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Development of A Hybrid Multi-tasking Machine Tool: Integration of Additive Manufacturing Technology with CNC Machining

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Abstract

Reduction in manufacturing cost and total in-process time is critical for industries in developed countries in order to maintain competitive advantage. At the same time, high added value manufacturing is also required. If not addressed, it will become increasingly difficult for the manufacturing industries in high-wage countries who are at a competitive disadvantage to survive in the future. In order to meet these requirements by creating a new possibility for machine tools, a Hybrid Multi-tasking machine tool has been developed by equipping Laser Metal Deposition functionality in addition to existing integrated turning and milling capabilities. The concept of a Hybrid Multi-tasking platform enables a further evolution of Done-in-One processes enabling building near-net shape components to be produced by additive manufacturing and then quickly generating the net shape through high-precision finish machining operations. It is particularly well suited to small-lot production of difficult-to-cut materials, such as aerospace alloys, high-hardness materials used in the energy sector, production tools and components and high-precision, specialty alloy designs common in medical device manufacturing. This paper introduces the features of the Mazak Hybrid Multi-tasking machine tool with application examples and demonstrates possibilities and tasks for the next generation manufacturing.
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Keywords: Hybrid Multi-tasking; Machine Tools; Laser Metal Deposition; Laser Cladding; Additive Manufacturing; Done-in-One

Nomenclature

3D	Three dimensional
AM	Additive Manufacturing
ATC	Automatic Tool Changer
CNC	Computer Numerical Control
DED	Directed Energy Deposition
LMD	Laser Metal Deposition
PBF	Powder Bed Fusion
SLM	Selective Laser Melting

1. Preface

Metal working process can be categorized into three types. The first one is removal processing which is represented by machining, grinding, polishing, laser cutting and so on. The second one is forming processing which is represented by casting, forging, stamping, injection molding and so on. The third process which has increasing focus is AM typified by 3D printing, rapid prototyping, coating, welding, jointing, etc. As the advantages of AM, it enables the production of metal parts with geometries that previously have not been possible with traditional technologies. In addition, AM is a suitable method for efficient small lot production through reduction of production lead time, set up and material preparation. However, in spite of these advantages, the majority of manufacturing industry still hardly regards AM as a truly viable manufacturing process alternative. There are a number of reasons for this; including poor accuracy and productivity of parts which are made using AM technologies. In addition, industrial scale AM equipment remains a significant capital expense. Another fundamental reason is that building parts by AM is not currently cost effective and is relatively slow compared to conventional manufacturing methods for similar

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geometry components. Therefore, in these days, a number of government-supported projects have been initiated for the development of equipment and materials for use on production lines to manufacture components in Japan and elsewhere.

On the other hand, the integration of AM with traditional technologies such as CNC machining has been widely practiced in academic and research area in order to utilize the advantages of both methods for many years [1, 2, 3, 4]. The concept of hybridizing AM and CNC machining is to enable in-process finishing of metal AM parts, typically achieving an order of improvement in accuracy and surface finish straight out of the machine as shown in Fig.1. However, the intended purposes of these hybrid concept systems were limited because these metal AM technologies have many tasks for practical applications. In addition, most of these hybrid concept systems platforms have drive axes configurations which focused on mainly additive manufacturing technologies. Therefore, they are not ideally configured for applications such as turning and 5-axis machining which are necessary functions in order to produce wide variety of complex components in one process for high-efficiency production. In order to solve these problems and propose a new manufacturing system for the next generation, Mazak has developed the Hybrid Multi-tasking machine named INTEGREX i-400 AM which has further enhanced and increased the scope of the Done-in-One (Intensive production system).

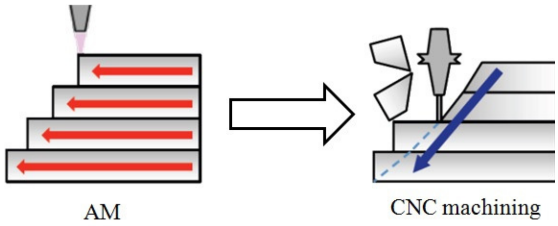

Fig. 1. Concept of hybridizing AM and CNC machining

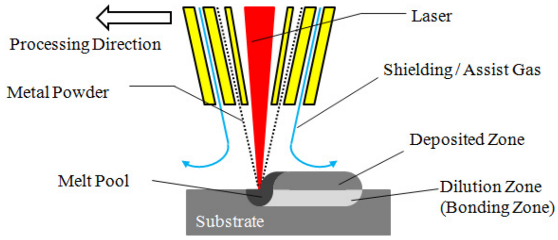

Fig. 2. LMD mechanism

2. Hybrid multi-tasking machine

2.1. Development background

Investigation has shown, hybrid concept systems have the potential and effective use for high functionality mold production, Near-net shape manufacturing, repair processing and coating. There are a number of companies which have launched hybrid machine incorporating SLM technology and milling function as a solution for high functionality mold manufacturing [5]. Mold manufacturing is relatively small for Mazak, therefore, the focus has been on the rest of three potential applications. Basically, DED technology has the advantage in these applications compared with PBF method including SLM. Therefore, Mazak decided to choose LMD technology which is one of DED as AM method for our hybrid machine because DED was developed technology from Laser cladding which is general production method in some industries. Fig. 2 indicates a simple mechanism of LMD. It is a process that uses a laser beam to form a melt pool onto a metallic substrate, into which powder is fed. The powder melts to form a deposit that is fusion bonded to the substrate. The required geometry is built up layer by layer.

Though AM has received a lot of attention as a new manufacturing technology in recent years, the strength of the evaluation of this method for building parts by AM has been less well-established. Therefore, AM has not been fully utilized as a real manufacturing method in industry. Typically, the qualification period for adoption of new manufacturing technologies normally takes long-time to be permitted as accepted manufacturing methods in aerospace industry where product safety is critical. Mazak took particular note that a significant advantage of LMD technology is the ability to combine a variety of different metals and alloys rather than building up 3D object. Though it is possible to say that there are many effective applications for LMD such as Near-net Shape, repair and coating manufacturing, it is estimated that the most effective application to utilize this significant advantage is material coating. In these days, there are many coating application requirements from the oil and energy industry and the medical industry. Coating is the technology which has been typically utilized in these industries and the strength evaluation method for this technology has been very well-established. In the point of raw material figure view, there are many applications which are full-machining from a long pipe shaft and a bar work piece in these industries. Therefore, Mazak consciously decided to select a multi-tasking machine "INTEGREX" which is designed for intensive production and an ideal platform for the hybrid machine to be developed. Fig. 3 shows the developed hybrid multi-tasking machine "INTEGREX i-400 AM".

2.2. Introduction of INTEGREX i-400 AM

The developed machine as the platform of CNC machining consists basically of 5 axes: 3 linear axes (X, Y and Z), a rotary C axis of the turning spindle, and a rotary B axis around the Y axis. In addition, this machine has a second turning spindle for higher productivity through the ability to carry out secondary operations in a single set up. In order to integrate LMD technology to the multi-tasking machine, Mazak developed two types of LMD heads as shown in Fig. 4.

Fig. 3. INTEGREX i-400 AM

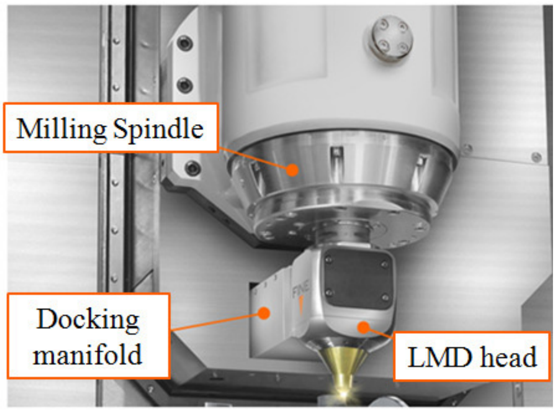

Fig. 5. LMD head and docking manifold

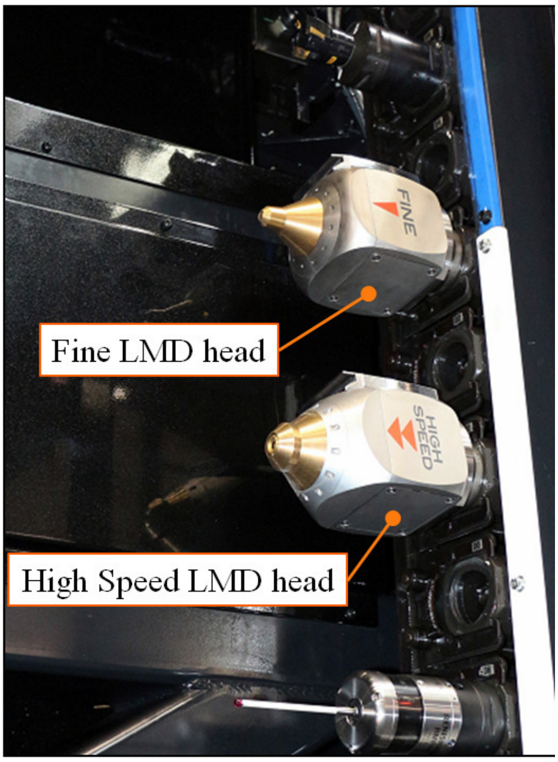

Fig. 4. ATC-able LMD heads in the tool magazine

One of them is "Fine" LMD head which is a co-axial laser cladding type. It is designed to confine the supplied amount of metal powder and the laser power aimed at high accuracy LMD for intricate feature generation with a bead size of W: 1 mm and H: 0.5 mm. The other is "High speed" LMD head which enables laser cladding with higher speed and more efficient deposition rate, delivering a bead size of W: 3 mm and H: 1 mm because the special lens in the head makes top-hat power distribution and focus for a high power multi-mode laser with a big laser spot size. In the case of LMD process for Inconel 718 powder, the deposition rate of "High speed" LMD head is about 1.0 kg/ hour. The various types of LMD head are selected according to the type of application process and enable to have a wider range of effective operations than using a single LMD head. They provide robust process flexibility to meet a range of application requirements.

These LMD heads are designed to be stored in the standard tool magazine thanks to the head interface design being the same as other machine tool holder interface. In this example, it is Capto-C6.

As the process of LMD, the AM head is loaded to the milling spindle by ATC. Then, the protection cover which is a countermeasure against contamination into optical parts in LMD head is removed from the head automatically and the head docks to the manifold. This provides a laser, metal powder and inactive gas. Fig. 5 shows the condition for LMD processing in this system.

Mazak developed this machine with safety-minded because a fiber laser is applied as a heat source to melt metal powder and substrates. For example, this machine was developed with covering the processing area fully to prevent a laser light leakage, improving the door interlocking system for an operator and applying a mineral glass for operating windows to protect operator's eyes. In addition, the fume extraction system is installed to avoid affect on the human body by suspended metal powder in the atmosphere of processing area. Extra lights for processing area, furthermore, are also placed on the basis of ergonomics to ensure enough visibility for operators.

3. Application example

Considering the potential purpose of use as mentioned above, Mazak developed an application example for oil-energy industry. The material of cylinder shaft substrate is Stainless Steel alloy (316S31), a popular material for casing pipes used in offshore oil due to the good corrosion-resistance

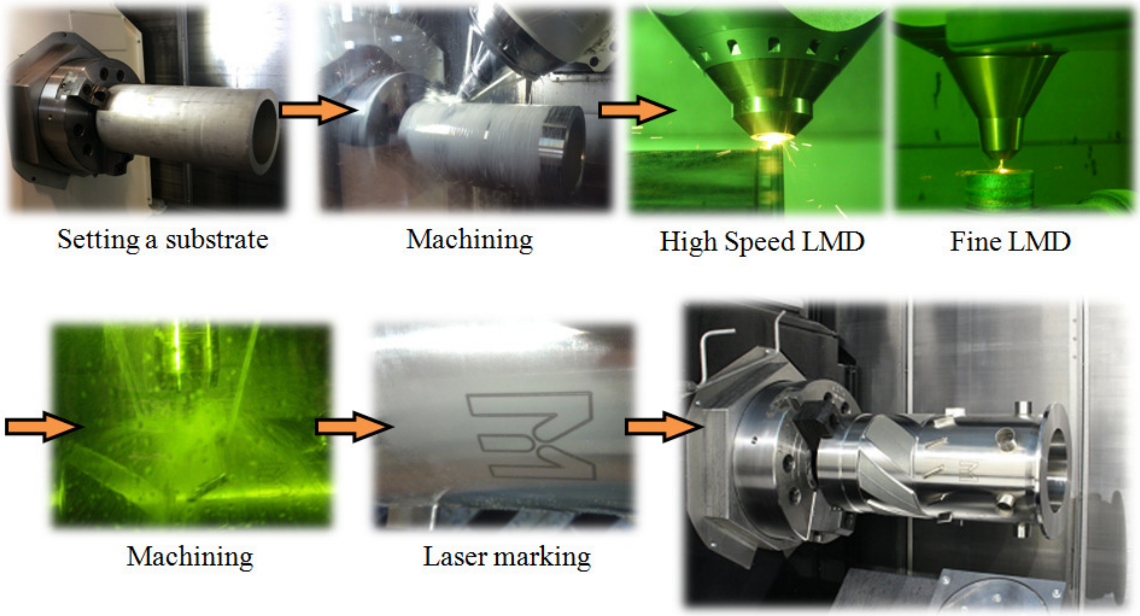

Fig. 6. Application example of a hybrid process by INTEGREX i-400 AM

against seawater. The metal powder for deposition is Nickel-base alloy Inconel 718 with characteristics ideal for environments with high-temperature, corrosion, oxidation and creep resistance. The particle diameter of the powder is approximately 50 – 100 µm. This is the application for the purpose to make a product with high-value adding, improving productivity and reducing production cost by jointing high-functional and dissimilar metal materials to substrates. In addition, this application includes laser marking in order to propose the idea which the hybrid machine can create a product in one process with ensuring traceability as well.

The hybrid process for the application by INTEGREX i-400 AM is shown in Fig.6. This application makes 6 parts of spiral coating, 12 fins and a flange in the hybrid process with "High Speed" LMD and CNC machining. 6 bosses are made in the hybrid process with "Fine" LMD and CNC machining. Our company logo is carved in 6 areas as laser marking which is done by Fine LMD head without metal powder feeding. Fig.7 indicates the cycle time of each part. As in Fig.7, the total cycle time of this application is 634 minutes. Considering about the case that the same shape of this work-piece is produced by machining from a solid material of Inconel 718, the cycle time in the hybrid process is not dramatically improved. However, it is clear that hybrid process gets a serious reduction in material cost and tool consumption. Even though the price of metal powder is still expensive in the market, the deposition area in this application is limited and the amount of metal powder consumption is less than 10 kg in this application. It is in the region of $2,000 as an indicative estimation. The Stainless steel substrate is about $500 by 50 kg. Therefore, the total material cost is about $2,500. On the other hand, in the case that the same shape of this work-piece is produced by machining from a solid material of Inconel 718, approximately 90kg of the solid material is necessary because of the size. It costs more than $90,000 in material only. In addition, it is obvious that the tooling consumption for machining Inconel 718 materials from 90 kg to 50 kg as a finished product is huge amount. Therefore, it is possible to say that there are many applications like this case that hybrid process has a big advantage comparing to conventional way, if all parts of the product are not necessary to be manufactured from the same high-valued material.

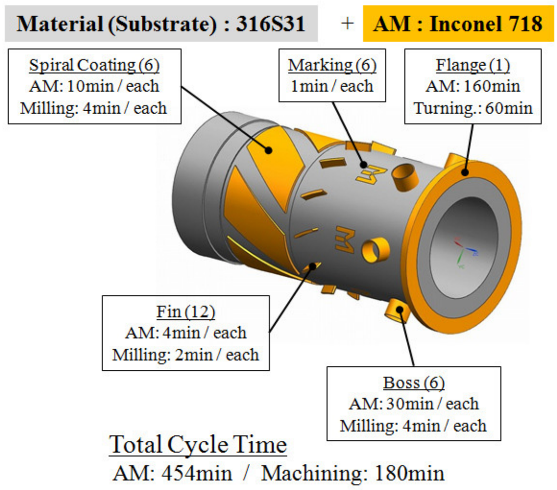

Fig. 7. Total cycle time of the application

4. Result of LMD process evaluation

In order to evaluate the deposited and jointed material in the point of strength and micro structural view, test pieces were manufactured that meet Japanese Industrial Standard number 10 by AM process in this machine with the same condition of this application as mentioned in the last chapter. The contents of the tests are mechanical strength testing, hardness measurement and microstructure observation for (A) the deposited Inconel 718 material and (B) jointing part between the deposited Inconel 718 material and the 316S31 substrate. These test pieces are not heat-treated. The specimens for the mechanical strength testing of (A) and (B) are shows in Fig. 8. The result is shown in Fig. 9, Table 1 and 2. As seeing these results, the mechanical strength of (A) the deposited Inconel

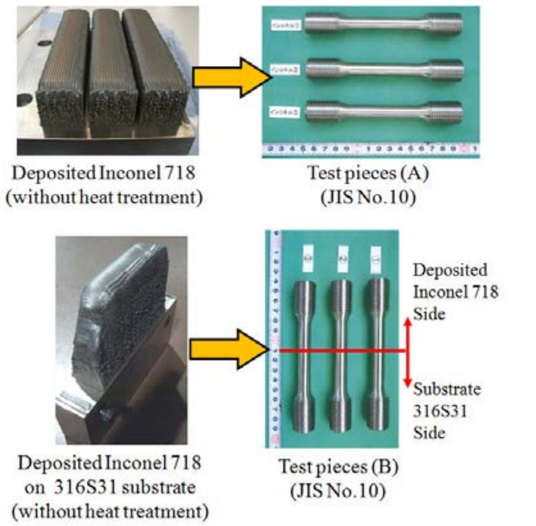

Fig. 8. Specimens for tensile strength testing

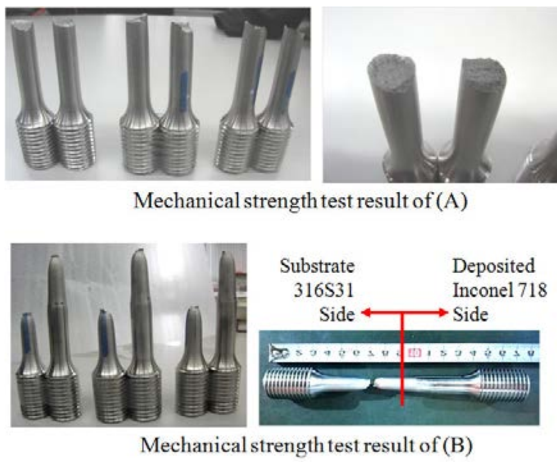

Fig. 9. Results of tensile strength testing

718 material is almost equivalent with it of a hot-rolled Inconel 718 bar which is no heat treatment. In the tensile strength test for (B) the jointing part between the deposited Inconel 718 material and the 316S31 substrate, the rupture point is not the centre of test pieces. Though the centre line is the bonded interface, the rupture point is at the side of 316S31 which the tensile strength is lower than Inconel 718. In fact, it means that the strength of joint between the deposited Inconel 718 material and the 316S31 substrate is higher than the mechanical strength of the 316S31 substrate itself. As indicated in Fig. 10 which is the microscopic picture of (B) the jointing part between the deposited Inconel 718 material and the 316S31 substrate, any defect is not observed in the high densely deposited material. In addition, as the feature of LMD, the amount of dilution and heat-affected zone in a substrate is quite small and it enables high mechanical strength of the jointing dissimilar materials. Therefore, it is possible to say that LMD has a potential to change the conventional product design and manufacturing process in a fundamental way.

Table 1. Mechanical strength testing result of (A)

	Average result of (A)	Inconel 718 Hot-rolled bar, No heat treatment
0.2% proof stress (N/mm^2)	587	591
Tensile strength (N/mm^2)	931	965
Elongation (%)	31.7	46
Reduction of area (%)	31.2	58
Hardness (HRC)	23	23

Table 2. Mechanical strength testing result of (B)

	Average result of (B)	316S31
0.2% proof stress (N/mm^2)	293	205
Tensile strength (N/mm^2)	563	520
Elongation (%)	39	40
Reduction of area (%)	80	60

5. Conclusion

Due to the technical limitation of AM, Mazak developed the Hybrid Multi-tasking machine tool equipped LMD function in addition to turning and milling capabilities. By utilizing this machine, it was found that there are many applications in some cases that a hybrid process has a big advantage comparing to conventional manufacturing method. Simultaneously, Mazak demonstrated the application example work with enough mechanical strength as an industrial product by the hybrid process. It is expected that this method will become popular in various industries for manufacturing prototype or high-valued products, repairing and coating products.

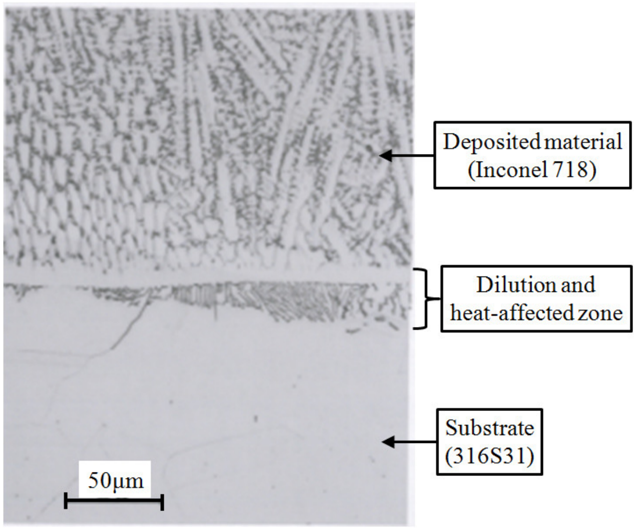

Fig. 10. Micrograph cross-section view of (B)

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