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A Study on the Status of Metal 3D Printing and Design Methods of Printing Materials

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Abstract

3D printing technology, which is capable of manufacturing complicated shapes much easier than conventional molding processes, such as casting/ forging, extrusion, injection, welding, and etc., as well as reducing manufacturing time and making various kinds of small quantity products end users want, is rapidly emerging as an innovative technology that can change the existing manufacturing industry paradigm. In particular, metal 3D printing technology has large industrial ripple effects because it can be applied to a wide range of industrial fields from existing main industries such as automobiles, space / aviation, and marine vessels to advanced industries such as defense, bio / medical, and electromagnetic fields, resulting in a growing interest in metal 3D printing in the corresponding industry sectors. However, the research on metal 3D printing technology worldwide is only at a beginning stage. In this study, the present status and problems of the development of the powder materials for metal 3D printing and the design methods of future materials for metal 3D printing shall be discussed.

Keyword : 3D printer, metal 3D printing, 3D printer material, the 4th industrial revolution

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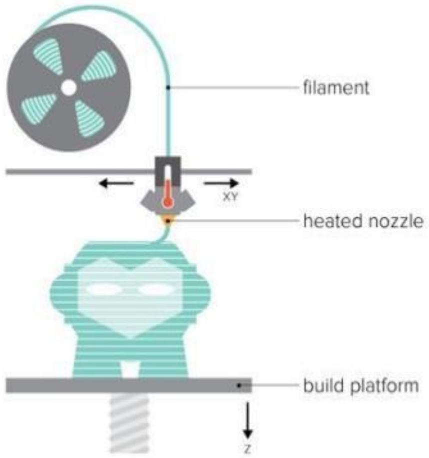
1. Introduction

3D printers, that have been called the alchemy of the 21st century, are attracting attentions from many fields. As many early technologies, bubble controversy was not negligible, but it is enhancing its utilization by gradually increasing its application range. Until the early 2000s, 3D printing technology was used only in some limited areas such as product model and prototype productions since its first development in 1981[1][2]. However, in recent years, it has been applied to various industrial fields, especially in the field of functional part manufacturing, with technological developments and economical reasons. The reasons why so many attentions are focused on the 3D printing technology is because of its advantages of being suitable for production of a small quantity of customized products while greatly reducing the assembly cost compared to the conventional manufacturing process and enabling consumers' direct productions. With such advantages, its area of application in manufacturing fields, such as medical, aviation parts and construction, is gradually increasing. Also, with the existing RP (Rapid Prototyping) applied to, it has a great impact on the automobile, medical, industrial, machinery, education, construction and consumer goods industries[3].

3D printing technology is a technology to produce three-dimensional products by stacking various layers of materials such as powder, liquid, wire, and pellets[Fig. 1].



[Fig. 1] Basic principle of stereolithography apparatus method

Since it can easily manufacture parts with complicated shapes that can not be realized by conventional manufacturing processing technology, it has recently been in the spotlight worldwide as a new processing technology. 3D printing technology cannot only dramatically shorten product development time compared to conventional processing technologies of casting, forging, welding and extrusion but it can also reduce the loss of raw materials, without having to have chips formed during the cutting process, and meet the customer's requirements of shapes and functions. Thus, it is recognized as an innovative technology that can change the paradigm of existing manufacturing industry[4].

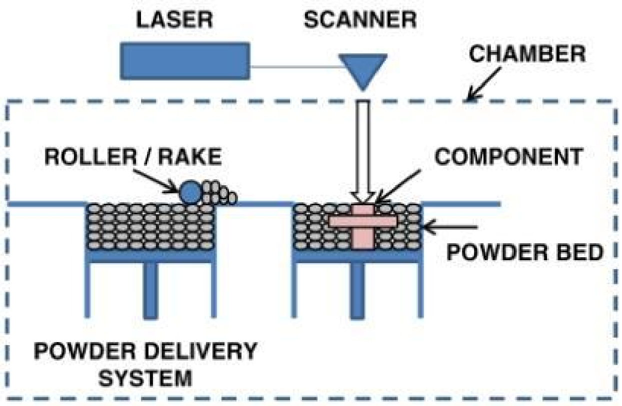
Currently, the 3D printing market is centered on equipment. However, if the product and service market expand with activated technology, it is expected that the material market will grow significantly grow because it consumes materials proportionally to the product productions. Moreover, the demand from material suppliers is expected to increase with market activation and growth, resulting in decreased material costs. The most widely used materials for 3D printing are polymeric resins, such as PLA and ABS, and metal powders, such as aluminum and titanium[5]. In particular, 3D printing utilizing metal powder is mainly used in molds, dentistry, automobiles and aerospace. The most valuable metal in the field of metal 3D printing is titanium since it satisfies various properties that 3D printing material should have, such as strength and corrosion resistance. Titanium can be used alone, but it is mainly used in the form of titanium alloy with manganese or aluminum[6].

Recently it has gained more attention with the capability of processing various materials such as metals and plastics. In particular, the utilization area of metal 3D printers is very wide. With recent expiration of the patent on the 3D printer technology, there are many prospects of rapid supplies. Unlike the earlier 3D printers that used plastic materials, metal 3D printers can fabricate variety of metal materials into desired shapes. Because metal 3D printers can make parts without molds, it can innovatively reduce manufacturing costs and time. It has a high rate of utilization as it can produce complex parts that cannot be easily produced with previous manufacturing processes[7][8].

However, the research on metal 3D printing technology worldwide is only at a beginning stage, This is because in order to apply 3D printing technology in industrial parts, beyond the existing application in prototype productions, the mechanical properties of the parts must be secured; however, density or the mechanical properties of the molded object are not yet sufficient enough to be applied to the industrial environment. In addition, not many studies have been conducted because metal 3D printing equipment is much more expensive than conventional plastic 3D printing equipment, the prices of materials are expensive and materials types are also very limited due to exclusive material supplies made by machine makers. In this study, the present status and problems of the development of the powder materials for metal 3D printing and the design methods of future materials for metal 3D printing shall be discussed[9].

2. Metal 3D Printing Technology

Metal 3D printers can be broadly divided into Powder Bed Fusion(PBF) method and Directed Energy Deposition(DED) method[Fig. 2][10]. PBF is a method in which powders are laid flat on a powder bed and sintered or fused by selectively irradiating a high energy laser or electron beam. The laser uses a galvanometer scanner to control the laser path and a deflecting lens composed of coils to move the electron beam. The biggest advantage of PBF is that it prints complex shapes without much problems. It is favorable in the production of difficult-to-cut materials and complexly shaped high value-added products. As such, it has an excellent precision. However, since the productivity is low and the sintering and fusing uniformity of laminated products is not good, the strength of products is weak and it is difficult to secure impact values. PBF has evolved from the introduction of the Selective Laser Sintering (SLS) process by Germany's EOS, which is based on powder and laser heat sources. Currently, many companies are developing solutions focused on selective SLM (Selective Laser Melting) process.



[Fig. 2] Powder Bed Fusion

In DED, when a high-power laser beam is irradiated on a metal surface, melting ground is generated instantaneously and metal powder is also simultaneously supplied to laminate in real time[11]. It can be stacked on top of existing products, in a way similar to welding, and can be used for repair and maintenance work. In addition, various powders can be used simultaneously to make alloys in real time or to use other materials. Although DED has a disadvantage of requiring post-processing due to low precision, it has high productivity, excellent reproducibility, and high strength and impact values. DED method can be classified into 'powder-based DED', which feeds and stacks powders coaxially using a high-energy laser or electron beam and 'solid-filler-based DED', which melts and laminates with various heat sources by feeding solid-filler materials, similar to welding. Powder-based DED has been researched and developed under various names such as DMD (Direct Metal Deposition), DMT (Direct Metal Tooling)7) and CLAD (Construction Laser Additive Direct), depending on the laser company[12].

[Table 1] PDF & DED

	Material	Power Source	Process
PDF	Power based	Laser	SLS(Selective Laser Sintering)
			DMLS(Direct Meral Laser Sintering)
			SLM(Selective Laser Melting)
		Electron Beam	EBM(Electron Beam Melting)
DED		Laser	LENS(Laser Engineered Net Shaping)
			DMD(Direct Metal Deposition)
			DMT(Direct Metal Tooling)
			CLAD(Construction Laser Additive Deposition)
	Solid Filter based	Electron Beam	EBAM(Electron Beam Additive Manufacturing)
		GTAW,GMAW arc	WAAM(Wire Arc Additive Manufacturing)
		GMAW arc	DML(Direct Metal Lamination)
			ADED(Arc Directed Energy Deposition)
		Plasma arc	IFF(Ion Fusion Formation)
			RPD(Rapid Plasma Deposition)
		GTAW arc	STAM(Spper-TIG Additive Manufacturing)

Metal 3D printing techniques are broadly divided into PDF and DED methods. It can be further subdivided depending on the type of material and powder source. It is also variously called by each laser company. It is recommended to use the table as the reference when too many terms cause trouble understanding[Table 1]. When choosing a metal 3D printer, PBF or DED method whichever is suitable for the type of processing can be selected. Because each technology has a clear advantage and disadvantage, no technology can be concluded to be more advantageous than the other, but the trend of recent technology development is leaning to one side.

According to the 'Trend of Metal 3D Printing by Welding' published by the Korean Welding and Joining Society, it is shifting worldwide from PBF to solid-filler-based DED to improve productivity. This is because solid-filler materials are more economical than special powder materials, such as Ti and Inconel, and solid-filler-based DED has better productivity. Therefore, despite the low precision and less degree of freedom, there is a remarkable increase in the number of studies carried out on DED process.

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3. Metal Powder Materials for 3D Printing

The metal powders used in metal 3D printing processes are mostly spherical powders produced by a gas atomizing method. The reason why spherical powder is used is that spherical powder has better fluidity compared to other angular or irregular powders. It is advantageous to increase the density and mechanical properties of the final fabricated object by using a powder having excellent fluidity for application and discharge of uniform powder layers. The reason why metal powder materials supplied by metal 3D printing equipment suppliers are expensive is because the production yield of raw material powder is very low. Generally, metal powders used in Powder Bed Fusion (PBF) method metal 3D printing are spherical powders having a size of 10 to 45 µm. However, when powder is produced by gas atomization method, the average powder particle size is about 80 µm with a particle size distribution of approximately 10 to 200 µm.

Among them, powder having a size of 10 to 45 µm is only about 10 to 15%, making the metal powder used for 3D printing costly. On the other hand, there are metal powders for 3D printing, other than those supplied exclusively by equipment manufacturers, including metal powders from Hoeganaes in Sweden, Sanvik-Osprey in the UK and Carpenter in the US.

However, to strictly speak, the metal powders supplied by the above companies are not materials developed for the exclusive use in 3D printing. The above companies manufacture and sell metal powders for the conventional powder metallurgy industry. Among their products, they sort out powders with the size of 10 to 45 µm from those prepared by gas atomization and sell them for 3D printing. However, unlike conventional powder metallurgy molding and sintering processes, it is essential to develop a newly designed alloy composition in order to improve density and mechanical properties of the fabricated objects in the 3D printing which fabricates the objects by rapidly melting powders with lasers and rapidly cooling molten metal. Nonetheless, most powder manufacturers currently do not manufacture or sell alloys exclusively designed for 3D printing.

Therefore, in order to expand the application of metal 3D printing technology in the manufacturing industry, the development of dedicated materials optimized for 3D printing must be preceded and printing processes using dedicated materials as well as post treatment and heat treatment processes must be also developed. The 3D printing material market, according to Wohlers Report, is expected to grow significantly from about $ 420 million in 2012 to about $ 2.5 billion in 2019. Also, the annual growth rate is expected to grow at a rapid rate of about 30%. However, plastics and polymers account for more than 70% whereas metal only takes up about 15%, indicating still insignificant market for metal 3D printing materials. On the other hand, as the importance of metal 3D printing technology becomes more and more increasing, documents showing the market prospects of metal 3D printing materials have been released one after another.

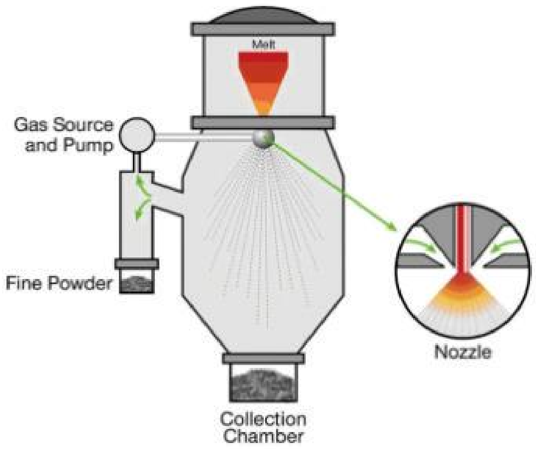
According to the data released by Smartech Markets Publishing in 2015, the metal powder market for 3D printing in 2014 is only about $ 200 million, but in 2023 it is expected to remarkably increase and reach about $ 950 million. By materials, four alloys, in the order of, Co-Cr alloy, Ni alloy, Ti alloy, and Fe alloy are expected to account for more than 90% of the market. In particular, non-ferrous alloys such as Co, Ni, and Ti occupy a higher proportion than iron-based alloys, indicating significantly increased applications in heat-resistant and wear-resistant materials in the energy and power industries and medical products such as dental and orthopedic implants. On the other hand, the metal materials used for 3D printing were less than 500 tons in 2014, but it is projected to remarkably increase to about 16,000 tons by 2025. Among them, Ti alloys account for more than 50%, which means that the use of Ti alloys to reduce weights in the aerospace industry will increase sharply.

Although, different estimates are reported for each sector of 3D printing applications, it is expected that the market for powder materials for metal 3D printing is expected to increase dramatically and the demands from high-tech industries such as aerospace, energy and power generation will increase explosively.

4. Manufacturing Methods of Metal Powders for 3D Printing

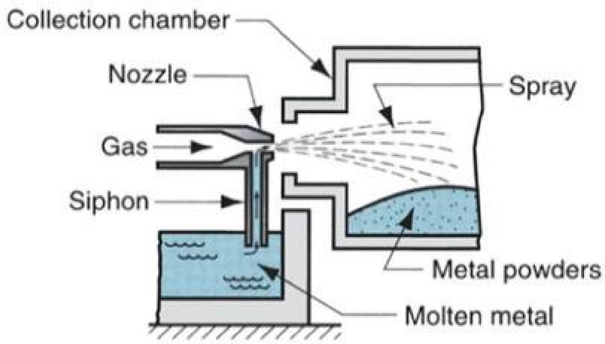
The metal powders used in 3D printing process is spherical metal powders having high fluidity, and are generally manufactured using gas atomizing method. As shown in [Fig. 3], the gas atomization method is a method in which a metal is heated and melted at a high temperature, and then compressed gas is sprayed to a molten metal stream flowing down from the molten metal nozzle to produce powders by scattering molten metal stream.

The advantages of gas atomization method are wide production range from single metals such as Sn, Zn, Al, Cu, Ni, and Fe to alloys such as Cu-Zn and stainless steel and mass production of metal powders with various properties. Also, the properties of the produced powder can be freely manipulated by controlling the spraying conditions of the molten metal, For gas spray method, gases of air, nitrogen, helium and argon are used for the spray of molten metal, and powder is produced when the molten metal is dispersed by the sudden gas expansion in the nozzle. The design of equipment varies depending on the injection method of the molten metal, melting method, and structure of the chamber. But, the main principle is that the energy of the rapidly expanding gas is transferred to the molten metal stream flowing through the gas nozzle, solidifying in the form of small powder. Since the spray of gas is carried out in an inert gas atmosphere, high purity alloy powder can be produced.



[Fig. 3] Overview of Gas Atomization Process Technology

Powders produced generally have a spherical shape and a wide range of particle size distribution of 10 to 200㎛. The figure in [Fig. 4] shows a low temperature gas spray process designed based on a horizontal gas spray system.



[Fig. 4] Outline of Horizontal Gas Atomization Process Technology

The high-speed gas passing through the nozzle serves the role of sucking up the lower molten metal through the pipe and moves the molten metal to the region where the gas expands. The higher the gas speed, more fine metal droplets are formed which lose heat during traveling through the chamber and solidify into a particulate state. In horizontal sprays, powder remains in the bottom of the chamber while the gas flows out through the filter. On the other hand, for refractory metals, inert gases and a sealed chamber are used to prevent oxidation. The shape changes of a droplet during its journey. At first, it is a ligament shape, but its shape gradually changes to a sphere. At this time, if the size is small, it tends to aggregate. The size of the powder is affected by the viscosity and temperature of molten metal and the acceleration. The higher the temperature of the bath compared to the liquidus, the lower the viscosity. After spraying, the solidification time of the droplet is increased and the powder becomes spherical. As a result, the shape of the final powder can be controlled by adjusting the temperature of the molten metal. Meanwhile, when turbulence occurs near the nozzle, small particles return back to the gas expansion zone and cause satellites to form around coarse powder.

Plasma Rotating Electrode Process (PREP), similar to centrifugal atomization, is also used for metal powder manufacturing, In this method, a metal to be produced is processed into a rod shape and rotated at a high speed to generate a plasma between cathodes. Then, the high-temperature plasma heat melts the metal rod and produces powders by centrifugation. It is mainly used for the production of powders of refractory metals such as Ti. It is reported to exhibit excellent properties as 3D printing powder, with low contents of bubbles. However, this method is very expensive due to its low yield. Also, it is too coarse to be used for PBF-type printing, having an average size greater 70㎛. In addition, Ti powders can be also prepared by HDH (Hydride-Dehydride) method, which forms TiHx hydrate having high brittleness by binding hydrogen and Ti, and then pulverizes the hydrate into powder and produces Ti powders after removing hydrogen. Although this process is known to be the cheapest process to produce Ti powders, because the shape of powders produced by this method is a square, a spheroidization process is necessary to improve the fluidity. The spheroidization process is generally a method of changing a rectangular powder into a spherical shape by surface tension in a high-temperature plasma using a jet plasma. However, since the spheroidization process is relatively expensive and the yield is low, there still is a limitation for mass production.

5.Conclusion

3D printers have been rapidly spreading worldwide in recent years, and the technology is expected to bring various impacts such as reducing production costs by reducing the amount of process scraps generated and reducing manufacturing costs compared to conventional manufacturing technologies. Currently, the 3D printing market using synthetic resins materials, has already been dominated by developed countries such as the US, Japan, and Germany. The price has been lowered so that it can be applied to the low-priced (home-use) method and materials have been smoothly supplied. Domestic technology level seems to be lagging behind the world level by more than 10 years and securing market leadership is not expected to be easy due to sufficient market maturity.

For this purpose, it is very urgent to develop a technology capable of manufacturing a material having excellent characteristics at a low cost. This is expected to determine the speed of development of the market and diversification of utilization fields, playing as a key factor for market development. In addition, despite the fact that interest in 3D printing is increasing in Korea, burden on initial equipment investment, production speed and prejudice and concern about strength and precision of product are obstructing the expansion of 3D printing market. Therefore, it is deemed necessary to promote 3D printing, setup opportunities for direct experience in 3D printing and supplement the government's support policy and business model to raise public awareness.

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