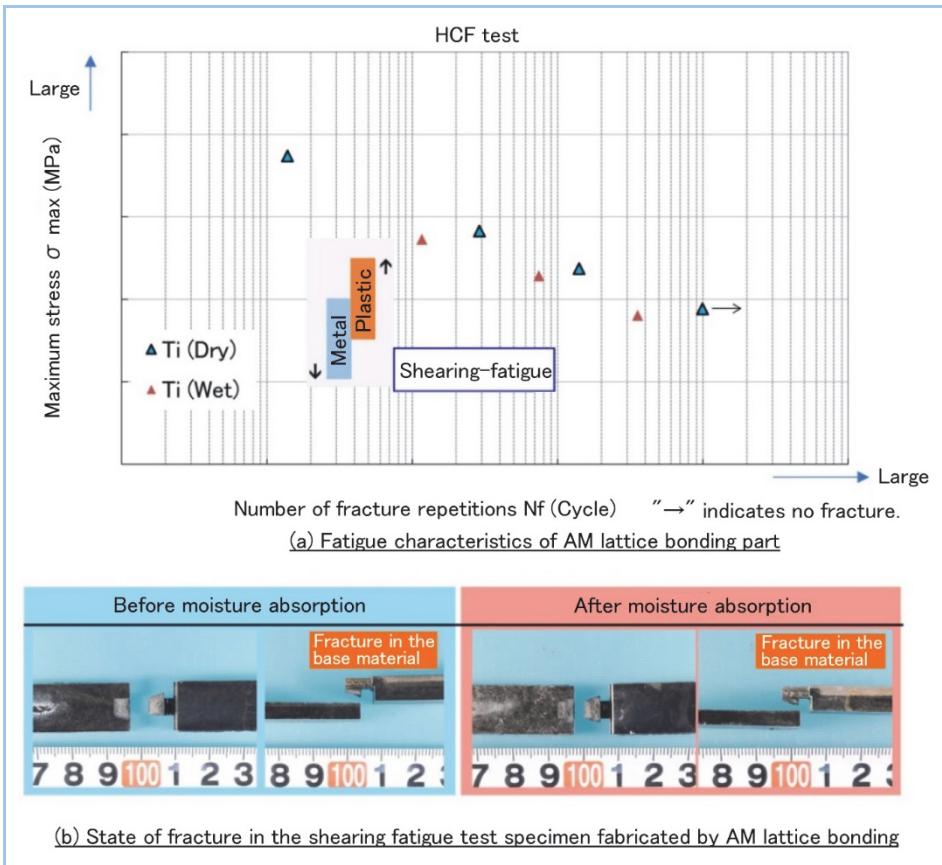


Figure 9 Fatigue characteristics of AM lattice bonding part

4. Application of plastic AM technology to jigs and tools

An aircraft is generally composed of over one million parts and the use of various kinds of jigs and tools is indispensable for the manufacturing of single parts, assembling and the testing of various functions. Many different jigs and tools must be manufactured in small batches and manufacturing and control of several hundred thousand jigs and tools—from palm-size hand tools to assembly jigs of several meters in size—have been challenges over many years in terms of manufacturing cost, control cost and manufacturing lead time. As such, MHI has been studying the application of plastic AM technology to jigs and tools aiming at reducing manufacturing costs and lead times. In particular,

jigs and tools with special shapes that are not commercially available are custom-made based on one-part, one-sheet drawings in many cases and the high manufacturing costs and long lead times have been issues. Therefore, we have targeted the jigs and tools that are known as "shop aids" for the application of plastic AM technology. Shop aid is a generic term for jigs and tools that require no warranty of accuracy and durability because they have relatively few effects on product quality. In shop aids, there are many jigs and tools to which the plastic AM can be applied with its general manufacturing accuracy (+0.2 mm) and rigidity (1 to 3 GPa) without causing any problems in terms of product quality. Accordingly, the cycle of designing, manufacturing and verification with actual equipment can be completed in a short time.

The principle of additive manufacturing by an FFF (Fused Filament Fabrication)-type AM equipment, which is used to manufacture jigs and tools, is depicted in **Figure 10**. FFF is the process of manufacturing a three-dimensional shape by melting and depositing a filament material with a heater in the head. The key features of FFF are: the prices of the equipment and material are inexpensive; the equipment for FFF is compact in size and can be set in any place such as experiment building, workshop and office; and the inside of a target object can be manufactured using a honeycomb structure or lattice structure. The FFF process is used in the Research & Innovation Center and several business domains such as Aero Structure Division in MHI. In FFF-type AM, if 3D data is available, manufacturing is completed in a short time of one or two days. Therefore, it is possible to quickly verify improvement ideas from manufacturing sites and apply those improvements onsite. As a result, the productivity of aircraft parts has been substantially increased.

As one example, the application to hand tool attachments that are used on the assembly lines of aircraft body panels at the Eba Plant and Oye Plant is described. The assembly work of aircraft body panels is comprised of drilling with hand drills, riveting with hand riveters, applying sealing agents with sealing guns, etc. Panels have different curvatures depending on the aircraft model or part. Panels assembled by commercially available tools often cause partial contact and backlash. We manufactured tool heads using the plastic AM equipment so that they have shapes that fit the curved surfaces of actual aircraft and mounted them to the existing hand tools used in assembly work. At the Oye Plant, a prototype of drill guide that allows dust collecting at the same time as drilling was manufactured by plastic AM and has been used for checking dimensions before manufacturing metal tools, etc. The hand tool attachments manufactured by plastic AM are shown in **Figure 11**.

These various hand tools need to be manufactured in large quantities according to the aircraft body size and parts to be applied. By using plastic AM, we were able to manufacture prototypes and verify their application to actual aircraft in a short time and at a low cost, contributing to the improvement of workability and safety, as well as the reduction of the burden on workers. Currently, additively manufactured jigs and tools are used on the aircraft production line at the Oye Plant and over several hundred kinds—and several thousand individual tools—are already in actual use.

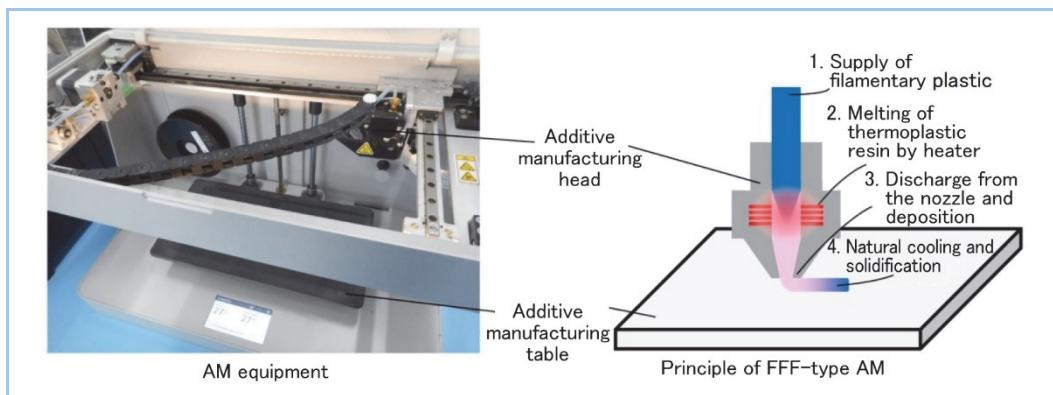


Figure 10 Principle of FFF-type plastic AM

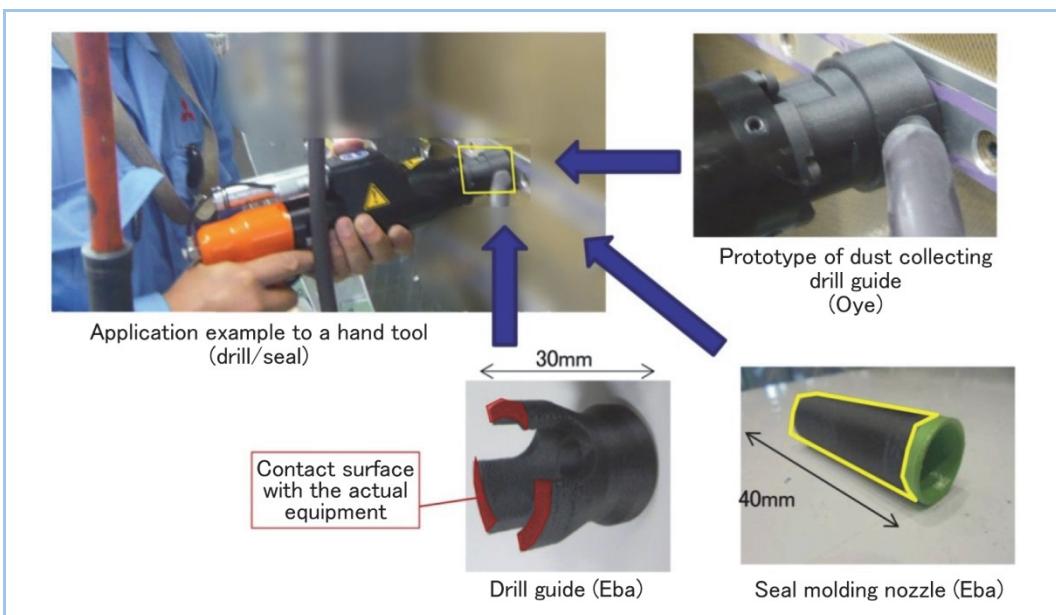


Figure 11 Prototypes of hand tool attachments made using plastic AM

5. Conclusion

For AM, multiple technologies, such as those for materials, equipment, manufacturing processes and quality assurance, must be developed. AM technologies have been developed at a rapid pace throughout the world, but the important thing in applying AM to products is to understand the fundamental physical phenomena such as melting/solidification, heat transfer and phase transformation and then establish an appropriate process that can satisfy the quality requirements for a target part.

In addition, for application to aerospace products, certifications by government agencies, etc., will be required. MHI will accelerate the development of products and research on fundamental technologies using the features of AM, without adhering to conventional design or manufacturing methods, while paying close attention to global trends of international standards.