Development of Metal-based Additive Manufacturing System with Directed Energy Deposition Technology

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Our company, Mitsubishi Heavy Industries Machine Tool Co., Ltd. (MAT), together with Mitsubishi Heavy Industries Ltd. (MHI), joined the Technology Research Association for Future Additive Manufacturing (TRAFAM) in 2014, which was established by the Ministry of Economy, Trade and Industry as a national project. Since then, the two companies have worked on the development of a metal-based additive manufacturing system with directed energy deposition technology. The system that MAT has developed is a hybrid system with an additive manufacturing function and a machining function, and it enables high-efficiency, high-precision additive manufacturing by applying the function of process monitoring during manufacturing and a powder feed nozzle with an increased shielding performance. At present, jointly with industrial users from various fields, we are promoting the development of an additive manufacturing method that can be put into practical use.

1. Introduction

Deposition-type additive manufacturing technology is also known as Directed Energy Deposition (abbreviated as DED). It is a technology for additive manufacturing in which a metal material, while being locally fed, is fused and solidified together with a substrate using an appropriate heat source. In the metal additive manufacturing system our company developed, a method of fusing the metal powder sprayed by a carrier gas using a laser beam was adopted. The principle of deposition-type additive manufacturing is shown in **Figure 1**.

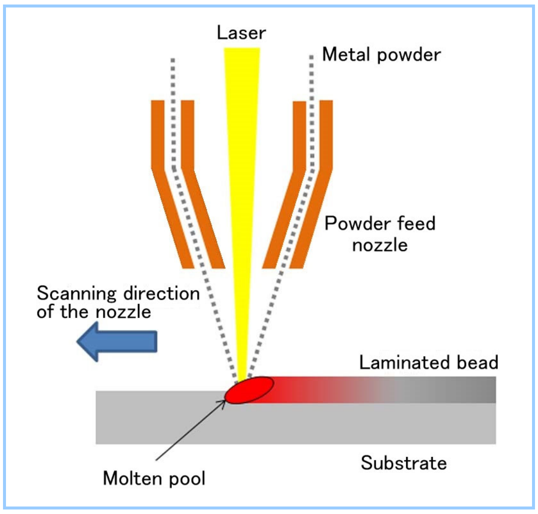

Figure 1 Deposition-type additive manufacturing method

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This method is characterized by the fact that since metal powder is locally fed, powder waste is reduced, the upsizing of the device according to the object to be manufactured is facilitated, and the additive manufacturing of a material different from the substrate is enabled. With these characteristics, this method is expected to be applied to the manufacturing, repair and functional improvement of high-functionality products in the aeronautical, space, motor and automobile fields. On the other hand, for the widespread use of this technology, there are challenges to be addressed, such as the improvement of productivity and the establishment of a quality assurance method and an additive manufacturing process. This report describes the outline of the developed metal additive manufacturing system and the efforts to address the challenges.

2. Outline of the deposition-type metal additive manufacturing

To increase the flexibility in the shape of the object to be manufactured and the manufacturing method, this system has both an additive manufacturing function and a machining function enabling 5-axis control by NC (numerical control). In addition, for providing the functionality required for mass production of the object to be manufactured, the structure of a general-purpose vertical type machining center is adopted. **Figure 2** depicts the inside of the developed system.

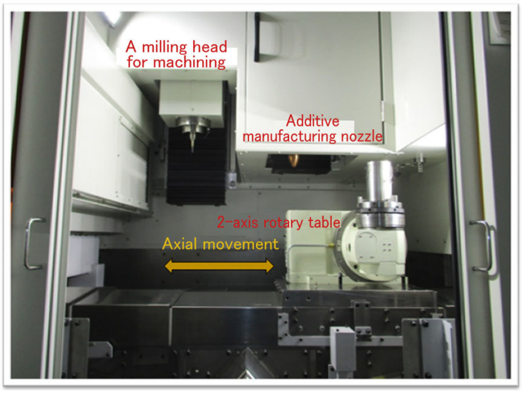

Figure 2 Inside of the additive manufacturing system

The units that make up the additive manufacturing functions include an additive manufacturing laser head, a laser oscillator and chiller, a powder feeding device and a dust collector for collecting powder. In the system, a fiber laser with a maximum output of 6 kW is used, and it is transmitted to the additive manufacturing laser head by optical fiber. In the additive manufacturing laser head, an optical element for focusing the laser beam, a powder feed nozzle for spraying metal powder and various sensors for observing the molten pool are incorporated. The powder feed device is connected to the powder feed nozzle through a pipe and stably feeds metal powder to the additive manufacturing part. A plurality of powder feed hoppers can be installed.

As the units that constitute the machining function, a milling head, an automatic tool replacement device and a storing magazine are provided. A high-speed spindle suitable for processing before additive manufacturing in repair and surface finishing after additive manufacturing was developed based on our ultraprecision spindle, and it provides superior rotational accuracy and high reliability.

As the parts used for both the additive manufacturing function and the machining function, a drive unit for moving the object to be manufactured and each head at a predetermined speed for positioning, a control unit for controlling each head and device and a control panel are provided. In view of safety, a machine cover with a laser shielding window, a door with an interlock, an automatic fire extinguishing appliance and an oximeter are also installed.

3. Development of process monitoring technology

For additive manufacturing of high-functionality material at the target additive manufacturing speed and accuracy, it is necessary to monitor the shape of the molten pool and the data of light emitted from the molten pool by the sensors in the additive manufacturing head and control the deposition conditions so that the obtained values fall within the thresholds for the material.

Therefore, in order to intensively conduct the analysis of the additive manufacturing process by monitoring and the element test for investigating the effects on the additive manufacturing quality, we manufactured a small-size additive manufacturing system with the functions required for the monitoring verification test. This additive manufacturing test system is comprised of a drive table, an additive manufacturing head, a powder feed device, a laser oscillator, a control device, etc. **Figure 3** presents the appearance of the system.

Figure 4 illustrates the developed process monitoring screen. It allows the display of the temperature distribution of the molten pool in a color image and the display of obtained waveforms in real time.

Figure 3　Process monitoring test system

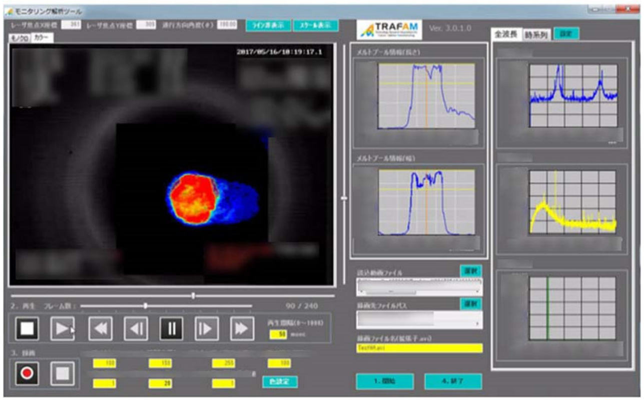

Figure 4　Process monitoring screen

Figure 5 gives examples of the display of the temperature distribution of the molten pool in a color image. It shows that the area of the part with high brightness (in red) of the molten pool increases with the increase in the laser output. This monitoring data is linked with the additive manufacturing program of the system and can be used as quality traceability data by estimating the correlation between the additive manufacturing quality and the monitoring data. Furthermore, this function can be used to stabilize the additive manufacturing quality in the future, improving the performance of the additive manufacturing system along with progress in the additive manufacturing optimization algorithm.

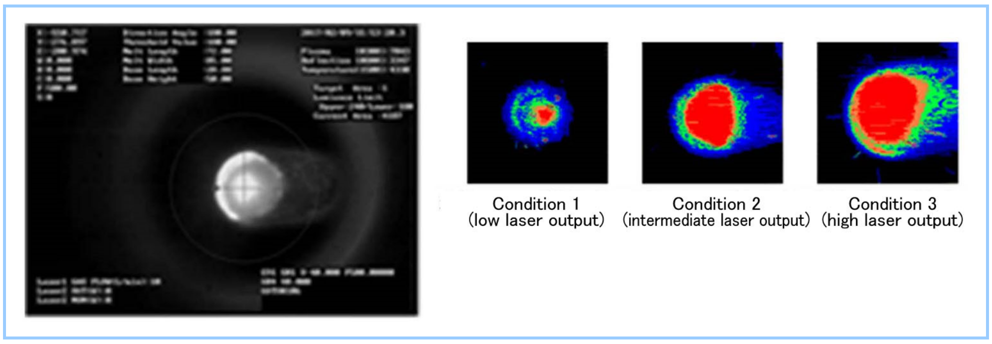

Figure 5　Images of the molten pool (change of the molten pool size and temperature distribution by laser output level)

4. Development of powder feed nozzle

For the practical use of high-quality, multi-layer additive manufacturing in the atmosphere using active metal such as Al and Ti alloys – without the displacement of the atmosphere by gas in the additive manufacturing system – and high-speed additive manufacturing, it is important to ensure the performance of the powder converging at the powder feed nozzle and the shielding performance, which has a significant effect on the additive manufacturing quality. Therefore, assuming that an appropriate nozzle is used according to the shape and accuracy of the object to be manufactured, we manufactured two types of nozzle, a 3-port feeding nozzle and an co-axial feeding nozzle, both of which ensure the powder converging performance and the shielding performance. In addition, in terms of the shape of the peripheral shielding, we manufactured a high-shielding type nozzle for spraying only a toric peripheral shielding gas in order to increase the flexibility of movement.

Figure 6 gives the state of powder convergence by each nozzle. In both of the nozzles, the focal position of the powder converges around the stand-off setting position of the nozzle during additive manufacturing. The converging diameter is about the size of the light condensing diameter in the optical system of the additive manufacturing head.

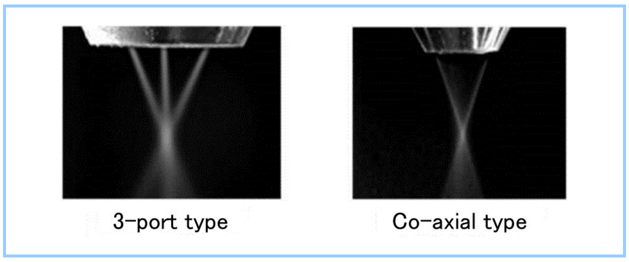

Figure 6 State of powder convergence by each nozzle

Figure 7 illustrates the periphery shield nozzle and the fluid analysis results for the shielding state. When periphery shielding is applied, the intrusion of air into the additive manufacturing part is prevented and the shielding area can be increased.

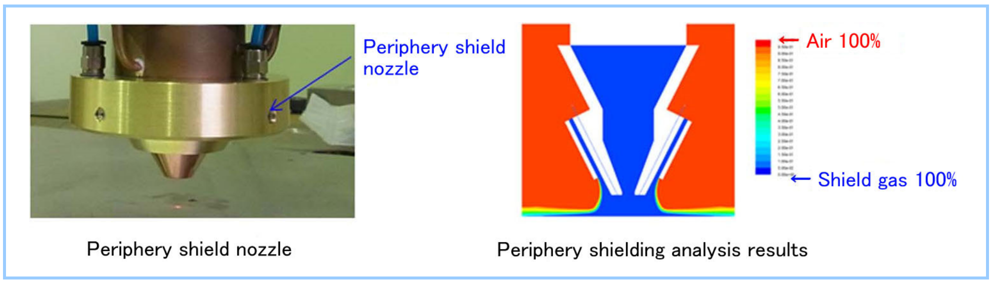

Figure 7 Periphery shield nozzle and fluid analysis results

5. Development of additive manufacturing process

We have prototyped production parts, together with industrial users in various fields, using the developed system toward practical use. Here, the prototyping of the blade-profile part, titanium alloy part and multi-layered additive manufactured part with dissimilar metals is described.

5.1 Additive manufacturing of blade-profile part

Using this system, we carried out additive manufacturing of a blade-profile part that simulates an actual part. **Figure 8** depicts the shape of the actually manufactured part. Applying the stainless steel (SUS304) powder to the periphery of the cylindrical substrate, 10 blades were manufactured, and then the blade strength (mechanical property), shape accuracy and internal defects were evaluated. For the evaluation of internal defects, an X-ray CT scanning device was used. **Figure 9** shows the scene of the additive manufacturing and the finished product.

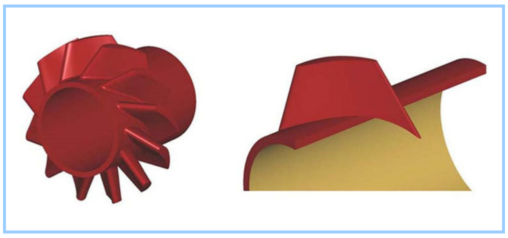

Figure 8 Shape of the blade profile

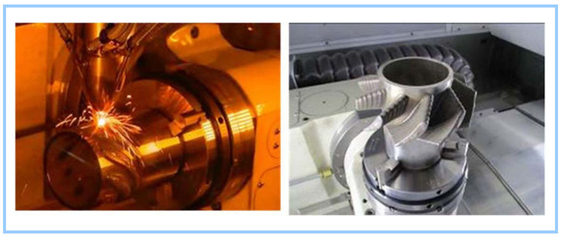

Figure 9 Scene of the additive manufacturing of the blade profile (left) and the finished product (right)

The results of the evaluation of the mechanical properties showed that the Young's modulus and drawing were 9% lower than the JIS values, but the other properties satisfied the JIS requirements. The heat deformation of the cylindrical substrate caused an error in shape, but it can be repaired by post-processing (cutting). Concerning the internal defects, although a few voids of about 0.05 mm were observed, no large defects were detected. **Figure 10** presents the shape accuracy evaluation results.

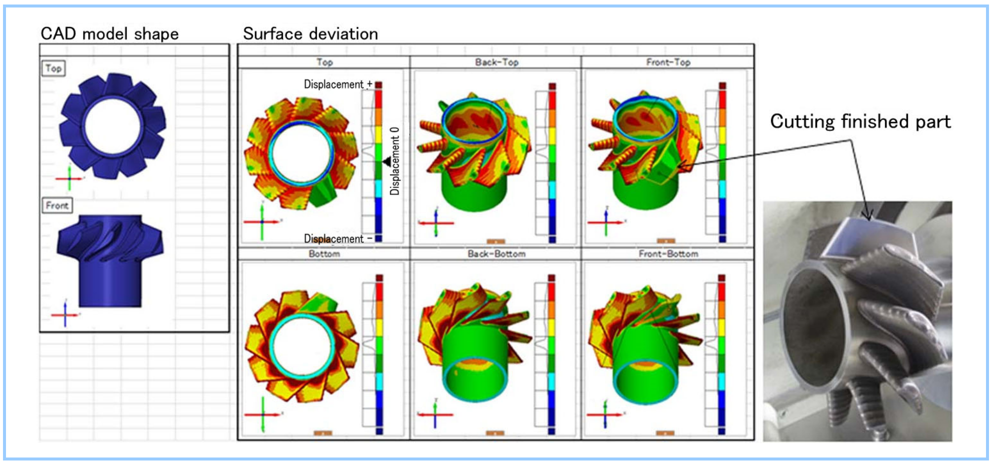

Figure 10 Evaluation of the additive manufacturing of the blade profile (shape accuracy)

5.2 Additive manufacturing of titanium alloy part

Toward the practical use of additive manufacturing of titanium alloy that easily undergoes oxidation in the atmosphere, we developed a nozzle with high shielding performance and evaluated the mechanical properties using the test specimen we made. As a result, the tensile strength and the proof stress satisfied the public standard for airplanes. No defects of larger than 0.05 mm were detected, and the chemical composition was also within the desired value. Fatigue strength equivalent to that of titanium forged material was obtained. **Figure 11** presents the test specimen made of titanium alloy and **Figure 12** gives the fatigue strength measurement results.

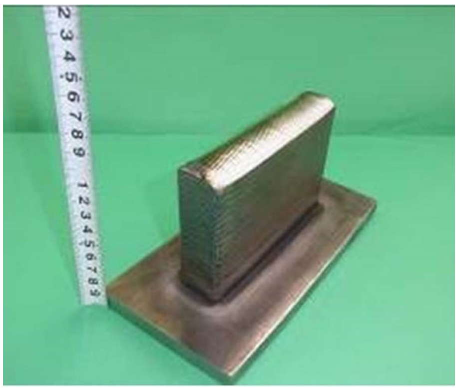

Figure 11 Titanium alloy specimen for additive manufacturing

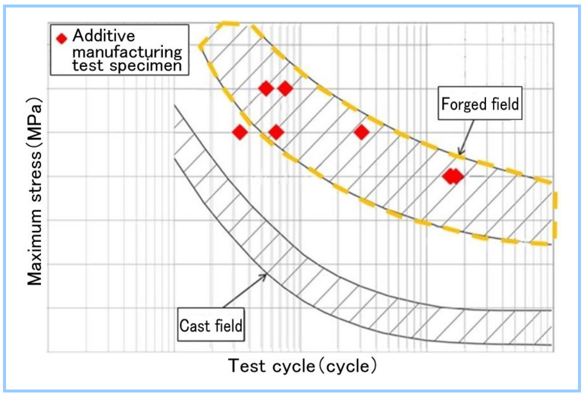

Figure 12 Measurement results of the fatigue strength of the titanium alloy

5.3 Additive manufacturing of multi-layer additive manufactured part with dissimilar metals

Table 1 lists the combination of materials used in the prototyping for the multi-layer additive manufactured parts. In multi-layer additive manufacturing with copper and ferrous metal, the layers were joined well via the intermediate material with the smallest and uniform thickness. **Figure 13** shows the results of multi-layer additive manufacturing with copper and ferrous metal.

Table 1 Combination of multi-layer additive manufacturing materials

Substrate	Additive material
Copper	Maraging steel
Chromium molybdenum steel	Stainless steel
Stainless steel	Cobalt base alloy

Figure 13 Results of multi-layer additive manufacturing with copper and ferrous metal

6. Conclusion

Our company is making efforts to develop the metal-based additive manufacturing system with Directed Energy Deposition Technology. In this report, the outline of the developed additive manufacturing system was described, and the development of the process monitoring, the powder feed nozzle and the additive manufacturing process, which are the key technologies, was introduced. In the future, MAT will promote the further advancement of these technologies and their practical use.

This research and development effort uses the achievements of the Ministry of Economy, Trade and Industry commissioned project "Monozukuri Revolution Program using 3D shaping technologies as a core (Technological Development for Next-Generation Industrial 3D Printers and Ultra-High-Precision 3D Shaping Systems)" and from the project supported by the New Energy and Industrial Technology Development Organization (NEDO).

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